World Premier International Research Center Initiative (WPI)
Executive Summary (For Extension application screening)

Host Institution	The University of Tokyo	Host Institution Head	Junichi Hamada
Research Center	Kavli Institute for the Physics and Mathematics of the Universe	Center Director	Hitoshi Murayama

A. Progress Report of the WPI Center

I. Summary

The Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) was proposed to study five interrelated, basic, yet ambitious questions about the Universe:

- How did the Universe start?
- What is the Universe made of?
- What is the fate of the Universe?
- What are its fundamental laws?
- Why do we exist?

While these questions have been asked by humankind for millennia, advances in the last decade or two now make it possible to address them by scientific methods.

The Kavli IPMU was founded from scratch with the WPI funding on October 1, 2007, as a unique interdisciplinary institute in the world that combines mathematics, theoretical and experimental physics, and astronomy. Since then, it has grown to an international research center of about 150 members. It has produced high impact signature papers with a clear "made in the Kavli IPMU" brand, with citation counts and the number of highly cited papers comparable to or better than world-leading institutes. We receive 800 visitors on average every year, half of them from abroad; about 700 job applications every year with more than 90% from overseas; and more than half of about 90 Ph.D. scientists on site are international. More than a third of the postdocs who have left the institute are already in faculty positions. We created an environment for strong mutual inspiration between mathematics and physics, and unexpected synergies between astronomy and mathematics as well as connections with condensed matter physics have emerged. We proposed to carry out experimental and observational programs from accelerators, underground laboratories, and telescopes, and have launched major experimental initiatives such as HSC, XMASS, and KamLAND-Zen successfully. The interdisciplinary environment allowed us to spawn new initiatives such as SuMIRe and LiteBIRD, garnering strong international attention. Our outreach program has been highly successful and mobilized more than 22,000 people, with strong media attention providing close to a thousand instances of international coverage. We spearheaded many unprecedented achievements in system reform at the University of Tokyo, such as split appointments, merit-based salary scales, and endowment donation from a foreign foundation.

II. Items

1. Overall Image of Your Center

Overall, the Institute came out exactly as proposed. Our unique building allows mathematicians, physicists, and astronomers to be located under the same roof, sharing seminars and the daily teatime. Interdisciplinary discussions have become commonplace. The Institute is highly international. Thanks to several high profile papers and international visibility, our members are invited to major conferences as keynote or summary speakers, including Strings, Lepton Photon, Neutrino Conferences, International Congress of Mathematicians, and Nobel Symposium. Many of our faculty members have been invited to write major review articles.

We fostered mutual inspiration of mathematicians and physicists despite big differences in purpose, culture, and language. We actively recruited key "interpreters" to overcome the barrier between mathematicians and physicists, and they played critical roles to make the interdisciplinary research a reality. This is crucial for addressing "what are the fundamental laws?"

Unexpected synergies emerged. We did not imagine that astronomers and mathematicians would interact, or phenomenologists and mathematicians would write joint papers, yet both happened. Our research building specifically designed to mix up people from different disciplines and the *mandatory* daily teatime for informal interactions have proved extremely successful.

The big projects proposed in the original proposal are well underway. XMASS was built and has produced the world's best limits on some dark matter candidates, addressing "What is the Universe made of?" The KamLAND-Zen effort has produced the world's best limit on possible transmutation between matter and anti-matter, addressing "Why do we exist?" The new 3-ton digital camera HSC with 870 million pixels was designed, built, and commissioned. An unprecedented 300-night survey is now approved and started, addressing "What is the fate of the Universe?"

2. Research Activities

Our research activities span a very wide spectrum from pure mathematics and theoretical physics to experimental physics and astronomy as summarized in the Progress Report. Here we do not try to cover more than 1500 papers exhaustively, but rather focus on a very few select results.

What is the Universe made of?

It has been known since 2003 that more than 80% of the matter in the Universe is mysterious dark matter not made of atoms. It is responsible for building up the stars and galaxies we see in the Universe today, yet its nature is completely unknown. Without it, we would not be here today.

We have created maps of dark matter in the Universe, even though we cannot see it directly in telescopes. According to Einstein's theory of relativity, gravity from dark matter acts on light, distorting the images of background galaxies (gravitational lensing). By studying the distortion of images, we can reconstruct 2D maps of dark matter, and "see the invisible." Our Professor Takada and collaborators carefully examined 30 clusters of galaxies with the Subaru telescope, and proved that the dark matter maps are consistent with what was expected based on our numerical simulations. In addition, we could demonstrate for the first time that they are not round but rather shaped like rugby balls. This work currently has 112 citations. We will extend this technique to build 3D maps of dark matter with SuMIRe (see B.1), and Takada is the co-chair of its science team.

It is believed that dark matter is composed of yet-to-be-discovered tiny particles. PI Suzuki leads the XMASS experiment trying to detect dark matter particles directly with a highly sensitive device in the Kamioka underground laboratory. It has demonstrated a versatile capability in looking for many different reactions, producing the world's best limit on certain candidates of dark matter.

What are its fundamental laws?

This is the area where ideas from theoretical physics and new development in mathematics intersect. The best physical theory that attempts to unify all matter and forces is string theory, which says that our Universe is actually nine dimensional rather than three; six extra spatial dimensions are made small on special types of spaces called Calabi-Yau manifolds. Because each possible Calabi-Yau manifold represents a solution to string theory, hence to a possible Universe of its own, we need to understand how many of them there are, to explain why the Universe is the way it is. We distinguish them from one another using quantities called topological invariants.

Using inspiration from physics, our young Associate Professor Toda could prove a conjecture by Fields Medalist Okounkov on equivalence of various topological invariants of Calabi-Yau manifolds. Yamazaki, then a graduate student in physics and now our Assistant Professor, pointed out to him that a paper in physics might be relevant to this research in mathematics. Thanks to Professor Hori, who came from a position both in the physics and mathematics departments at Toronto, and acts as a key "interpreter" between physics and mathematics at our Institute, Toda could use the inspiration from the physics paper and prove this conjecture. As a result, he was invited to give a talk in the summer of 2014 at the International Congress of Mathematicians, which is held only once every four years, and also received two Prizes from the Mathematical Society of Japan.

Some of the manifolds with completely different shapes mysteriously lead to the same Universe. Professor Hori discovered a new type of this phenomenon called *duality*. Using the combination of these results in mathematics in physics, we hope to generate a list of all possible Universes.

Why do we exist?

To understand why we exist, we need to understand how stars are born. Yoshida, who became the youngest Professor in the Faculty of Science, managed to simulate how the very first stars in the Universe formed from first principles without assumptions. This was published in Science, with 106 citations; he received a prize from International Union of Physics and Applied Physics.

In what types of galaxies do stars form best? By combining observations that study not only stars but also dark matter, our Assistant Professors Leauthaud and Bundy discovered that there is a "just right" size of galaxy to form stars most efficiently. This paper received 94 citations and was tied for 9th most cited paper in astrophysics in 2012.

For life to emerge, we need chemical elements beyond helium. They are formed inside stars and spread by explosions called supernovae. How? Associate Professor Maeda and PI Nomoto observed a number of supernovae a year later and could see "inside" after the ejected materials became transparent. They discovered for the first time that most of the supernova explosions were not spherical and the gas is spreading out in a bipolar jet-like form. It received 85 citations.

Another essential ingredient to answering this question is to understand why anti-matter disappeared, leaving matter behind. Our members proposed a theory that neutrinos are responsible for this miraculous feat because they are the only elementary matter particles without an electric charge. Our Assistant Professor Kozlov pushed the KamLAND group to look for a possible conversion between matter and anti-matter through neutrinos, and the resultant KamLAND-Zen effort has produced the best limit in the world.

In addition we uncovered clues on how supermassive black holes grow, and determined the distribution of cosmic dust accompanied by dark matter. Professor Vagins showed we can detect supernova neutrinos from cosmological distances by doping gadolinium into Super-Kamiokande.

How did the Universe start?

Our Universe is believed to have started with an explosive expansion called inflation. Before inflation, the whole Universe we see today was supposed to be much smaller than the size of an atom. Yet we do not have a definitive experimental proof of this paradigm. On the other hand, Associate Professor Mukohyama discovered an alternative theory that does not need inflation. If it pans out, it presents a completely new paradigm. This is a brave idea, and has a 96 citations because of its potential impact. We will attack this exciting problem with LiteBIRD (see B.1).

The discovery of the Higgs boson in 2012 also sparked active research. It shows the state of the Universe a billionth of a second after the Big Bang. In order to extrapolate it to even earlier moments, we need a consistent theory that explains the observed mass of the Higgs boson; this proved to be difficult. PI Yanagida and others came up with a supersymmetric theory called pure gravity mediation by combining crucial contributions of our members, and predict a new type of candidate for dark matter. It may be verified in the near future. This series of papers is highly cited.

What is the fate of the Universe?

The discovery of accelerated expansion of the Universe in 1998 came as a huge surprise and was already awarded a Nobel Prize in Physics. About 70% of the cosmic energy density is supposed to be mysterious dark energy acting as anti-gravity to push the cosmic expansion, and is responsible for determining the fate of the Universe. But the discovery relied on assumed properties of a type of supernovae called type-Ia. Using the currently available cosmological galaxy survey data, we found a new method to confirm the accelerated expansion without relying on supernovae. This paper was selected for 2013 Highlights Collection of *The Astrophysical Journal*.

3. Interdisciplinary Research Activities

We promote interdisciplinary interactions with daily teatime, joint seminars, and interdisciplinary workshops. These have led to many publications that otherwise would not have been possible. Even though physics and mathematics cannot be fused into a single discipline, mutual inspiration has been highly successful. A few key "interpreters" helped foster communication between mathematicians and physicists. We found exact results in physical theories with supersymmetry, which turned out to have applications in understanding connections between different geometries. Interaction with mathematicians led to deeper understanding in quantum physics.

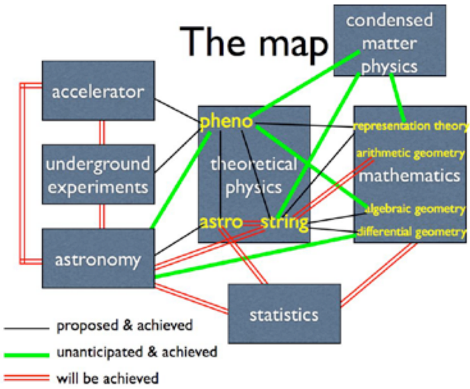


Fig.1 Synergies at Kavli IPMU in three categories: proposed & achieved; unanticipated & achieved; and will be achieved in the extension period.

Unexpected synergies (see Fig.1) emerged between astronomy and mathematics as Einstein's theory of gravity describes the evolution of the Universe using techniques in differential geometry. An interdisciplinary workshop co-hosted by the Institute for Solid State Physics, a neighbor institute on the same campus, inspired work on condensed matter physics and material science. PI Ooguri worked with a condensed matter physicist and showed that an analog of a dark matter candidate creates instability in a magnetic system that can be studied in the laboratory. We even published a paper on biology using game theory in mathematics.

Quimby, a postdoc who discovered the new and brightest class of supernovae called superluminous supernovae, was puzzled by a claim by the US-based Pan-STARRS group that the observed supernova PS1-10afx was an even brighter new type. He realized immediately that its properties resembled a well-known type called type-Ia, though it appeared 30 times brighter. He mentioned this puzzle at teatime. Werner, a postdoc working on mathematics, pointed out it was mathematically possible to obtain this magnification by gravitational lensing, but only if there is an unobserved object exactly along the line of sight towards the observed supernova. Such a possibility appeared implausible in practice. However Assistant Professor Oguri, a physicist with experience working with large data sets, quickly estimated that there is about one such chance in the Pan-STARRS data set. Together with other supernova experts at the Institute, they published this interpretation based on this teatime discussion. It was controversial for a while because the Pan-STARRS group led by Harvard stood by their original claim. Our group observed the host galaxy long after the supernova faded away, and could prove that there is an unresolved faint galaxy in the foreground exactly along the line of sight. This result was published in Science and was covered by more than 50 media outlets internationally as: “Tokyo theory correct; Harvard theory wrong.”

Study of fundamental laws also has applications in ordinary magnets, crystals of ice, superfluids, and neutron stars. The concept of spontaneously broken symmetry proposed by Yoichiro Nambu appeared to give incorrect predictions for these systems. Director Murayama worked with a condensed matter physicist and generalized Nambu’s work with help from mathematicians: a single theory now applies to all these cases, solving the fifty-year old problem. This series of works was published in four *Physical Review Letters* and chosen for Editor’s Suggestion and Physics Synopsis.

4. International Research Environment

We have world-class international PIs who are heavily involved in our daily research activity. We managed to create an intense “flow” of scientists to and from the Kavli IPMU. We attracted excellent scientists from abroad, while Institutions outside Japan recruited many of our members. The traffic of visitors is so high that it is easier to meet leaders in the fields at the Kavli IPMU than at typical universities in the US or Europe according to our American postdocs. We hosted 77 international workshops, and about a half of attendees came from abroad.

The quality of our members is excellent. We attract about 700 job applications annually competing for about 18 postdoc positions. Among 63 postdocs who left the Kavli IPMU since its inception, 28 are already in faculty positions. We could recruit a senior professor from Yale, while some others accepting offers from us turned down prestigious offers in the US and Europe. We successfully retained faculty members and high-level postdocs against offers from other leading institutions.

We provide an international and interdisciplinary environment to graduate students at the University of Tokyo (UTokyo) through workshops of *Program for Leading Graduate Schools*, and taught classes on scientific writing in English to more than 110 UTokyo graduate students.

We created an extensive support system for non-Japanese scientists to kickstart their life and research in Japan. Our website offers a wide variety of useful information on life in Japan, subsequently copied by other departments and institutions. We send our staff to municipal offices, banks, real estate agencies, and cell phone stores in order to help our newcomers. We provide orientation sessions, “survival Japanese” classes, online safety training, and 24-hour service for emergency health care and pregnancies. We have received the President’s Award twice as a result.

5. Organizational Reforms

We achieved system reform within UTokyo including

- Merit-based salary scale,
- Joint (split) appointments,
- Tenured positions with non-traditional external funding,
- *Nenpo* system (no traditional bonus or retirement benefit allowing higher pay and mobility),
- Flexible management of positions,
- Extensive assistance by bilingual administrative staff, and
- Endowment donated by a foundation outside Japan.

In fact, Director Murayama was the first example of split appointments and merit-based salary scales. The University also provided vigorous support to the Kavli IPMU by

- Building the research building specifically designed to foster interdisciplinary interactions,
- Building the international lodge to support non-Japanese members,
- Creating a new organizational structure called Todai Institutes for Advanced Study (TODIAS) to house the Kavli IPMU as a permanent entity,
- Designating the Kavli IPMU as a “special district” with a high degree of autonomy,
- Providing competent staff to interface with the traditional administrative system, and
- Providing permanent positions and resources to secure a sustainable future.

Some of our administrative staff have expertise in computing, finance, art, and music, which surprisingly proved very important in the operation of the Institute.

6. Others

The Kavli IPMU is the first institute in Japan endowed with a foreign donation and named after the donor. It is evidence of our high international visibility. Another measure of our international visibility: citation counts. Thomson Reuters' Web of Science showed that the Kavli IPMU has 117 papers since 2007 with more than 50 citations, 24 citations per paper on average. These numbers are comparable to or better than those of world-leading institutes covering similar research areas as our Institute, such as Institute for Advanced Study (Princeton), Kavli Institute for Theoretical Physics (Santa Barbara), Yukawa Institute for Theoretical Physics (Kyoto), Perimeter Institute (Canada), and International Center for Theoretical Physics (Trieste), over the same period.

World Premier International Research Center Initiative (WPI)
Progress Report of the WPI Center
(For Extension Application Screening)

Host Institution	The University of Tokyo	Host Institution Head	Junichi Hamada
Research Center	Kavli Institute for the Physics and Mathematics of the Universe	Center Director	Hitoshi Murayama

** Write your report within 30 pages. (The attached forms are in addition to this page count.) Keep the length of your report within the specified number of pages.*
Common Instructions:
** Please prepare this report based on the current (31 March 2014) situation of your WPI center.*
** Use yen (¥) when writing monetary amounts in the report. If an exchange rate is used to calculate the yen amount, give the rate.*

1. Overall Image of Your Center (write within 2 pages including this page)

Describe the Center's current identity and overall image. For centers that have had a change in their directors, describe that transition and the effects of the change.

- *On the sheets in Appendix 1, list the Principle Investigators, and enter the number of center personnel, a chart of the center's management system, a campus map showing the center's locations on the campus, and project funding.*

The Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) was proposed to address five fundamental questions about the Universe, how it began, what it is made of, what its fate is, what its fundamental laws are, and why we exist in it. We proposed to address these questions by combining mathematics, physics, and astronomy, employing accelerator-based experiments, underground experiments, and observations at telescopes, exactly as the name of the Institute suggests. This Institute did not exist before the WPI funding; it literally started from scratch. In seven years, the Institute grew to a size of approximately 150 people on site including graduate students and support staff.

Overall, the Institute came out to be exactly as proposed. Our unique building allows mathematicians, physicists and astronomers to be located together, sharing seminars and the daily teatime. Interdisciplinary discussions have become a commonplace. The Institute is highly international; more than a half of the members are not Japanese nationals. Since the Institute did not exist before 2007, every member was hired under the leadership of the Director. The quality of the hires is evidenced by the fact that about 90% of the postdocs have been offered positions at other excellent institutions after their term at the Kavli IPMU, and more than twenty among them are on faculty positions by now. Our faculty members have been constantly wooed by other institutions in and outside Japan, while we successfully recruited many against offers from other places.

In the original proposal, mathematicians were supposed to be located on the Komaba campus, while the rest of the Institute on the Kashiwa campus. With extraordinary effort and crucial hires, we managed to place the mathematicians together with physicists and astronomers on the Kashiwa campus. Many papers were written based on mutual inspiration of mathematicians and physicists. Key "interpreters" to overcome the language barrier between mathematicians and physicists played critical roles to make it a reality. This is crucial to address the questions "what are the fundamental laws?"

Our research produced many high impact papers with clear "made in the Kavli IPMU" brand. Our citation counts are similar to other world-leading research institutions. Thanks to several high profile papers and high international visibility, our members are invited to major conferences as keynote or summary speakers, including Strings, Lepton Photon, International Congress of Mathematicians, Neutrino, and Nobel Symposium. Many of faculty members were invited to write major review articles. We advertise positions internationally and attract nearly a thousand applications each year.

The large projects proposed in the original proposal are well underway. The direct dark matter detection experiment XMASS was built and produced world best limits on some candidates. It is addressing the question “what is the Universe made of.” The KamLAND-Zen effort produced the world best limit on neutrinoless double beta decay. Gadolinium loading of water Cherenkov detector was tested in EGADS R&D project and was proven to be viable; deployment in the full Super-Kamiokande detector is becoming imminent. Hyper Suprime-Cam (HSC) was designed, built, commissioned, and the 300-night survey was approved by the Subaru Advisory Committee. Data from the initial few nights are being analyzed. Combined with the theoretical research by our members, they address the question “why do we exist.”

In addition, interdisciplinary environment hatched new ideas and launched new projects. Prime Focus Spectrograph (PFS) was proposed in 2009, approved, designed, is under construction, and slated for the first light in 2017. The combination of imaging survey using HSC and spectroscopic survey using PFS on the same telescope of 8.2m aperture promises to be a world-leading observational program, addressing the question “what is our fate”. The Kavli IPMU is the lead institution for the MaNGA project in SDSS-IV, proposed in 2011, designed, built, commissioned, and is already taking data. We proposed to join the Belle II experiment and were given the biggest responsibility in the construction of the heart of the experiment (Silicon Vertex Detector). We are now proposing LiteBIRD satellite experiment to look for primordial gravitational waves as the evidence for the cosmic inflation, to address the question “how did the Universe begin?”

Unexpected directions also emerged. Collaboration with condensed matter physicists became very active, with many high-impact papers. We did not envision close interactions between mathematicians and astronomers, but they did happen and also produced high-visibility papers. We are now making extra effort to have statisticians involved as we come to the phase of analyzing big data.

The Kavli IPMU led the system reform of not only the University of Tokyo (UTokyo) but also National Universities at large. We made split appointments possible with institutions inside and outside Japan, starting with the Director. We offer merit-based salaries. The Kavli IPMU employed so-called “nenpo system” which improves the mobility of the members. The support staffs take extensive care of non-Japanese members to settle and kickstart life in Japan. We now have several tenured positions based on the “nenpo system” and are free from restrictions of traditional ones inherited from the civil servant system. We named the Institute after a donor, Mr. Fred Kavli, the first time in the Japanese universities. It helped raise the international visibility of the Institute. The University itself created a new organization called Todai Institutes for Advanced Study (TODIAS) to house the Kavli IPMU as a permanent entity within the University. Many of these reforms have permeated UTokyo, and the recent initiative from Ministry of Education, Culture, Sports, Science and Technology (MEXT) to reform the National Universities incorporated our effort.

We have also made impact on graduate program at UTokyo. Our faculty has already contributed to the graduate programs at Department of Physics and Department of Mathematical Sciences through supervision of graduate students and lectures on voluntary basis. We partnered in two *Programs for Leading Graduate Schools*. It presents opportunities for interdisciplinary research to graduate students at UTokyo in our international environment. In addition, our international faculty lectured on scientific writing in English in Department of Physics, a very popular course among graduate students. However, not all members were granted access to graduate students, which still is a challenge.

Since the inception, the Kavli IPMU has been very active in public outreach. We mobilize many thousands of people to our public lectures and events every year. We organize schools for high-school students, some of them dedicated to female students. Our members published popular science books with high impact approaching a million copies altogether. We believe we are helping the nation by attracting young minds to science, building the work force of next generation.

We have focus, and did not pursue everything we found exciting. Some hot research areas were not pursued consciously because we need to maintain focus within the finite size of the Institute. For instance, we originally envisioned joining experiments at the Large Hadron Collider (LHC), but LHC was well underway at the time of the launch in 2007, and it was not clear we could make a major impact. We redirected our effort to Belle II instead where we are making a major impact. We could have opened up areas in mathematics much wider, but we rather focused on algebraic, differential, arithmetic geometry and representation theory not to dilute our effort. We could have ventured into exoplanets thanks to our access to the Subaru telescope, yet we maintain our focus on extragalactic science, in particular cosmology.

Challenges remain. Since the Institute started from scratch based on the fixed-term funding of the WPI program, all of our members started on fixed-term appointments, with an unstable situation. Six faculty members left for other institutions that offered them tenure. However the University promised nine tenured positions. TODIAS allowed us to put proposals to MEXT for operating funds and we were granted four tenured positions. More effort is underway to secure the future of the Institute in a sustainable and stable fashion.

2. Research Activities (within 15 pages)

2-1. Research results to date

2-1.0 The Big Picture

We proposed to address five basic and interrelated questions about the Universe:
(1) How did the Universe start?
(2) What is the Universe made of?
(3) What is the fate of the Universe?
(4) What are its fundamental laws?
(5) Why do we exist?

These questions clearly need time scale of millennia to be solved fully. The initial phase of the Institute focused on how to turn these big questions into well-defined specific scientific questions that can be addressed based on the combination of mathematics, theoretical physics, experimental physics, and astronomy in a relatively short time scale of decades. Therefore, the initial phase emphasized theoretical investigations and smaller projects to try out various directions, that gradually came to a well-defined strategy for major experimental and observational programs. Those projects conceived at the beginning are now producing data, while much more are coming in the next few years. We describe the accomplishments in this context. When we refer to papers in Appendix 2(3), we use square brackets (curly braces) such as [2]({3}) *etc*. And we mark the Kavli IPMU's members, PIs, faculties, postdoctoral researchers and affiliate members with a single underline.

2-1.1 How did the Universe start?

This question is one of the most difficult problems while we made some important progress. Based on the initial investigations, it became clear that this question has three parts.

(a) The "Big Bang" itself, namely when the whole Universe collapses to a point with infinite energy density according to the Einstein's theory of gravity. It is a space-like singularity, which cannot be described by the Einstein's theory in terms of smooth spacetime. Therefore we need to build a quantum theory of gravity, such as string theory, working closely with mathematics of singular geometry and their resolutions. It overlaps significantly with the Question (4).
(b) The inflation that is believed to have expanded the initial microscopic Universe to a macroscopic one, while creating seeds of structure we see in galaxies today due to quantum fluctuations. Then the question is what caused inflation and how to prove it observationally. At the same time, we should consider possible alternatives to inflation.
(c) The subsequent evolution of the early Universe is governed by the elementary particles, and many extensions of the currently accepted standard model of particle physics predict different behaviors, especially with extra dimensions of spacetime or supersymmetry.

Research results 1: Modified Gravity

One of the greatest difficulties in attempts toward the theory of quantum gravity is the fact that general relativity is not renormalizable. This would imply loss of theoretical control at short distances. In January 2009, P. Hořava proposed a new theory of gravity that evades 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 renormalizable and unitary (as proven by our members D. Orlando and S. Reffert, chosen as Highlights of *Classical and Quantum Gravity*). Based on this candidate theory of quantum gravity, S. Mukohyama proposed a new mechanism for generation of cosmological perturbations [1]. This mechanism can solve the horizon problem and generate almost scale-invariant cosmological perturbations even without inflation, in any versions of the theory proposed to date. The same mechanism can produce almost scale-invariant gravitational waves in the early Universe without inflation. More recently, along with collaborators, S. Mukohyama calculated all parameterized post-Newtonian parameters in the *U(1)* extension of the theory and showed that the theory passes all solar-system tests of gravity. On the string theory side, an application to Big Bang singularity clearly requires time-dependent spacetime solutions. Some *exact* results are obtained for time-dependent solution by S. Hellerman and M. Kleban, while singularities in geometry are an active area of research by T. Milanov, K. Saito, and others.

Research results 2: B-Mode Polarization of Cosmic Microwave Background

Initiated by W. Hu and N. Sugiyama, the study of anisotropy in cosmic microwave background (CMB) proved theoretically very clean and experimentally tractable. The so-called B-mode polarization of CMB is now believed to provide a definitive test of inflation, where K. Sato is one of the first people to point out this possibility of exponential expansion in the early Universe. More recently, the BICEP2 result which claimed a positive detection of B-mode spawned further excitements and theoretical activities by H. Murayama, F. Takahashi, T. Yanagida and others, even though it remains unclear whether the foreground issues is resolved. We became involved in the POLARBEAR experiment at the small scale to study feasibility of future directions. It converged to the LiteBIRD satellite proposal led by M. Hazumi (joint appointment with KEK), which we actively work on with JAXA, KEK, and National Astronomical Observatory of Japan (NAOJ). Even though this type of outcome is not apparent in research publications, we consider the conceptual design of the proposal to be a significant achievement from the initial phase. This direction has become the major direction for the next five years.

Research results 3: Pure Gravity Mediation and Theories of the Higgs Boson

The discovery of the Higgs boson in 2012 sparked an active research at the Kavli IPMU. The Kavli IPMU has also become known as one of the major centers of so-called "model building" activity in the world, aiming at proposing a more natural and fundamental theory of elementary particles that govern the behavior of the early Universe. One major progress is the development of the pure gravity mediation (PGM) model that T. Yanagida found at the Kavli IPMU [2, 3], which is now accepted in the world as one of its prime candidates. The PGM model was built on the supersymmetric (SUSY) extension of the standard model (SM) based on very important past studies: The radiative correction to the Higgs mass [T. Yanagida, et al. (1991), J. R. Ellis, et al. (1991), and H. E. Haber, et al. (1991)], the anomaly mediated SUSY breaking [H. Murayama et al. (1998) and L. Randall et al. (1998)], the leptogenesis for the baryon asymmetry of the Universe [M. Fukugita and T. Yanagida (1986)], and the Sommerfeld enhancement for dark matter annihilations [J. Hisano, S. Matsumoto, and M. Nojiri (2004)]. Many authors of the studies are now the members of the Kavli IPMU, and the building this model would not have been possible without the WPI program.

The PGM model is now known to be the minimal model involving the mediation of the SUSY breaking. It predicts a split-type spectrum for SUSY partners: Almost all the partners have the masses of $\mathcal{O}$(10-100)TeV, while gauginos, the SUSY partners of the SM gauge bosons, still remain at the $\mathcal{O}$(0.1-1)TeV scale. The mass of the Higgs boson is predicted to be what we observed at the Large Hadron Collider (LHC) [2], while it is compatible with null observations of new physics signals at the initial phase of the LHC, and it ameliorates the problem of too-large SUSY contributions to flavor-changing neutral currents. The model is also very attractive from the cosmological point of view: It is completely free from dangerous cosmological problems (the gravitino and the Polonyi problems) that many SUSY models suffer from, and thus compatible with the successful leptogenesis, which gives the primary answer to the question "Why do we exist?" In addition, the neutral wino, which is the SUSY partner of the neutral weak gauge boson, is predicted to be a dark matter particle [3], and it satisfies all conditions for the weakly interacting massive particle (WIMP) giving the most part of the answer to the question "What is the Universe made of?" Moreover, if the inflation scale is confirmed to be high, as suggested by the recent BICEP2 result, the PGM model will offer another possibility of an interdisciplinary research, because the model is known to be the one of the few SUSY models compatible with such a high-scale inflation and its UV completion can only be studied with researchers in string theory and mathematics.

The measured mass of the Higgs boson sparked further active research at the Kavli IPMU including S. Matsumoto, H. Murayama, M. Nojiri, and many postdocs and students.

2-1.2 What is the Universe made of?

We learned only in 2003 the composition of the Universe quantitatively thanks to the results from the WMAP satellite based on the study of the anisotropy in cosmic microwave background. More than 80% of matter in the Universe is an unknown kind dubbed dark matter, which was responsible in forming stars and galaxies from the seeds planted by the inflation, which also touches on the question "Why do we exist?" To understand the nature of dark matter has become the focus for this question. In particular, we aim at

(a) Understanding the distribution of the dark matter and its evolution
(b) Unraveling the nature of dark matter using the combination of astronomical data, underground direct detection experiment, indirect detection via cosmic rays, and particle accelerators.

In both questions, the combination of theoretical, observational, and experimental activities is crucial. Yet we made a conscious decision not to be involved in cosmic ray experiments, as we believed we could make bigger impact on other areas.

Research results 4: Dark Matter Distribution

Gravitational lensing, the prediction of Einstein's General Relativity, provides us with a unique means of revealing the dark matter distribution. The deep potential well of galaxy clusters causes a coherent, correlated distortion in background galaxy images – the so-called weak lensing shear. The 8.2m Subaru telescope is the best available facility for making accurate weak lensing measurements thanks to its wide field of view and exquisite image quality, enabling us to explore the mass distribution over the entire region.

The team, being led by M. Takada and N. Okabe, has collected the Subaru data for a sample of most massive clusters that are selected from the previously known X-ray cluster catalog. They succeeded in collecting the Subaru data for all 50 clusters that are brighter than the certain X-ray luminosity threshold in the redshift range z=[0.15,0.3] and accessible from the Subaru telescope. Hence, their sample is a volume-limited sample of X-ray clusters and is not based on any gravitational lens based selection (*e.g.*, not based on previously-known strong lensing clusters). This project is a part of the international collaboration Local Cluster Substructure Survey (LoCuSS).

In [4], they have used the Subaru data for 30 massive clusters, a subsample of the above Subaru data, in order to make a detailed weak lensing study of the mass distribution in a cluster region. They found that the average mass distribution is in a remarkable agreement with the prediction from N-body simulations in the ΛCDM model. In particular, they demonstrated that combining the different clusters allows measurement of the average mass profile of the clusters with a few percent.

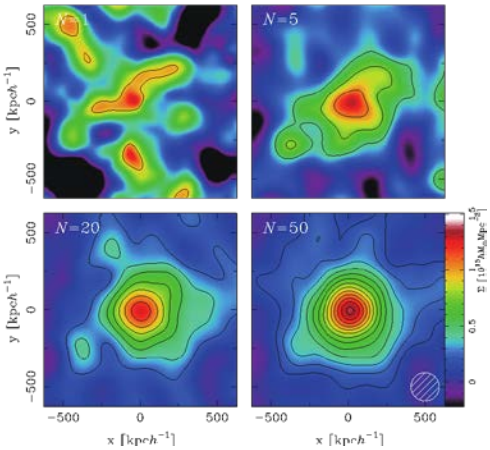


Fig.1 The average mass (mostly dark matter) distribution in a massive cluster region, reconstructed from the weak lensing measurement of X-ray luminous clusters. The top-left to bottom-right panels show the mass maps obtained by combining the data from 1 to 50 clusters as indicated (N. Okabe et al. 2013).

In a series of published papers, they have also used the Subaru data to develop a novel method of making a full use of the two-dimensional weak-lensing signals in order to constrain the "shape" of dark matter distributions. Again by using the unique sample of massive clusters, they detected the ellipticity of dark matter distributions at 7σ (M. Oguri *et al.* MNRAS 83, 3008, 2011). The mean ellipticity is found to be e=0.46±0.04 (68% C.L.), in excellent agreement with the theoretical prediction [5]. The theory has shown that the shape of dark matter distribution arises from the collisionless nature of dark matter. Thus their lensing measurements give a convincing confirmation of the ΛCDM model. This series of cluster weak lensing studies are a perfect preparation for the upcoming Subaru Hyper Suprime-Cam (HSC) Survey.

Research results 5: Dark Matter Detection

Y. Suzuki and his collaborators designed and built the XMASS experiment for direct detection of dark matter. XMASS is a single-phase liquid xenon detector with a total target mass of 835 kg, currently the largest in the world. 632 PMTs are used to cover 62% of the inner detector surface characterizing the highest photoelectron yield among such detectors of ~14 photoelectrons (pe)/keV, achieving the lowest energy threshold in the world of 0.3 keV_{ee} (note: $_{ee}$ means electron equivalent). The data analyses were conducted using the data taken in its commissioning phase. By using only 6.8 days of data and applying a simple cut that removes only characteristic Cherenkov events happening in the PMT quartz windows with the analysis threshold of 0.4 keV_{ee}, the limit excluded a large part of the region where DAMA/LIBRA group claimed from their observation of the annual variation [6]. This demonstrates the high sensitivity of the large target mass and lower energy threshold.

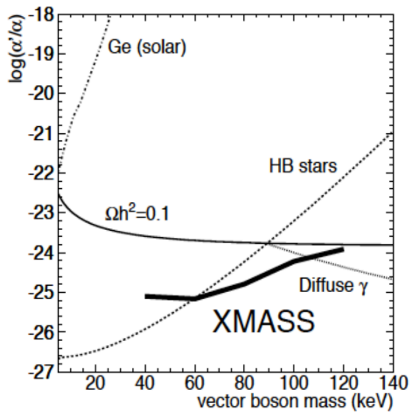


Fig.2 Limits on coupling constants between electrons and dark matter vector bosons. The thin solid line corresponds to the coupling constant required to reproduce the observed dark matter abundance. The dotted line and dashed line correspond to the astrophysical constraints. The experimental constraint (dash-dotted line) assumes production in the Sun.

XMASS is able to detect e/γ events as well as nuclear recoils. The γ–rays (39.6 keV) from the de-excitation of the excited state of ^{129}Xe are the signatures of the inelastic scattering of dark matter. The energy of the signals is high enough for a precise determination of the event vertex. Within the innermost part of 41 kg, the background level of $3x10^{-4}$ ev/keV/kg/day was yielded. Then the upper limit for the inelastic cross section obtained was 3.2 pb for the 50 GeV WIMPs. This is the best limit obtained so far through this kind of analysis method.

XMASS here looked for bosonic super-WIMPs in the keV region. These warm dark matter particles are interesting because the problem of the unwanted small galactic scale clumps seen in simulations of the development of the large-scale structure based on the cold dark matter scenario may be softened. The bosonic particles cause monochromatic peaks when they are absorbed in the target. XMASS has used the same dataset and methods of the inelastic scattering analysis already mentioned. The limit surpasses the existing astrophysical constraints, entering a new territory (Fig.2).

Axion-like particles can be observed by looking for *e*/γ events in the detector. The dark matter QCD axion has a mass between 10^{-6} and 10^{-3} eV and can hardly be detected. But axion-like particles may be produced for example in the Sun and can be detected by XMASS through the axio-electric effect. The production rate, the energy spectrum and the detection mechanism are known. XMASS looked for such solar axions, and set the most stringent limit on the axion-electron coupling, $|g_{aee}|<5.4 \times 10^{-11}$ (90% C.L.) [7].

Y. Suzuki and collaborators are now designing XMASS1.5, with 1 ton fiducial mass and sensitivity, $\sigma_{SI} < 10^{-46}$ cm^2 for WIMP nucleon spin-independent cross sections.

The indirect detection of the wino dark matter from astrophysical gamma-ray observations is also important, for strong signals are expected thanks to the Sommerfeld effect, pointed out first by M. Nojiri, S. Matsumoto and M. Hisano, for the wino dark matter annihilation. The PGM model [3] predicts the wino dark matter. In order to test the model robustly, however, one has to know the dark matter distribution in our galaxy precisely. The study is now being developed by an interdisciplinary activity involving particle and astro-physicists.

2-1.3 What is the fate of the Universe?

It was discovered in 1998 that the expansion of the Universe is accelerating. It is attributed to yet another mysterious component of the Universe called dark energy. The fate of the Universe hinges on the nature of dark energy, and therefore to understand its nature has become the focus for this question. We need to

(a) Consider theoretical possibilities for the origin of current accelerated expansion
(b) Discriminate among them using astronomical observations.

In addition, search for proton decay at Super-Kamiokande serves another approach to this question.

Research results 6: Theory of Dark Energy and Modified Gravity

The popular way to incorporate dark energy into theory of gravity is via Einstein's cosmological constant. However, its value must be 120 orders of magnitude smaller than what is naturally expected in quantum field theory. Alternative description of dark energy may be necessary by modifying the Einstein's theory of gravity at finite distances. On the theoretical side, whether there exists such a consistent extension of general relativity by a mass term is an important question in classical field theory. Since Fierz and Pauli's pioneering attempt in 1939, this issue has attracted a great deal of interest, and the massive gravity is one of the most interesting attempts in this direction. A. E. Gümrükçüoğlu and S. Mukohyama, along with A.D. Felice, discovered a new type of nonlinear instability in massive gravity for the first time ever since a similar discovery by Boulware and Deser in 1972. Since then, along with international collaborators, S. Mukohyama initiated a new search for consistent theories and cosmological solutions in massive gravity, including anisotropic cosmological solutions by A. E. Gümrükçüoğlu, C. Lin and S. Mukohyama, an extension of quasi-dilaton massive gravity by A. D. Felice and S. Mukohyama [8], and stable de Sitter solutions in rotation-invariant massive gravity by D. Langlois, S. Mukohyama, R. Namba and A. Naruko. They also published several invited reviews on the subject in international journals.

Research results 7: New Observational Constraint on Dark Energy

Sloan Digital Sky Survey (SDSS) is currently the most massive galaxy surveys enabling a high-precision cosmology, and the Kavli IPMU is an institutional partner. We consider it as a precursor to the SuMIRe survey described below. The team being led by M. Oguri has conducted a large survey to search for gravitationally lensed quasars in the massive SDSS datasets, and successfully discovered nearly 50 new gravitationally lensed quasars from a sample of 100,000 quasars [9]. The strong lensing of quasars is caused by a chance alignment of an observer, a quasar and a foreground galaxy that acts as a lens, along the line of sight. The probability of this chance alignment is directly proportional to the time evolution of the volume of the Universe, and hence provides a sensitive probe of dark energy. M. Oguri et al. used the largest, homogeneous sample of strongly-lensed quasars to find an evidence of non-zero dark energy contribution when combined with the CMB constraint.

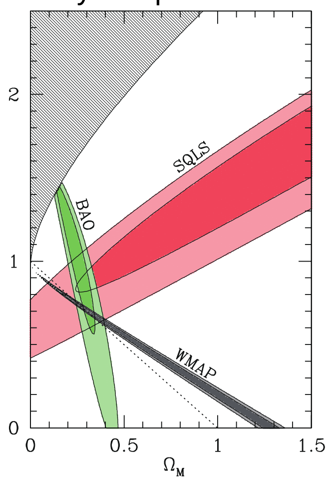


Fig.3 Marginalized constraints on Ω_M and Ω_Λ for the non-flat model, obtained from the statistics of strongly-lensed quasar sample (SQLS) in the SDSS data (M. Oguri *et al.* 2012).

Research results 8: SuMIRe

The Subaru Measurements of Images and Redshift (SuMIRe) project promises to further revolutionize astrophysics and cosmology research at the Kavli IPMU in a few years at the forefront of observational cosmology. The first part of the SuMIRe project is the imaging survey of the Universe, done with the new 1.5 degree-diameter wide-field camera HSC. The construction is now completed, led by NAOJ, the Kavli IPMU as well as international partners, Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) in Taiwan and Princeton. Its engineering first light was successfully carried out in 2013 August. The HSC has 870 million pixels, is 3 meter tall and weighs 3 tons. Its single pointing covers the entire Andromeda Galaxy (M31). N. Yasuda and others from Princeton and NAOJ have been developing the software/pipeline system that enables an automated reduction/analysis of the HSC data. The completion of HSC was widely publicized around the world, including newspapers and broadcastings as well as in scientific papers such as a Nature article (2012, Nature, 489, 190).

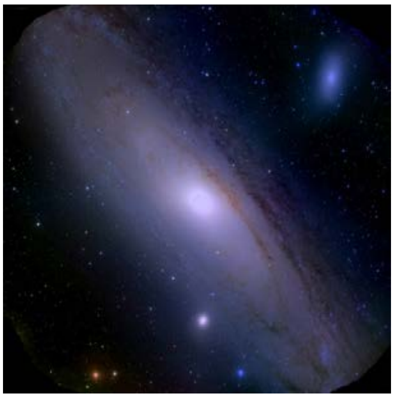


Fig.4 The HSC image of M31, created by the HSC pipeline developed at the Kavli IPMU.

In 2013 May, the proposal "Wide-field imaging with Hyper Suprime-Cam: Cosmology and Galaxy Evolution" for the Subaru Strategic Program (SSP) was granted for 300 nights observing time, under the leadership of the HSC Science team (chair: M. Takada). This survey is the largest-ever galaxy survey carried out with the Subaru telescope, and is possible only with HSC within a timescale of 5 years, because it otherwise requires more than 1000 years on the Hubble Space Telescope. Its goals are to measure dark energy parameters by weak lensing and the properties of evolving galaxy populations and their relation with the dark matter distribution.

The Prime Focus Spectrograph (PFS) takes a role for the spectroscopic component of the SuMIRe project. The PFS project was endorsed by the Japanese community in January 2011 as one of the main future instruments of the Subaru telescope. Furthermore, in December 2011, a Memorandum of Understanding (MOU) on the PFS Project was signed between NAOJ and the Kavli IPMU. With this agreement, the NAOJ supports the PFS project as an international project in its design, construction and observation. The PFS is an optical/near-infrared multi-fiber spectrograph with 2400 fibers, each of which is set onto a target position quickly by a fiber positioner using two-staged rotational Piezo motors. The fibers patrol within 1.3 degree diameter, a significant portion of the extended field of view with the new Wide Field Corrector lens system built for HSC.

Under the strong leadership of the Kavli IPMU (PI: H. Murayama, Project Manager: H. Sugai, System Engineer: N. Tamura, and Project Scientist: M. Takada), the PFS collaboration successfully passed the Preliminary Design Review in February 2013, and is now in the construction phase. The PFS project is an international collaboration of the Kavli IPMU and NAOJ (Japan), University of Saõ Paulo/Laboratório Nacional de Astrofísica (Brazil), Caltech/JPL, Princeton, Johns Hopkins (USA), Laboratoire d'Astrophysique de Marseille (France), ASIAA (Taiwan), and Max-Planck-Institute for Astrophysics (Germany).

The PFS offers unique opportunities in survey astronomy and cosmology. The PFS team is planning to use 300 Subaru nights to carry out cosmology, galaxy evolution and galactic archeology programs, which are aimed at addressing the nature of dark energy, the nature of dark matter and the origin of galaxies and our Milky Way [10; also see H. Sugai *et al.* SPIE, 8446, 2012]. The combination of HSC and PFS will sustain the Subaru telescope as a world-leading telescope even in 2020 era when TMT, the biggest project of the Japanese astronomical community, will play a central role in astronomy, for target selection. We are planning to have the technical first light at Subaru in mid-2017.

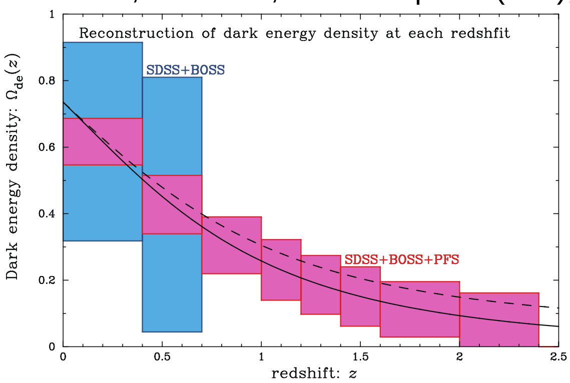


Fig.5 Expected accuracy of reconstructing the fractional dark energy density parameter, $\Omega_{de}(z)$, from the baryon oscillation measurements of the Hubble expansion rate and the angular diameter distance at each redshift bin up to z=2.4. The solid curve is the cosmological constant model, and the dashed curve is an early dark energy model (M. Takada *et al.*, 2014).

2-1.4 What are its fundamental laws?

This question obviously touches on all the other questions. Our focus here is the tight connection between mathematics and the physical theories such as string theory. Given the unusual structure of the Institute where physicists and mathematicians share the same building and daily research activities, we have mutual stimulation to make progress in developing new mathematics and new physical theories. At the same time, the lessons gained in this activity have applications in other areas of science, such as condensed matter physics and even biology.

Traditionally, the intersection between physics and mathematics centered around analysis.

The invention of Einstein's theory of gravity, quantum mechanics, gauge theory and string theory shifted the emphasis to geometry and representation theory. Therefore, this is the current area of focus. In addition, we believe that supersymmetry would play a crucial role in the search for the ultimate laws of the Universe. The infinitely many degrees of freedom in physical theories made mathematically rigorous treatment impossible for a long time. Supersymmetry makes the situation dramatically different. In some of the physically relevant observables, precise cancellation between bosonic and fermionic degrees of freedom occurs, and the remnant can often be treated in mathematical rigor. In fact, this is the well-known secret behind much of recent development in mathematics, such as formulation of Gromov-Witten (GW) theory and its variants, as well as "the 40% of Fields Medal since 1990's" mentioned in Center's proposal for the WPI program. Therefore, the particular focus areas are supersymmetric gauge theories, and compactification of string theory preserving supersymmetry that requires Calabi-Yau 3-folds and related algebraic geometry.

An important tool is the concept of duality, where apparently totally different descriptions address the same subject. The mirror symmetry in complex and symplectic geometry originated from duality in string theory. In addition, Witten pointed out that the S-duality in compactification of maximally supersymmetric gauge theories in four dimension on Riemann surfaces is relevant to the geometric Langlands program, which is regarded as the testing grounds for the Langlands program for the arithmetic geometry and the number theory.

Research results 9: Derived Category of Coherent Sheaves and Counting Invariants

Algebraic Geometry is one of the research areas in mathematics, in which we study the geometric objects (called algebraic varieties) defined as the solution spaces of polynomial equations. In particular, the three-dimensional Calabi-Yau manifold appears as an extra dimension in string theory. The derived category of coherent sheaves on an algebraic variety is the category consisting of bounded complexes of holomorphic vector bundles on it. This is an abstract notion, but draws an attention in recent years, as it gives a mathematical formulation of D-branes in Type II-B string theory. Several interesting symmetries involving derived categories have been found based on the ideas from string theory. Kontsevich's Homological mirror symmetry conjecture is one of them, and it relates the derived category of coherent sheaves on a Calabi-Yau manifold with the derived Fukaya category on its mirror symplectic manifold. This is an amazing conjecture relating different kinds of geometry, algebraic geometry and symplectic geometry.

In 2002, Bridgeland introduced the notion of stability conditions on derived categories. This is a mathematical formulation of Π stability in string theory, and it gives the notion of semistable objects in the derived category. It is known that the set of stability conditions on the derived category forms a complex manifold, which is expected to be related to the moduli space of complex structures on its mirror manifold. Hence this is an important research subject in the study of mirror symmetry. However this space is quite difficult to study. In particular, the existence of a stability condition on a Calabi-Yau 3-fold is not known.

On the other hand, in 1998, Thomas introduced the invariants (called DT invariants) counting stable coherent sheaves on Calabi-Yau 3-folds, as a higher dimensional analogue of Donaldson invariants on algebraic surfaces. The DT invariants correspond to counting BPS states in string theory, and they are interesting not only for mathematicians but also string theorists. The DT invariants counting rank one stable sheaves count curves on Calabi-Yau 3-folds. In 2003, Maulik-Nekrasov-Okounkov-Pandharipande (MNOP) conjectured that the rank one DT invariants are equivalent to GW invariants, the invariants counting world sheet in string theory. In order that conjecture makes sense, MNOP also conjectured (called rationality conjecture) that the generating series of rank one DT invariants is a rational function with a certain automorphic property. The MNOP conjecture was proposed in Okounkov's Fields medal lecture at the ICM 2006, and has attracted many mathematicians. Moreover in 2007, Pandharipande-Thomas (PT) introduced the notion of stable pairs on Calabi-Yau 3-folds, and conjectured that invariants counting stable pairs are equivalent to rank one DT invariants.

Y. Toda applied the idea of Bridgeland stability conditions to the study of DT invariants, especially the MNOP conjecture. He has developed moduli theories of semistable objects in the derived category, and constructed DT type invariants counting semistable objects in the derived category. By investigating the dependence of these invariants under a change of stability conditions, he proved (a version of) conjectures on DT invariants, say DT/PT conjecture, MNOP rationality conjecture, *etc* [11]. Also his study of stability conditions led to a conjectural Bogomolov-Gieseker type inequality for Chern characters of certain two term complexes, which tuned out to connect classical and modern problems in algebraic geometry [12,13].

Research results 10: Langlands Correspondence and p-adic Cohomology Theory

The history of arithmetic geometry began with Weil. His conjecture implied that the world of varieties over finite fields, which is a priori far from the one we live, has similar topological structure.

Motivated by it, Grothendieck constructed cohomology theories for such varieties: ℓ-adic étale cohomology for any prime number ℓ different from the characteristic p of the finite field we fixed, and crystalline cohomology (p-adic theory). The ℓ-adic cohomology theory can be seen as an analogue of singular cohomology theory, with which we may extract the topological structure. In the complex geometry, singular cohomology can also be computed by using differential forms: de Rham cohomology. An analogy of this somewhat differential geometric approach is the p-adic cohomology theory.

Given that there are infinitely many cohomology theories, what are the relations among them? Influenced by the Langlands correspondence (LC), Deligne proposed a conjecture on the existence of ℓ-adic and crystalline "companion" in his "Weil II", one of the most influential papers in mathematics. This conjecture roughly states that no matter which cohomology theory we use, the cohomological information is essentially the same. The existence of ℓ-adic companion in the curve case was shown partly by Drinfeld and fully by Lafforgue by establishing LC for function fields. Both of them were awarded the Fields Medal. Using this result, later on, Deligne and Drinfeld constructed the ℓ-adic companion for more general varieties, even though there are still some cases yet to be treated. T. Abe's main achievement was to establish an analogue of LC for the p-adic theory, and showed the existence of crystalline companion in the curve case [14]. For this, a sequence of fundamental and hard works in p-adic cohomology theory was required: product formula for epsilon factors, construction of theory of weights, and construction of six functor formalism for some stacks for p-adic theory [14,15]. Each of these achievements was considered to be hard to obtain in p-adic theory. He used systematically the theory of arithmetic *D*-module initiated by Berthelot, which tended to be avoided by specialists because of the complexity of the theory. On one hand, his results complete the foundation of p-adic cohomology theory. On the other hand, it opens a door to investigate "motivic property" of varieties over finite fields by means of p-adic differential equations, category of which is much wider than that of ℓ-adic objects.

Research results 11: Primitive Forms and Mirror Symmetry

Study of period integrals over elliptic and higher genus Riemann surfaces, started by Euler and developed by Abel, Jacobi, Gauss and Riemann, is a classic in mathematics. Primitive form was introduced as a higher dimensional theory of period integrals for vanishing cycles at an isolated critical point of a function *F* (K. Saito 1983). It turns out that the theory of primitive forms for a function *F* is relevant in the complex geometric (B-model) aspects of N=(2,2) supersymmetric Landau-Ginzburg (LG) theory in physics, having *F* as its superpotential. Therefore, it has become a common subject for physicists and mathematicians in the Math-String seminar at the Kavli IPMU.

The dualities between different string models in physics give strong non-perturbative means to calculate the partition functions. For instance, Witten showed that the LG model and the sigma-model on a Calabi-Yau manifold give different phases of the same physics. The mirror symmetry (worked out by physicists K. Hori, Vafa et al.) is one of the dualities, which has a strong impact on mathematics, since it predicts an unexpected duality between complex geometry and symplectic geometry. As described below, new progress on this subject took place at the Kavli IPMU, which, in the last year, and the LG-LG mirror symmetry was confirmed using primitive forms.

At a Math-String seminar, Hori and Saito made it clear that the primitive form theory is mirror dual to the symplectic geometric (A-model) theories such as GW theory of a compact Kähler manifold or Fan-Jarvis-Ruan-Witten (FJRW) theory of a LG orbifold (2013). A mathematically rigorous formulation of the LG-LG mirror symmetry conjecture claims the coincidence of the pre-potential function obtained from a primitive form for the function *F* and the generating function of FJRW invariants for the dual function F^T. More precisely, a primitive form induces a flat (Frobenius) structure and its (genus 0) pre-potential on the deformation parameter space of *F*. From that data, higher-genus pre-potential is reconstructed on the generic point of the parameter space (Givental, Teleman). There were still difficult problems: 1. The higher-genus potentials given by Givental needed to be extended to the entire deformation parameter space, 2. they didn't have any explicit formula and means to analyze primitive forms except for ADE- or simply elliptic singularities. We solved both problems last year at the Kavli IPMU.

T. Milanov proved that a semisimple Frobenius structure satisfies a local Eynard-Orantin (EO) recursion. As an application [16], he proved a conjecture of Givental on the analytic extendability of the total ancestor potential in whole deformation parameter space. This gives an answer to the problem 1. He is pursuing further direction to use the periods of the primitive form in order to characterize GW invariants via the methods of Vertex Operator Algebras (VOA) representations and integrable systems. In collaboration with B. Bakalov [18] he managed to construct a VOA representation and proved that for simple singularities it can be used to characterize the generating function of FJRW invariants.

In a workshop at the Kavli IPMU (2012), S. Li presented the idea to approach higher genus formula by heat kernels. This inspired a collaboration of K. Saito with S. Li and C. Li, where they developed a new approach to primitive forms that relies on polyvector fields. Furthermore, using the idea of Barannikov-Kontsevich, they developed the perturbative construction of primitive forms, in particular, an explicit formula for all weighted homogeneous singularities (arXiv:1311.1659). This gives an answer to the problem 2. Then, jointly with Y. Shen, an expert in the FJRW theory at the Kavli IPMU, they finaly confirmed the LG-LG mirror symmetry holds including a negatively weighted deformation parameter [17]. It shows also that 4^{th} derivatives of the pre-potential, corresponding to 4-point correlators in the FJRW theory, determine the whole structure. The method is quite general and the confirmation of the LG-LG mirror symmetry for all invertible polynomials is ongoing.

Research results 12: Discovery of a New Connection between Finite Group and Calabi-Yau Geometry

One of long-term research objectives of H. Ooguri has been to find exact results in superstring compactification. In his Ph.D. thesis in 1989, he studied string compactification on a four-dimensional Calabi-Yau space (called *K3*), and showed how the resulting particle spectra can be organized into the so-called elliptic genus. Surprisingly, when he expanded the elliptic genus in the characters of the N=4 superconformal algebra, all the expansion coefficients turned out to be positive integers. It took 20 years for him to find out what these integers meant. In 2010, H. Ooguri with T. Eguchi and Y. Tachikawa, discovered that these integers are dimensions of representations of the largest Mathieu group M_{24} [19]. Thus they conjectured that the elliptic cohomologies of *K3* are representations of M_{24}. A weak version of their conjecture, christened “Mathieu Moonshine,” was proven by Terry Gannon, mathematician at the University of Alberta, in 2013.

One of the essential ingredients of the Mathieu Moonshine is the mock modular forms discovered by Ramanujan. At this point, we cannot but quote an article by Freeman Dyson presented at the Ramanujan Centenary Conference in 1987: “*The mock theta-functions give us tantalizing hints of a grand synthesis still to be discovered. … My dream is that I will live to see the day when our young physicists, struggling to bring the predictions of superstring theory into correspondence with the facts of nature, will be led to enlarge their analytic machinery to include mock theta-functions…*”. The Mathieu Moonshine realizes Dyson’s dream by pointing out a “grand synthesis” of mock modular forms, the Mathieu group, the Calabi-Yau and string compactification. In the past couple of years, H. Ooguri’s discovery has been vigorously studied both by mathematicians and physicists. As evidence for its world-wide impact, we would like to point out that conferences devoted to the Mathieu Moonshine have been held at ETH in Zurich, the Simons Center in Stony Brook, and Imperial College in London.

In [20], H. Ooguri and M. Yamazaki (then student, now faculty) showed how the smooth geometry of Calabi-Yau manifolds emerges from the thermodynamic limit of the statistical mechanical model of crystal melting. In particular, they showed that the thermodynamic partition function of molten crystals is equal to the classical limit of the partition function of the topological string theory by relating the Ronkin function of the characteristic polynomial of the crystal melting model to the holomorphic 3-form on the corresponding Calabi-Yau manifold.

Research results 13: Supersymmetric Gauge Theories

Together with L. F. Alday and D. Gaiotto, Y. Tachikawa proposed the so-called Alday-Gaiotto-Tachikawa conjecture in 2009. This conjecture was first phrased in the theoretical physics language, but it was soon reformulated as a precise mathematical conjecture. Large parts of it have been rigorously proven since then. It was originally considered for a restricted class of groups, and the work [21] contains a big step toward the understanding of the general case.

As another example of the interplay between physics and mathematics, Y. Tachikawa, together with O. Aharony and N. Seiberg in the work [22], found hitherto neglected discrete parameters in general gauge theories. These new parameters are best described in terms of the cohomology of the classifying spaces, a subject intensely studied in algebraic topology, to which many Japanese mathematicians contributed in the 1980s. But this subject was rarely used in physics thus far. So it was greatly helpful that as an affiliate member, Y. Tachikawa could directly ask mathematicians, and could consult books at the Kavli IPMU library, which has a comprehensive coverage of all areas of mathematics.

Research results 14: Methods in Quantum Field Theory and String Theory — Duality

Quantum field theory and string theory are expected to provide the theoretical framework for the ultimate laws of the Universe, but it is in general difficult to understand the physics of a given theory. A key to overcome the difficulty is “duality”. It is a phenomenon that different theories yield the same physical observables. The strongly coupled regime in one theory is often mapped to the weakly coupled regime in the dual theory. It is particularly important in string theory, which is studied by combining several different approaches — string perturbation theory, low-energy supergravity, and quantum field theories on various branes. In the past seven years, the Kavli IPMU made major contribution in discovering new dualities and developing new methods in quantum field theory and string theory. These are products of continuous interaction between physicists and mathematicians, and could not have been achieved without the existence of the Kavli IPMU.

The origin of the interaction goes back to the recognition that the language of category is well suited to describe a class of objects in string theory, called "D-branes". D-branes are interactions on the boundary of string worldsheet and form a type of category, which is often of the type studied earlier in mathematics, such as derived categories of coherent sheaves. Through this relationship, some facts in string theory yield mathematical conjectures to be proven, such as equivalence of derived categories, while mathematical results give some hints toward understanding string theory. K. Hori, who initiated such interaction, discovered a new class of dualities in two-dimensional supersymmetric gauge theory [23], which may be regarded as the two-dimensional analog of four-dimensional Seiberg duality. It is tested using the recently developed method [23,24] concerning exact results on partition functions on the sphere, the hemisphere, and the torus. It is also used to construct a new class of superstring vacua, including a new class of Calabi-Yau manifolds. The discovery may well be progress toward Center's research objective that "we will create the new mathematics needed for a unified description of the Universe" and may provide a step forward establishing "mathematical foundation for the formulation of new physical theories with well-defined and testable predictions".

K. Hori discovered a new class of dualities in two-dimensional supersymmetric gauge theories ([23]). Such theories are particularly important since the superconformal fixed points in the infra-red limit can be used as the worldsheet theories of superstrings. The duality enables us to construct a new class of superstring vacua. On the mathematical side, the duality provides a unifying scheme to understand recent mathematical discoveries concerning equivalence of derived categories, and furthermore, it generates new conjectures to be proven. This duality motivated lots of important research, including the exact computation of the partition function on the two-dimensional sphere (Benini *et al.* 2012, Doroud *et al.* 2012) and its relation to the Kähler potential on the moduli space (H. Jockers *et al.*, {5}). These works in turn motivated K. Hori and collaborators at the Kavli IPMU to develop the method further, and they computed the exact partition functions on the hemisphere [24] and the torus {10}.The results yield general formula for the D-brane central charges and the elliptic genera.

Duality in systems without supersymmetry was also studied in the Kavli IPMU. S. Sugimoto employed gauge/string duality — the duality between quantum field theory on D-branes and low energy supergravity of string theory — to extract information about QCD, such as properties of baryons (K. Hashimoto, T. Sakai and S. Sugimoto, *Prog. Theor. Phys*. **120** (2008) 1093), in the set up of D4/D8-brane configurations called Sakai-Sugimoto model. S. Sugimoto also analyzed an electric-magnetic duality of string-theoretical origin and used it to understand confinement and dynamical symmetry breaking in four-dimensional gauge theory without supersymmetry (S. Sugimoto, *Prog. Theor. Phys.* **128** (2012) 1175).

Research results 15: F-theory: Its Phenomenology Applications and Duality

T. Watari has been addressing the fundamental laws by using one of formulations of string theory called F-theory, since his earlier paper in 2006 (*Nucl. Phys*. **B747**, 212). It is an essential part of such studies of F-theory, however, to deal with such mathematics as singular geometry and sheaf cohomology, and that was why the progress in this direction had remained very slow until 2008.

A few physics-math collaborations had been formed around the world to address these questions by the beginning of 2008. Physicists and mathematicians at the Kavli IPMU set up one of such teams, and produced results including Ref. [25, 26]. The team of the Kavli IPMU employed string duality between F-theory and Heterotic string in order to study physics associated with singular geometry of F-theory. Based on mathematical computations using Heterotic string and also by refining string duality, it was shown that quarks and leptons are described by smooth sections of line bundles in F-theory, despite the presence of singularities in the geometry [25]. Once the theoretical formulation had been clarified, it was reliably shown [26] that the mass scale of right-handed neutrinos is given by parameters that are already measured. The mass scale obtained in this way is just about right to account for the atmospheric neutrino oscillation in Super-Kamiokande.

Research results 16: Application to Condensed Matter Physics

One of the most remarkable and surprising achievements in string theory is the AdS/CFT (anti de-Sitter/conformal field theory) correspondence. The AdS/CFT correspondence and its generalization argue that quantum gravity (or string theory) in a certain spacetime is equivalent to a quantum field theory which lives on its boundary. This clearly reveals a remarkable fact that gravity can be rewritten as a theory without gravity, so called holographic principle. Therefore this radically changes our idea of gravity and spacetime. This will be crucial to understand Planck scale physics, which is responsible for the origin of our Universe.

T. Takayanagi studied what will happen if a CFT is defined on a manifold with boundaries (called BCFT) and discovered a beautiful construction of its holographic dual (called AdS/BCFT) {16}. This new formulation of holography allows us to prove the g-theorem, which is a boundary analogue of the c-theorem. He was an invited speaker at strings 2011 conference as because of this work.

The AdS/CFT correspondence offers us a very convenient method to study strongly interacting quantum systems. This is because when quantum gravity effects are suppressed, the string theory becomes equivalent to strongly coupled gauge theories according to the AdS/CFT. This allows us various applications of AdS/CFT to various problems in condensed matter systems. For example, one of the most interesting problems in condensed matter physics will be the high T_c superconductors. It has been well-known that there exists a special metallic phase when one heats up a high T_c superconductor, called the strange metal phase. This phase has unusual properties such as an anomalous specific heat and conductivity, which differs from the standard metal (Landau Fermi liquids). N. Ogawa, T. Ugajin and T. Takayanagi succeeded a systematic study of strange metal phases by using AdS/CFT [27]. They proved that a metallic phase always becomes a strange metal in strongly coupled large N gauge theories. This analysis has been done by introducing a novel quantity called entanglement entropy, which can be regarded as a new order parameter of quantum systems. Since this paper initiated an application of holographic entanglement entropy to condensed matter physics, it has been appreciated internationally and has earned more than 120 citations. Indeed, their method has been employed several times by a famous condensed matter theorist; Subir Sachdev (Harvard), to study a novel phenomenon called hidden Fermi surfaces.

When symmetries are reduced all phenomena in the Universe are characterized by the universal concept called spontaneous symmetry breaking that earned Yoichiro Nambu the Nobel Prize. The famed Higgs boson, recently discovered at the LHC, condensed in the Universe when the gauge symmetry of the standard model was reduced. Many supernovae result in neutron stars where the number symmetry is broken. Similarly, water freezes to ice when the translation symmetry is broken to lattice symmetry, and a piece of iron becomes a magnet when electron spins align and their rotational symmetry is broken. Even though these phenomena had been known for half a century, H. Murayama, working with a condensed matter physicist H. Watanabe, were first to discover a universal theory that applied to all of them [28]. The correct mathematical language turned out to be presymplectic structure on homogeneous spaces, where the mathematics allowed them to classify possibilities and make precise predictions on numbers of the gapless excitations called Nambu-Goldstone bosons and their characteristics. This result spawned seven papers so far including four *Physical Review Letters*, one selected for Editor's suggestion and Physics Synopsis. It also predicts perverse behavior of topological solitons, solutions to non-linear partial differential equations [29]. The momentum operators do not commute due to a central extension, akin to Witten-Olive extension of supersymmetry algebra by magnetic charges.

2-1.5 Why do we exist?

This is a complex and rich question. We see the following concrete approaches to address it:

(a) Origin of asymmetry between matter and anti-matter. It may come either from neutrinos or the quark sector.
(b) Formation of stars and galaxies and their subsequent evolution.
(c) Assembly of galaxies from smaller objects.
(d) Planet formation.

Even though all of these are exciting subjects, we made a conscious decision to leave out (d) because we cannot cover everything. The area (c) was initially not anticipated, but as a result of initial investigations, large-scale survey instruments such as SuMIRe discussed earlier can address (b) and (c) at the same time, and hence (c) is now included in our strategy.

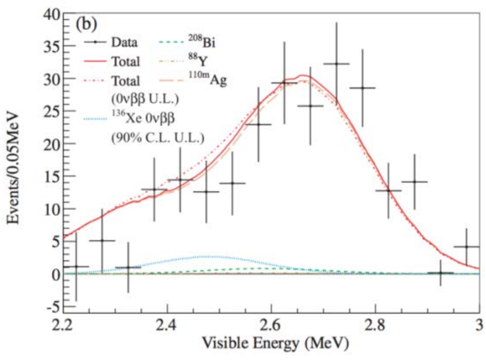


Fig.6 Energy spectrum of selected candidate events together with the best-fit remaining backgrounds, and the 90% C.L. upper limit for 0νββ decays.

It was our own PIs (M. Fukugita and T. Yanagida) who proposed the theory that neutrinos are responsible for creating asymmetry between matter and anti-matter. Therefore it is crucial to understand the properties of neutrinos better. This is approached from underground, accelerator, and astronomical surveys.

Research results 17: Neutrino Properties

Neutrinos are the only known particles that may not be distinguished from anti-particles. This nature is thought to be a key to unravel the big mysteries in particle physics and cosmology, particularly “the matter dominance in the Universe”. So far, the only viable experimental approach to study this is a search for neutrino-less double beta decay ($0\nu\beta\beta$). The primary milestone is an examination of the previous claim by a ^{76}Ge detector, called Klapdor-Kleingrothaus (KK) claim.

KamLAND-Zen utilizes the established and existing large ultra-low radioactive environment and instruments of KamLAND. It holds the world’s largest amount of $\beta\beta$ nuclei (320 kg of 90% enriched ^{136}Xe) as xenon-loaded liquid scintillator in a mini-balloon at the very center of KamLAND. The project has achieved the world’s largest exposure, 89.5 kg yr, of ^{136}Xe and the world’s best sensitivity in 2012. The obtained best lower limit for the $0\nu\beta\beta$ half-life, 1.9×10^{25} yr at 90% C.L (Fig.6). or 3.4×10^{25} yr if combined with the EXO-200 result, can be converted to the effective Majorana neutrino mass of 120-250 meV as an upper limit [30]. The wide allowed range comes from the theoretical uncertainty of the nuclear matrix element (NME). None of the available modern calculations of NME provided consistent half-lives between the combined ^{136}Xe $0\nu\beta\beta$ half-life limit and the finite half-life of ^{76}Ge $0\nu\beta\beta$ from the KK-claim. It resulted in the 97.5% C.L. exclusion of the KK-claim and passed the primary milestone.

KamLAND is surrounded by the nuclear power reactors and their effective distance of about 180km provides unique opportunity to measure neutrino oscillations involving first and second neutrino mass eigenstates. Nuclear power reactors emit only electron-type anti-neutrinos. KamLAND can detect these electron-type anti-neutrinos via the inverse beta decay reaction of hydrogen atoms. Electron-type anti-neutrinos transform into another undetectable flavor (muon-type or tau-type) anti-neutrinos during their travel and transform back into original flavor by a quantum mechanical effect called neutrino oscillation. KamLAND observed two cycles of neutrino disappearance and reappearance very clearly as a smoking-gun evidence of the neutrino oscillation and measurement of the cycle brought very precise determination (2.4%) of neutrino mass-squared difference [31]. It is the most precise measurement of neutrino mass information ever.

S. Saito, M. Takada and A. Taruya have, for the first time, developed a perturbation theory of large-scale structure formation for a mixed dark matter model containing cold dark matter and massive neutrinos (S. Saito, M. Takada & A. Taruya *Phys. Rev. Letters* **100** (2008) 191301; *Phys. Rev.* D **80** (2009) 083528). Since massive neutrinos have a large free-streaming scale as a consequence of the thermal Big Bang history, they imprint a characteristic signature in the clustering features of galaxies. They compared the perturbation theory model to the galaxy power spectrum measured from the SDSS, and then derived an upper bound on the sum of the three-flavor neutrinos, given as $m_{\nu,\mathrm{tot}}<0.81$eV (95% C.L.) [32]. The analysis includes marginalization over nuisance parameters to model the effect of possible nonlinear galaxy bias. Since an *N*-body simulation for a mixed dark matter model is still challenging and the perturbation theory is known to serve as an accurate model in the weakly nonlinear regime, their constraints can be considered as one of the most robust neutrino mass constraints. S. Saito is now a member of the core team in the SDSS collaboration, and he and his collaborators are pursuing a further improved constraint of neutrino mass with the Data Release 11 data of the SDSS-III BOSS (F. Beutler, S. Saito *et al.*, arXiv:1403.4599).

Research results 18: Evolution of Galaxies

K. Bundy and N. Suzuki are leaders in the SDSS-IV project; K. Bundy is a PI of Mapping Nearby Galaxies at APO (MaNGA), one of the core projects in the SDSS-IV project, and N. Suzuki is developing the pipeline for eBOSS survey, the spectroscopic survey of emission-line galaxies extending to higher redshift. The SDSS-IV surveys have started, and more exciting results, led by our members, will be delivered soon.

How have galaxies, objects directly seen with a telescope, been formed in the ΛCDM paradigm of hierarchical structure formation? This is an important, yet unresolved problem in cosmology. Understanding the formation history and evolution of galaxies requires that we probe the mass and shape of the dark matter halo and understand how these quantities shape the growth and assembly of observed stellar and gaseous material. A. Leauthaud, K. Bundy and their collaborators tackled this problem by combining all the available observables, weak gravitational lensing, galaxy clustering and the stellar mass estimate of each galaxy from the COSMOS datasets, with ΛCDM based *N*-body simulations [33]. They found that the dark matter halo-to-stellar mass ratio, M_{DM}/M_*, varies from low to high masses, reaching at a minimum of $M_{\mathrm{DM}}/M_*\sim27$ at $M_*=4.5\times10^{10}M_{\mathrm{sun}}$, where the accumulated stellar growth (mostly for the central galaxy) has been most efficient in its history. This paper was tied for the 9th most highly cited paper in the field of astrophysics in 2012.

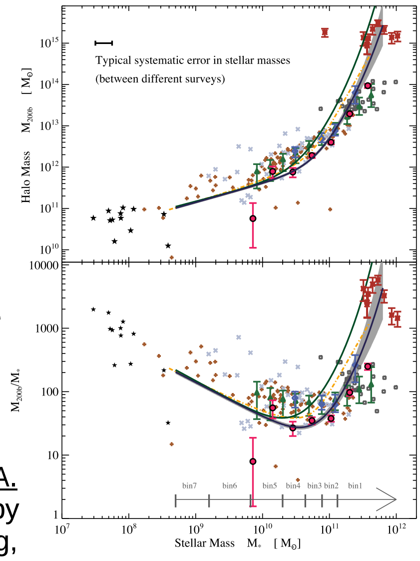


Fig.7 The stellar-to-halo mass relation from z=0.2 to z=1. The solid line with the shaded gray region shows the result from this COSMOS study (A. Leauthaud et al., 2012)

J. D. Silverman and his collaborators extended this dark matter and baryon connection even to much smaller scales. They used the COSMOS data to identify a close pair of galaxies in redshift space (therefore a cleanest sample of physically close pairs), and then showed that the close pairs display an enhancement of an active galactic nucleus (AGN) in the galaxies, which are observed by the Chandra X-ray satellite, compared to isolated galaxies of similar stellar mass [34]. Thus, their results imply that close encounters between galaxies, at scales of kpc, trigger gas accretion onto massive black holes at the galaxy centers, at AU scales (~10^{13}cm). This suggests a connection between physical processes differing by almost 10 orders of magnitudes in their length scales.

B. Ménard, M. Fukugita and their collaborators used the SDSS datasets to show a simultaneous detection of gravitational magnification and dust reddening effects, based on the measurement of a correlation between the brightness of ~85,000 quasars at $z > 1$ with positions of 24 million foreground galaxies at z ~0.3 [35]. By utilizing the fact that the gravitational lensing effect is achromatic (independent of wavelength), they used the relative correlation strengths in different wavelengths in order to infer the reddening, therefore the amount of dust surrounding the lensed galaxy (host halos and large-scale structure). Cosmic dust is one of the most problematic ingredients in astronomy, but they thus developed a novel method to unveil the spatial distribution. They found that the radial profile of dust distribution is similar to that of dark matter from 10kpc to 10Mpc. The result implies a cosmic dust density of Ω_{dust}~5×10^{-6}, roughly half of which comes from dust in halos of ~L^* galaxies (typical luminous galaxies). Thus their results put stringent constraints on the global dust production rate over the cosmic time (also see B. Ménard & M. Fukugita, *ApJ*, **754**, (2012) 116).

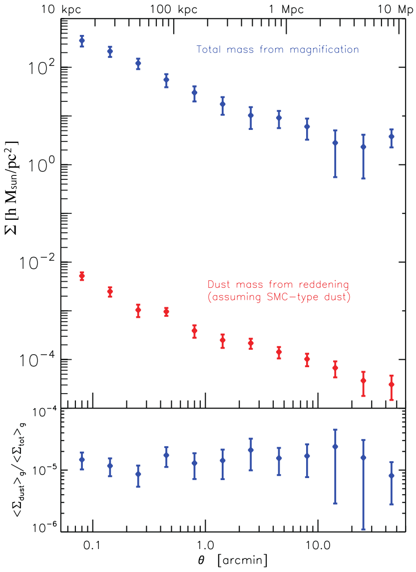


Fig.8 The mean surface mass density profile for dust and total matter around galaxies selected with *i (i band magnitude)* <21. The lower panel shows the dust mass to total mass ratio. (B. Ménard *et al.* 2010)

Research results 19: Formation of First Stars and Black Holes

All elements heavier than lithium, including not only dust but everything surrounding us (the Earth and our body), are produced in stars and supernova explosions. We have been carrying out theoretical and observational studies of formation of early stars and galaxies. One of the most important problems is the nature of the first generation of stars in the Universe. N. Yoshida and his collaborators have succeeded in performing state-of-the-art supercomputer simulations to study the generation of primordial stars from the pristine, remnant gas from the hot Big Bang Universe, based on first principles of physics [36]. For the first time, the entire formation process of primordial stars has been followed in a self-consistent manner, from a diffuse primordial gas through to the early stages as a star with thermonuclear burning.

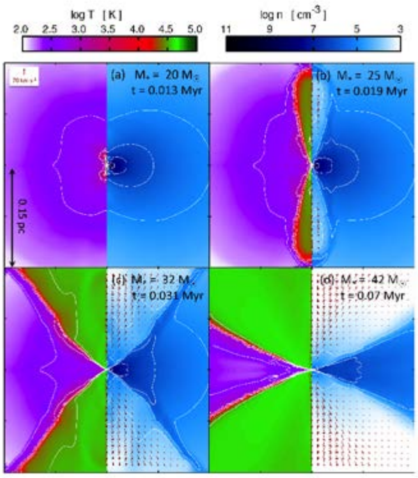


Fig.9 UV radiation feedback from the primordial protostar. The spatial distribution of gas temperature (left), number density (right) and velocity (right, arrow) are shown in each panel. The four panels show snapshots at times when the stellar mass is $M_*=20M_{sun}$ (a), 25 M_{sun} (b), 35 M_{sun} (c), and 42 M_{sun} (d). The elapsed time since the birth of the primordial protostar is labeled in each panel (T. Hosokawa *et al.* 2011)

Research results 20: Supernovae and Evolution of Chemical Elements

Supernova explosions, phenomena at the end of a certain class of stars, display rich observational signatures. However, the physics involved in supernovae remains unresolved. The team being led by K. Nomoto has been for many years the world leader in the research of supernovae. K. Maeda, K. Nomoto and their collaborators have conducted the Subaru observations of a carefully selected sample of supernovae remnants to study the nature of supernova explosions in combination with numerical simulations [37]. Type Ia supernovae (SNe Ia) form an observationally almost uniform class of stellar explosions, in that more luminous objects have slower decline-rate. This one-parameter behavior allows SNe Ia to be calibrated as cosmological "standard candles", leading to the discovery of an accelerating Universe. The Kavli IPMU team, however, revealed that the true nature of SNe Ia is more complicated. The observational data for some of SNe

Ia imply a signature of an asymmetric explosion, which is also indicated by numerical simulations suggesting that the initial thermonuclear sparks are ignited at an offset from the center of the white-dwarf progenitor.

After the Big Bang nucleosynthesis, the first heavy element enrichment in the Universe was provided by supernova explosions of population III stars. The early history of the chemical enrichment is recorded in the chemical abundance of long-lived low-mass, metal-poor stars that were formed in the early Universe and are found from the halo region of our Milky Way. Recent several large surveys discovered a large number of metal poor stars.

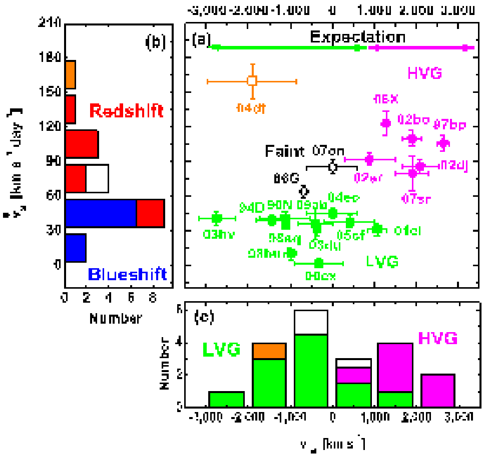


Fig.10 Relations between the features in the early- and late-phases of type Ia SN remnants. (a) Early-phase velocity gradient (vertical axis) as compared to late-phase emission-line shift velocity (horizontal axis). SN Ia sample displays a diversity of the observed features: low- and high-velocity gradients (LVG and HVG, respectively), and red- and blue-redshift (K. Maeda *et al.* 2010)

The paper [38] by K. Nomoto and others takes the approach to analyze the elemental abundance patterns observed in stars whose iron content is extremely small and compare them with the theoretically predicted abundance patterns produced by supernova explosions of the first stars. This paper shows that this approach is very successful to reveal the nature of the first stars in the Universe. To explain the very distinct abundance patterns of the iron-poor stars, such as very large ratios of CNO elements over Fe, the first stars have masses 20-50 solar masses and their explosions undergo a large amount of fallback onto the black hole.

The supernova relic neutrinos (SRN) are a diffuse neutrino background originating from past supernovae. This signal has not been observed, but it is expected to lie in the 10~30 MeV energy range, in the gap between the energy of solar and atmospheric neutrinos. The search for SRN was performed by Super-Kamiokande (SK) and a flux upper limit was obtained to be between 2.8 and 3.1 /cm^2/sec with a total positron energy above 16 MeV, which is within a factor of 2 to 5 of the model predictions [39].

This search was limited to above 16MeV because of the cosmic ray induced background. In addition, the “invisible muon background”, due to electrons produced by decay of muons with energies below the Cherenkov threshold, produced by atmospheric neutrinos, is significant above 16 MeV. At present, the SK detector can detect only positrons efficiently, but if it could detect neutrons then the background constraining the SRN search would be greatly reduced. Such a reduction could be attained via coincidence detection of positrons and neutrons. By adding 0.2% gadolinium sulfate ($Gd_2(SO_4)_3$) into the water tank, this goal can be achieved because gadolinium has a thermal neutron capture cross section of 49,000 barns (about 5 orders of magnitude larger than that of protons) and emits a gamma cascade of 8 MeV that can easily be detected by SK.

In order to study the effect of dissolving Gd in the SK tank, an R&D project called EGADS (Evaluating Gadolinium's Action on Detector Systems) has started in the Kamioka mine led by the Kavli IPMU staff members [40]. The EGADS project has started in 2009, and a 200 m^3 stainless steel tank with ancillary equipment has been constructed. The tank is equipped with a selective water filtration system that removes impurities while retaining the Gd, a 15 m^3 premixing and pretreatment plastic tank, and a device to measure the water attenuation length (called UDEAL). From February 6 to April 20 2013, the 200 m^3 was stepwise loaded with Gd until the final 0.2% concentration was attained. After $Gd_2(SO_4)_3$ was homogeneously dissolved in the 200 m^3 tank, good water quality was maintained, which corresponds to 85% Cherenkov light yield compared with pure water. This dissolution test was performed before mounting the PMTs to measure the effect of the Gd in the stainless steel tank. In the summer of 2013, 240 PMTs were installed in the 200 m^3 tank. Most are 20-inch PMTs of the same type used in the SK tank. The same cabling and waterproofing are also used. The Gd effect test using the PMTs has been started in April 2014.

2-2. Research environment including facilities and equipment

Describe the degree to which the Center has prepared a research environment appropriate for a world premier international research center, including facilities, equipment and support systems, and describe the functionality of that environment.

A new research building for the Kavli IPMU designed by Prof. Hidetoshi Ohno was built in Kashiwa Campus (5,900 square meters) in January 2010. This building has helped us greatly in achieving interdisciplinary research. All the offices are lined up in a spiral from the 3rd to 5th floor, making the three floors effectively a single floor. This arrangement avoids the traditional problem that people on different floors rarely see each other. We intentionally mix people from different disciplines in the office allocation. It also makes everybody equal along the same spiral. The 53rd BCS (Building Contractor Society) prize and the Prize of Architectural Institute of Japan 2011 were awarded to Prof. Ohno and the builders. The laboratory space in the building has been used to assemble the Silicon Vertex Detector of the Belle II experiment as well as to test Photo Multiplier Tubes to design a future neutrino experiment. The Kavli IPMU Kamioka Satellite Office (500 square meters), which became available in March 2009, has been functioning as a base for the Kavli IPMU researchers working on Super-Kamiokande, KamLAND and XMASS. All of the partner institutions as well as the two Kavli IPMU satellites are connected via video conference system. They are used daily for seminars and discussion. The Kavli IPMU built a new 3-ton digital camera with 870M pixels called Hyper Suprime-Cam for a major cosmological survey together with NAOJ, Princeton, and ASIAA (Taiwan).

We have built the underground laboratory in Kamioka on March 2008 where we have arranged Germanium detectors, a GC-MASS Spectrometer, an API-MASS Spectrometer and so on that are important devices to evaluate the radioactive contamination and to understand backgrounds of the detector components. They are commonly used by those who are working on the underground experiments

The 390m^2 Kavli IPMU Library has a collection of over 15,000 books and journals. 90% of the collection is in all areas of mathematics as 100 year old math journals are still to be relevant. In the library we often find physicists consulting math literature to find language to describe their problem.

2-3. Competitive and other funding

Describe the results of the Center's researchers to date in securing competitive and other research funding.

- *In Appendix 2, describe the transition in acquiring research project funding, and note any external funding that warrants special mention.*

H. Murayama received a research grant called FIRST (the Funding Program for World-Leading Innovative R&D on Science and Technology) selected by CSTP (the Council for Science and Technology Policy, Cabinet Office of Japanese Government). The project, SuMIRe (Subaru Measurement of Image and Redshifts) is a large-scale international survey project aiming at uncovering the origin and future of the Universe. Y. Suzuki received research grants and has succeeded in constructing the world's largest liquid Xenon detector (XMASS) in order to make an observation of Dark Matter in the laboratory experiment. K. Inoue received a research grant to construct a mini balloon inside the KamLAND detector and set limits on the lifetime of neutrinoless double beta decay. M. Nakahata received a research grant to build Evaluating Gadolinium's Action on Detector Systems (EGADS). He has built a 200-ton scale model of Super-Kamiokande detector with 240 50-cm phototubes, and a novel selective water filtration system. M. Vagins received a research grant for modifying EGADS to detect neutrinos from nearby supernovae.

2-4. State of joint research

Describe the results of joint research conducted with other research organizations both in and outside Japan.

Members of the Kavli IPMU collaborate widely with researchers from other research organizations. For instance, among the 40 most significant papers listed in Appendix 2, 24 of them involved collaborators at institutions outside Japan.

The Kavli IPMU leads several large projects. The SuMIRe project is led by H. Murayama (core researcher PI), H. Sugai (project manager), N. Tamura (project system engineer), and M. Takada (project scientist), all at the Kavli IPMU. It involves both physicists and astronomers from the Academia Sinica Institute for Astronomy and Astrophysics (ASIAA, Taiwan), Jet Propulsion Laboratory of NASA, Caltech, Princeton University, Johns Hopkins University, Laboratoire d'Astrophysique Marseille, Universidad São Paulo, the Laboratório Nacional de Astrofísica (Brazil), and Max Planck Institute for Astrophysics. The underground experiments, KamLAND (led by K. Inoue), XMASS (led by Y. Suzuki) and Super-Kamiokande (led by Y. Suzuki and M. Nakahata), an accelerator experiment, Belle-II, an accelerator-based long-baseline neutrino oscillation experiment T2K (Tokai-to-Kamioka), and a Cosmic Microwave Background Polarization experiment, POLARBEAR are all operated by large international collaborations and have all produced world class scientific results already.

The UNIFY exchange program has two main scientific objectives; to gain new insights on the quantum mechanical description of the gravitational interaction and to explore recent developments in String Theory and Quantum Gravity in the fields of Cosmology, Black Hole Physics and Gauge Theory. UNIFY involves CNRS laboratories in Paris, Humboldt Univ. and the Albert Einstein

Institute in Berlin, the Univ. of Santigago de Compostela, the Univ. of Porto, the Perimeter Institute for Theoretical Physics in Canada, the Yang Institute for Theoretical Physics at Stony Brook and Caltech in the USA, and the Kavli IPMU. UNIFY institutions have organized a number of thematic work programs and have exchanged researchers for the training of the next generation of theoretical physicists and have established long lasting collaborations among its partners. LeCosPA at National Taiwan University and the Kavli IPMU have signed an MOU to cooperate in the field of particle astrophysics and cosmology. They have collaborated on research topics such as string cosmology, and theory and observation of dark energy and dark matter.

2-5. Appraisal by society and scientific organizations

Describe how society and/or scientific organizations in and outside Japan have recognized the Center's research achievements.

- *In Appendix 2, list the awards received and invitational lectures given by the Center's researchers.*

Several members are recognized by international scientific organizations, including American Mathematical Society, Humboldt Foundation, American Academy for Arts and Sciences, the International Union for Pure and Applied Physics etc. Almost all the members have invitations to major meetings.

It deserves special mention that researchers at the Kavli IPMU were invited to write major review articles; K. Nomoto (with C. Kobayashi, N. Tominaga) wrote "Nucleosynthesis in Stars and the Chemical Enrichment of Galaxies" in *Annual Review of Astronomy and Astrophysics*, **51** (2013) 457-509, M. Kawasaki, K. Nakayama, "Axions: Theory and Cosmological Role" in *Annual Review of Nuclear and Particle Science*, **63** (2013) 69-95, N. Yoshida (with V. Bromm) on "The First Galaxies" in *Annual Review of Astronomy and Astrophysics*, **49** (2011) 373-407, H. Ooguri (with R. Kitano, Y. Ookouchi) on "Supersymmetry Breaking and Gauge Mediation" in *Annual Review of Nuclear and Particle Science*, **60** (2010) 491-511, S. Petcov and K. Nakamura on "Neutrino mass, mixing and oscillations" in Review of particle physics, *Physical Review*, **D86** (2012) 010001.

The survey conducted by JSPS in April-July 2011 showed that more than 64 (39)% of the valid responses (313) sent to authors of papers in related fields and leading scientists selected by the program officers knew the name of the institute (Director). More than 70% of them answered that they feel "strongly interested" or that it "sounds appealing" to join research at the Kavli IPMU.

2-6. Feeding research outcomes back into society

2-6-1. Applications of research results

Describe the applications created from research results, their effect in spawning innovation, intellectual properties (IPs) obtained, and joint research activities conducted with corporations, etc.

Unprecedented requirements on instrumentation from our science lead to breakthrough devices that help the industry. Building the world's largest camera and spectrograph has certainly required breakthroughs in technologies in many areas. Canon developed a new corrector lens to widen the field of view from 0.5 degrees to 1.5 degrees, with a high-precision aspherical lens. It enables a new production process for semi-conductors. The company has also built the lens barrel, which employs a ceramic material from Kyocera that achieves a significant reduction in weight and low thermal expansion coefficient suitable for space technology. The sensor was co-developed by Hamamatsu Photonics and NAOJ for a particularly good sensitivity in the red. The precision instruments should also prove critical in space deployments.

2-6-2. Achievements of Center's outreach activities

If the Center has conducted its own unique outreach activities, describe those worthy of special mention.

- *In Appendix 2, list and describe media coverage, press releases, and reporting.*

The Kavil IPMU has been extremely active in the outreach to the general public and high-school students, because we believe our science would excite the public, improve the scientific literacy, and attracts the young minds to science, technology, engineering, and mathematics which are crucial for the future of the country. We mobilized more than 22,000 people in our outreach events, organized schools for high-school students, and female students in particular. We also attract keen attention from the media, both domestically and internationally. The number of the media coverage exceeds 1,000 so far. Nearly a million copies have been printed of popular books written by our members.

The Kavli IPMU is involved in the Space Warps project. It is a citizen science project where everyone can be a part of real research on the Internet. Einstein predicted that massive objects, such as stars, would bend the space around them such that passing light rays follow curved paths. This is called strong lensing. To date human beings are better suited in distinguishing the lens features from other objects that look like lenses. As cosmic surveys are getting bigger we have asked citizen scientists to help find such lenses. We received over a million classifications within one week of the project launch with the help of over 5,000 registered users. So far we received over 18 million classifications from over 51,000 citizen scientists spread across the continents. We have discovered several new lenses with the help of citizen scientists. Some keen citizen scientists have mastered tools to make models for lenses to understand them further.

3. Interdisciplinary Research Activities (within 3 pages)

3-1. State of Strategic (or "Top-down") Undertakings toward Creating New Interdisciplinary Domains

Teatime is held at Piazza Fujiwara on the third floor from three o'clock everyday, as the only *duty* for members of the Institute. All researchers including visitors are *required* to join the teatime. It is considered an important opportunity for researchers to meet each other, talk to scientists from different fields, discuss science in a relaxed atmosphere and come up with new ideas. The building itself is designed from the ground up to promote interdisciplinary activities as described in 2-2.

All faculty members in all fields are involved when hiring new faculty members, interviewing the candidate, attending the talks, and discussing the suitability. This is considered important for the candidates also because they get to know all faculty members, not just ones in their field of interest. Whether a candidate can take an interdisciplinary approach to research is one of the most important considerations at the time of hiring. Newly arrived faculty members and postdocs introduce themselves at all-hands meetings. The Kavli IPMU does not have departments for each discipline; the operation of the Institute avoids compartmentalization.

3-2. State of "Bottom-up" Undertakings from the Center's researchers toward Creating New Interdisciplinary Domains

In order to encourage interdisciplinary research, the Kavli IPMU has been regularly holding joint seminars of different fields. There are three kinds of these joint seminars: institute-wide colloquia, mathematics-string (MS) theory seminars, and astronomy-cosmology-particle physics (ACP) seminars. In the MS Seminar, we invented a creative format: introduction to non-experts in the first 25 minutes, a 5 minutes break, and the technical seminar in the final 60 minutes. It was observed that this format improved the mutual understanding to a great extent. We are always keen to improve the format further, constantly monitoring its effectiveness. In addition, there are less formal seminar series to enhance specific areas of interdisciplinary subjects. They include: Topological String Seminar (organizer: K. Hori and K. Saito), DMM Seminar (organizer: Y. Toda and Uehara). Here "DMM" stands for "Derived category, Mirror symmetry and McKay correspondence". We also started the mathematics-astronomy seminar in fall 2011 to enhance the collaboration between mathematicians and astronomers to develop new mathematical approaches in the gravitational lensing analysis and extract maximum amount of information from the data.

We specifically designate select colloquia as "interdisciplinary", intended for the entire Institute. This is a result of a few years' trial-and-error in order to provide common ground on important topics for all members. For example, on July 4, 2012, a large fraction of members, including astronomers and mathematicians, watched the webcast announcing of the discovery of the Higgs boson. Motivated by this development, on April 24, 2013, T. Yanagida explained the Higgs boson after its confirmation on March 14, 2013. It was highly appreciated by all members.

The Kavli IPMU has hosted a number of interdisciplinary workshops. A collaboration between string theorists at the Kavli IPMU (H. Ooguri) and condensed-matter physicists at ISSP (Oshikawa) emerged from Focus Week "*Condensed Matter Physics Meets High Energy Physics*" which was jointly organized by the Kavli IPMU and ISSP in February 2010. Their joint paper "*Instability in Magnetic Materials with a Dynamical Axion Field*" was published in *Physical Review Letters*. There has also been intriguing and fruitful interaction between the field of homological algebra and algebraic geometry (mathematics) and that of two-dimensional quantum gauge theories (physics) at the workshop "*Homological Projective Duality and Quantum Gauge Theory*". Another Workshop "*Geometry and Physics of the Landau-Ginzburg Model*" dealt with an important model in the study of supersymmetric quantum field theory and superstring theory. We also hosted several workshops dealing with common problems in particle physics and cosmology, such as Focus Week "*Gravity and Lorentz Violations*" and the Workshop "*Supernovae, Dark Energy, and Cosmology*." The workshop "*Curves and Categories in Geometry and Physics*" provided a forum for mathematicians working on geometry and physicists working on string theory. The Workshop "*Particle Physics of the Dark Universe*" dealt with dark matter, which is obviously a common problem in particle physics and cosmology. A Focus Week on new invariants and wall crossings, held in May 2009, was attended by 32 mathematicians and 34 physicists.

Participants of the Kavli IPMU Workshop on Black Holes, which was held in February 2011, discussed a wide range of topics regarding black holes, from their astronomical observations to their quantum properties in superstring theory and loop quantum gravity. A number of leading researchers got together and spent ample time discussing different aspects of the black holes.

We believe that a collaboration between statistics and astronomy would prove successful, given the anticipated large data sets from HSC and PFS surveys. We held a workshop entitled "*Statistical Frontiers of Astrophysics*" to start exploring the connection. Furthermore, we recently submitted a proposal to the JST CREST program jointly with statisticians from the Institute of Statistical Mathematics.

3-3. Results of research in fused research fields

Describe the Center's record and results by interdisciplinary research activities.

- *In Appendix 3, list the main papers published (up to 20 papers) on the Center's interdisciplinary research and provide a description of each of their significance.*

One of the Center's aims is to bring physicists and mathematicians together to develop new formulations of the fundamental laws of Nature. However, an important fact is that physics and mathematics have very different purpose — not only the language but also the way of thinking are extremely different at the deep level. The researchers brought together are of course aware of this difference, and have been continuously making an effort to overcome the difficulty coming from the difference. Thus Mathematics and Physics are not meant to be *fused*. The WPI working group quoted C.N. Yang (Nobel Laureate in Physics) from his talk at the Newton Institute: "*Mathematics and Physics are like dual seed leaves. They are overlapping. When they grow, the intersection becomes larger but this is because each leaf becomes larger. They never become one leaf"* in their report from the 2011 site visit. We completely agree. We do not attempt to erase the boundaries between experimental physics, theoretical physics, astronomy and mathematics, while strongly encourage and pursue steady communication for mutual inspiration between the disciplines. As a result, we see increasingly active interactions between mathematicians and physicists, which led to publications. A partial list is given in Appendix 3. In addition, there are unanticipated types of interdisciplinary activities. Given the importance of differential geometry in Einstein's theory of relativity, which in turn is crucial for cosmology, we see impact of pure differential geometry and topology in understanding data from telescope observations. Furthermore, we will further try to enhance the connection between the two in terms of statistics needed for analyzing large-scale data anticipated from HSC and PFS.

From the outside, theoretical physics and mathematics might look deceptively similar: both use mathematical equations, for example. But in reality, the researchers in the two fields speak two rather different languages, having diverged during the last 200 years of the developments in each field. Therefore, it requires a highly non-trivial effort to translate a physics conjecture into a well-formulated mathematical one, or to translate a mathematical proof back into physical theories. To carry out this translation, the Kavli IPMU is an ideal environment, as there are always theoretical physicists and mathematicians at the same time, both eager to communicate with each other.

For this purpose, we have are a couple of key "interpreters": Y. Tachikawa, K. Hori, and H. Ooguri. In the spring semester of 2012, Y. Tachikawa gave a series of informal lectures on the basics of the Alday-Gaiotto-Tachikawa conjecture at the Kavli IPMU, to facilitate the discussions between physicists and mathematicians. During the lectures, there was often a lively debate between the speaker and the audience how to best translate a physics concept into a mathematical language. Thanks to this lecture series, Y. Tachikawa has become known not just to mathematicians at the Kavli IPMU but to the mathematical community at large as a physicist who can speak in the language of mathematicians; this led to his being invited to many lectures in mathematics departments at other universities, and to many talks at the mathematics conferences. There is not yet any published paper that directly arose from this activity; this type of interdisciplinary cross-talk requires many years of preparation to result into a scientific paper. At least, an unpublished version of the lecture notes are available at Y. Tachikawa's webpage, hosted by the Kavli IPMU.

Recently, there has been revived activity to exactly compute partition functions of supersymmetric field theories on curved manifolds, using "supersymmetric localization", *i.e.*, cancellation between the path-integrals of bosonic and fermionic variables. Members of the Kavli IPMU played dominant roles in obtaining exact results in two-dimensional supersymmetric gauge theories, which are particularly important since the superconformal fixed points in the infrared limit can be used as the worldsheet theories of superstrings. In {5}, M. Romo and collaborators observed that the partition function on the two-sphere, computed by F. Benini *et al.* (2012) and Doroud *et al.* (2012), determines the Kähler potential on the moduli space of string vacua. This is a paper written jointly by physicists and mathematicians. K. Hori and M. Romo then computed the partition function on the hemisphere and the result provides a general exact formula for the central charge of the D-brane placed at the boundary [24]. In {10}, R. Eager, K. Hori and Y. Tachikawa computed with F.

Benini the partition function on the two-torus and obtained a general formula for the elliptic genus. K. Hori and J. Knapp {13} used these results to test the duality [23] to obtain useful information of the theory. These results could not have been obtained without the Kavli IPMU. Indeed, the computation of the two-sphere partition function by F. Benini *et al.* and Doroud *et al.* were partly motivated by K. Hori's work [23]. On the other hand, using techniques in string theory, A. P. Braun, Y. Kimura and T. Watari classified elliptic fibrations modulo isomorphism on *K3* surface with large Picard number {14}.

There are also papers in mathematics inspired by physics. Y. Toda introduced the notion of Gepner-type Bridgeland stability conditions on triangulated categories inspired by Gepner construction of Calabi-Yau background on worldsheet conformal field theories {6}. This paper draws heavily from the physics literature of H. Ooguri et al, and acknowledges K. Hori. K. Saito proposed a new approach to the geometric theory of discrete groups based on Ising model in physics {7}.

As encouraged by the working group, we also ventured into interdisciplinary research with condensed matter physics. Partly as a result of a workshop jointly organized with the neighboring Institute for Solid State Physics on the same campus, H. Ooguri published a paper with condensed matter physicist M. Oshikawa {15}. An axion is a hypothesized particle that is also a candidate for dark matter of the Universe. They pointed out that there is an axion-like excitation in magnetic material that causes instability and screens the applied electric field. They showed how this effect can be realized experimentally. H. Murayama produced a series of papers with a condensed matter physicist H. Watanabe (also with a nuclear physicist T. Brauner) including four *Physical Review Letters* {18}. Even though it has been known for more than half a century that a spontaneous breaking of continuous symmetries lead to gapless excitations called Nambu-Goldstone bosons (NGBs), there was no universal theory that determined the number and behavior of these excitations. After the authors solved this problem in [28], many applications emerged. For instance, the authers clarified how the combination of internal and spacetime symmetries lead to a reduced number of NGBs due to an operator relation they called *Noether constraints.* A vortex lattice in rotating Bose-Einstein condensates clearly exhibits this phenomenon. Some gapped states can also be studied exactly, akin to the BPS states in supersymmetric gauge theories {17}. T. Takayanagi developed a powerful technique to compute entanglement entropy using the holographic dual of boundary conformal field theory {16}. This allowed a holographic construction of quantum Hall effect, and led to a large body of works including [27].

An unanticipated interdisciplinary activity emerged between astronomy and mathematics. We have a clear focus on the HSC imaging survey on the Subaru telescope to study cosmology using gravitational lensing. Lensing occurs because of the curvature of spacetime due to the presence of a mass distribution of (mostly) dark matter. How a background image is distorted by the foreground mass distribution is a well-defined question in differential geometry, and even exact results on the number of lensed images had been obtained using the Gauss-Bonnet theorem. M. Werner, with background in both astronomy and mathematics, found a new geometric method to determine the deflection of light in the equatorial plane of the Kerr solution using the Gauss-Bonnet theorem {1}. He further developed a novel mathematical model for the distribution of cosmic voids together with astrophysicists {2}. Recent wide-field galaxy surveys show that the large-scale galaxy distribution appears as complex network of filaments and voids of various physical sizes. They proposed that the geometrical concept of a four-dimensional de Sitter configuration of spheres in Euclidean 3-space can be used to describe the number density of cosmic voids as observed. Advanced tools in geometry are also crucial in applications to black holes {19} and dark matter.

The best illustration of interdisciplinary activity appeared at our regular teatime. R. Quimby, an astronomer who discovered a class of the brightest supernovae called superluminous supernovae, was puzzled by a claim by the US-based Pan-STARRS group that the observed supernova PS1-10afx was a yet brighter new type. He realized immediately that the light curve and spectra resembled standard type-Ia supernova, while it was 30 times brighter. M. Werner pointed out it was mathematically possible to obtain this magnification by gravitational lensing if there is an unobserved object exactly along the line of sight towards the observed supernova. Such a possibility appeared implausible in practice. However M. Oguri, a physicist with experience working with large data sets from SDSS, estimated quickly that there is about one chance in the Pan-STARRS data set. Together with other supernova experts at the Kavli IPMU, they published this interpretation based on this teatime discussion {3}. It was controversial for a while because the Pan-STARRS group stood by their original claim. About a year later, long after the supernova faded away, R. Quimby *et al.* used the 10m Keck-I telescope to observe the host galaxy, and could prove that there is an unresolved faint galaxy in the foreground exactly along the line of sight {4}. This result was published in Science and was covered by more than 50 media internationally.

In addition, unexpected directions emerged from our interdisciplinary environment. S.J. DeDeo was keen to apply mathematical methods he acquired during his research in astrophysics at the Kavli IPMU to other areas, and found a useful application in studying conflicts in monkey society using the game theory in mathematics. This type of spinoff is difficult to plan and predict. Nonetheless it is an evidence {20} that the fundamental research at the Kavli IPMU can have far-reaching impact on a wide area of science.

4. International Research Environment (within 4 pages)

4-1. International Circulation of Best Brains

4-1-1. Center's record of attracting and retaining top-world researchers from abroad

Describe the participation of top-world researchers as PIs and the residing of joint researchers at the Center.

- *In Appendix 4, give the number of overseas researchers among all the Center's researchers, and the yearly transition in their numbers.*

From the development stage, we had a firm belief that the key to gaining international recognition is to bring top-level leaders and talented young researchers from around the world, and to create an environment in which researchers in different fields learn each other's languages and work together toward common goals. We have established such a fascinating research environment here at the Kavli IPMU. It functions as the center for the "brain circulation." In 2013, all 18 Principal Investigators (five international: 28%) are world-leading scientists. A. Bondal is a leading expert and a founder of the theory of derived categories. This theory has an enormous influence on various areas of mathematics, mathematical physics, and string theory. He holds a joint professorship at the Kavli IPMU and stays six months a year. S. Katsanevas's scientific interests include neutrino physics and astroparticle physics. He is now the Director of the Astroparticle Physics and Cosmology (APC) laboratory, Université Paris Diderot, Paris 7. He plays a crucial role in bridging the Kavli IPMU and European community together. D. Spergel is one of the best theoretical astrophysicists in the world. He is a member of HSC and PFS executive committees as well as our Scientific Advisory Committee of the Kavli IPMU. He is Chair of the Department of Astrophysical Science at Princeton University, and helps us with administrative aspects as well. He comes to the Kavli IPMU a few times a year. H. Sobel is one of the leaders in neutrino physics in the world. He participates actively in Super-Kamiokande and T2K experiments and visits Kamioka Branch several times a year.

A large fraction of our researchers is international, and many of our members are considered as world class. Out of 245 member researchers including faculty members, postdoc, long-term visitors and graduate students, 99 (41%) are international. If we count the number of researchers paid with WPI funds, out of 92 researchers 55 (60%) are international. On average about 800 researchers per year visit us. The numbers of visitors each year are (multiple visits in a given year are counted as one)

	2007	2008	2009	2010	2011	2012	2013
total*	168	372	432	862	630	835	1017
international	65	103	345	478	392	497	544

(*revised in the final version)

Many of these visitors are world-class scientists. To keep the Kavli IPMU as a hub of exciting intellectual exchanges, we invited many prominent researchers to stimulate young researchers. Nobel laureates in Physics, George Smoot (2010), Jerome Friedman (2011), David J. Gross (2009 & 2011), Brian P. Schmidt (2012), and Fields Medalists Shing-Tung Yau (2009), Maxim Kontsevich (2010) visited us to give lectures and seminars. It must be also noted that Fabiola Gianotti (2013), the former spokesperson of the ATLAS experiment at LHC, CERN, and Lisa Randall (2014) from Harvard, well-known for her theory of warped extra dimensions and a popular author, visited us to give seminars to our researchers and public lectures as outreach activities to encourage participation of women in science.

We attract topnotch scientists. For example, we are very proud that we could attract M. Kapranov, a full professor at Yale, to one of our first tenured positions. Given his well-known status as a leader in higher category theory and driver behind many important mathematical concepts recently, this is a significant boost of our international standing. We could recruit M. Hartz, a neutrino experimentalist, despite Wilson Fellow offer from Fermilab, one of the most prestigious positions in experimental particle physics in the US. We successfully retained K. Bundy and A. Leauthaud, a couple of astronomers, against an offer of tenured Lecturer positions at Portsmouth, and S. More, also an astronomer, against two tenure-track offers from India. Note that he came initially as a five-year postdoc turning down the Hubble Fellowship, the most prestigious postdoc position in astronomy in the US. These are testaments of our exciting research program that cannot be done elsewhere in the world. In addition, we retained our faculty members against offers from other Japanese institutions: Y. Toda, M. Takada, T. Abe.

4-1-2. Employment of young researchers at the Center and their job placement after leaving the

Center

Describe the Center's employment of young researchers, including postdoctoral researchers, and the positions they acquire after leaving the Center.

- *In Appendix 4, enter the following:*
  - *The state of international recruitment for postdoctoral researchers, applications received, and selections made*
  - *The percentage of postdoctoral researchers from abroad*
  - *The positions that postdoctoral researchers acquire after leaving the Center*

Our policy for mobilizing and circulating the world's best brains is to recruit the brightest young people as post-doctoral researchers and provide them with the best research environment so that they can realize outstanding accomplishments during their there-year term at the Kavli IPMU and become strong candidates for either faculty positions or other post-doctoral positions at prestigious research institutions. Every year we have about 700 applications on average, mostly (90%) from abroad. The number of new postdoctoral researchers hired with WPI funds is 18 annually on average, mostly (80%) from abroad. By the end of FY 2013, we hired 107 postdocs and 82 (80%) are non-Japanese. About 40 postdoctoral researchers are resident at the Kavli IPMU on average.

There are several key ingredients in attracting this many applications and recruiting. The first is to make the hiring cycle commensurate with the West, namely advertised in the fall, offers in winter, and appointments in the early fall. We made a special deal with academicjobsonline.org as the first non-US institution to use the system. We also developed our own system for online job application database, which is now used at other Japanese institutions. Our offer letters include detailed description of our policy and support system, in addition to salary levels competitive with leading institutions in the US.

For faculty hiring, we follow practice in the US. We "beat the bushes" to attract as many applications as possible by advertising the positions heavily through publications, web, and through personal connections to senior scientists around the world. We treat the candidates as VIPs, because the candidates are on sellers' market, not on buyers' market; as many of the candidates on our short lists are also being considered at other leading institutions, making them feel welcome and wanted is a crucial element of recruitment. Candidates on the short lists are invited for talks, and interviewed individually by our faculty members for 30-60 minutes each. While we evaluate the strengths of the candidates, we also convince the candidates on the strength of the research environment we have and on how well they will be supported through their careers. The terms are negotiated. We also make effort to find positions for spouses as much as we can.

It is clear that an affiliation at the Kavli IPMU is now a successful career path. Of 107 postdocs we hired 63 had left the Kavli IPMU, some before expiration of the three-year term. We have been able to recruit postdocs from a large number of research institutions in the world and many of them have been recruited from top-level research institutions such as Harvard, Princeton, MIT, UC Berkeley, Caltech and Chicago in US, University College London, Amsterdam, Ludwig-Maximilians, and ETH in Europe, and top-level research institutions in other regions such as Seoul National U, U of Chile, U of Sao Paulo, and TIFR. Out of the 63 postdocs who left the Kavli IPMU, 28 found a faculty position already (McGill, Arizona State, Iowa State, Chonnam National, Zhejiang, Hong Kong, Yokohama National, Kobe, Kyushu, Tohoku, Kyoto, Tsukuba University, Tokyo University of Agriculture and Technology, NAOJ, and others), and 30 found another postdoc position at prestigious institutions such as CERN, Princeton, Cambridge, Caltech and Max-Planck Institute.

As for young faculty members, F. Takahashi was recruited as Associate Professor at Tohoku University, K. Maeda as Associate Professor at Kyoto University, A. Mikhailov as Assistant Professor at Universidade Estadual Paulista - Instituto de Fisica Teorica, São Paulo, Brazil, N. Yoshida as the youngest Full Professor at Faculty of Science at UTokyo, T. Takayanagi as the youngest Full Professor at Yukawa Institute for Theoretical Physics (YITP) at Kyoto University, S. Sugimoto also as Full Professor at YITP, Y. Tachikawa as Associate Professor at Faculty of Science at UTokyo.

4-1-3. Overseas satellites and other cooperative organizations

- *In Appendix 4, describe the state of the Center's agreements concluded with overseas satellites and other cooperative organizations.*

The Kavli IPMU's UC Berkeley Satellite was established on Berkeley campus in December 2009 based on a comprehensive academic exchange agreement that was signed by UTokyo and University of California Berkeley, brokered by Director Murayama. It provides a framework for conducting collaboration between the Kavli IPMU and Berkeley in a wide range of fields involving particle physics, cosmology and mathematics. Activity is taking place in the field of particle theory involving string theory and phenomenology. Further collaboration in Sloan Digital Sky Survey (SDSS) is going on at the Berkeley satellite. It also facilitates our finding candidates in the US for the post of Kavli IPMU staff researchers.

H. Murayama spends a half of his time at the satellite during his stay at Berkeley that is 30% a year, and supervises overall activity with the help of two Research Directors, T. Yanagida of the Kavli IPMU and L. Hall of Berkeley. The team consists of 7 other faculty members, and approximately 10 postdoctoral fellows and 20 students. Y. Nomura, L. Hall, H. Murayama and S. Rajendran collaborate with T. Yanagida, S. Matsumoto and M. Nojiri in particle phenomenology, and M. Aganagic, R. Bousso, O. Ganor and P. Hořava, with H. Ooguri, K. Hori and S. Hellerman in string theory.

As the results of the Satellite activity, two or three collaborative papers have been published annually. Also, more than ten researchers at the Kavli IPMU and the Satellite are visiting mutually for further collaborative research.

There are 15 other cooperative organizations covering the fields of mathematics, physics and astronomy including Princeton University in the USA, Deutsches Elektronen-Synchrotron (DESY) in Germany, TRIUMF in Canada and Tsinghua University in China. TRIUMF and the Kavli IPMU made a new and creative agreement on a promising joint position established in 2012. Based on this agreement, in 2013, one prominent postdoctoral researcher from Toronto University won the tenure-track assistant professor position at the Kavli IPMU and started his research in a neutrino physics experiment. In addition, we have a number of agreements on research projects by international collaborations, including SDSS III and IV, interim Palomar Transient Factory (iPTF), Prime Focus Spectrograph (PFS) on Subaru telescope under the Kavli IPMU's leadership, and others.

4-2. Center's record of holding international symposia, workshops, research meetings, training meetings and others

- *In Appendix 4, describe the main international research meetings held by the Center.*

From the starting stage of the WPI program, the Kavli IPMU has hosted many conferences, workshops and seminars every year. The numbers of major international research meetings hosted by the Kavli IPMU were; 4 in 2007, 7 in 2008, 12 in 2009, 16 in 2010, 12 in 2011, 11 in 2012 and 15 in 2013, respectively. Focusing in 2013, 389 (45%) out of the 867 total participants who attended 15 meetings came from foreign institutions. The subjects that were covered in these meetings and the speakers were carefully selected so as to keep the timeliness of topics and the discussion highest quality. Among these international meetings, "*Condensed Matter Physics Meets High Energy Physics*" (2010; 200 participants 40 from abroad), "*CLJ2010: from Massive Galaxy Formation to Dark Energy*" (2010; 160 participants 107 from abroad) and "*Primitive forms and related subjects*" (2014; 81 participants 41 from abroad) are the examples of those with highly exciting and stimulating quality.

At the same time, Kavli IPMU researchers presented numerous seminars and talks at both foreign and domestic institutions and conferences. These activities helped to raise the visibility of the Kavli IPMU in the international community.

We have also made impact on globalization of the graduate programs at UTokyo. Our faculty has already contributed to the graduate programs at Department of Physics and Department of Mathematical Sciences through supervision of graduate students and lectures on voluntary basis. We partnered in two *Programs for Leading Graduate Schools*, one for "Frontiers of Mathematical Sciences and Physics" (FMSP) and the other "Advanced Leading Graduate Course for Photon Science" (ALPS). It presents opportunities for interdisciplinary research to graduate students at UTokyo within our international and interdisciplinary environment. For example, Kavli IPMU-FMSP Tutorial Workshop "*Geometry and Mathematical Physics*" was attended by about 50 participants, mostly young researchers and graduate students. Another Kavli IPMU-FMSP workshop "*Mirror Symmetry in Physics and Mathematics*" discussed primitive forms and related subjects in exceptional singularities in geometry and field theory. All lectures were given in English providing important training to young researchers and graduate students. In addition, our international faculty lectured on scientific writing in English in Department of Physics, a very popular course among graduate students. So far more than 110 students took the course.

4-3. System for supporting the research activities of overseas researchers

Describe the Center's preparations to provide an environment conducive for overseas research to concentrate on their work, including for example living support in various languages or living support for their families.

The Kavli IPMU is proactive in helping international researchers with life in Japan, so that they can kick start and concentrate on their academic research. Support consists of the assistance needed to get their life in Japan started such as:

- Obtaining Certificate of Eligibility and Professor Visa before arrival.

- Extensive orientation about life in Japan and at the Kavli IPMU, such as a deposit and key money in keeping with the Japanese custom, grant application systems, *etc.*
- Resident's registration at local municipal office; our staff accompanies to the municipal office for foreign resident's registration procedure.
- Finding housing; we have made arrangements with real-estate offices with English-speaking staff and our staff often accompanies the visits to properties, and signing contracts.
- Opening a bank and credit card account; many banks do not offer English application forms.
- Obtaining a cell phone; a staff helps them signing a contract.
- Day Care on the campus; staff explains how on-campus day care works, in particular phone calls when breast-feeding is needed.
- Various needs in daily life, including emergency health care and pregnancy.
- Free "survival Japanese" lessons to newly arriving international researchers and their family to kickstart their life in Japan. They are also welcome to take more advanced classes if interested.

We subsidize the full-time researchers a half of the tuition at international schools; this is important since children experience great difficulty in Japanese public school system. Our staff has been visited by many research organizations as a model of support for international researchers.

Concerning visitors, it is necessary to help them with mundane but non-trivial problems they encounter during their stays. We prepared the Kavli IPMU website in English and Japanese with useful information for both visitors and employees for professional and daily living issues including safety. This attempt was well appreciated by the University, and the Kavli IPMU Administrative Division was honored UTokyo President's Award for Operational Improvement twice, in 2008 and 2013. In addition to the items mentioned above, the University has made a special effort to provide housing for Kavli IPMU researchers. The Kashiwa International Guesthouse was opened in March 2010 where the Kavli IPMU was allocated 16 units. To further enhance living support, the Kavli IPMU has made a contract with 24-hour service center for foreigners.

It should be noted that the Kavli IPMU administration helps researchers to prepare application forms for research grants. We conduct training session how to write successful grant proposals, and provide help on forms that are supposed to be filled in Japanese. This encourages researchers to secure the research funding such as Grant-in-Aid without any serious barriers. As a result of these efforts, eight young international researchers out of 29 applicants won Grant-in Aids in 2013. The success rate is about 30% and is almost the same level as that of our Japanese young researchers.

4-4. Others

Describe the Center's policy for sending Japanese researchers overseas to gain international experience, and give examples of how the Center is working to create career paths for its researchers within a global environment of researcher mobility.

The Kavli IPMU has a policy that all full-time researchers have to spend one to three months abroad each year. This policy provides an ample opportunity, especially for young members, to expose themselves by giving talks at conferences and seminars abroad. This greatly helps them to raise their visibility in the international community and opportunity for subsequent career developments. We provide 500,000 yen of research support annually, which is intentionally insufficient to pay for the entire trips. The young researchers are supposed to contact host institutions on their own to arrange support and opportunities for talks. Otherwise they are simply "guests" and may not be paid enough attention. This approach is clearly successful given the fraction of our postdocs moving on to other academic positions. The large number of international visitors is also helping them with exposure; some American postdocs remarked that they met far more famous scientists here at the Kavli IPMU than at a typical American University.

This also helps young researchers to learn about the international landscape of research and learn information for career paths. One young postdoc researcher at the Kavli IPMU moved to IAS in Princeton and after years, he came back to the Kavli IPMU as a faculty member. Later on, he moved to IAS again for further collaborative research activities while keeping his position at the Kavli IPMU.

Two other good examples of researcher mobility through the Kavli IPMU, those are:

1. One mathematician came to the Kavli IPMU as a postdoc after having received Ph.D. from UC Berkeley and a teaching experience as a lecturer at MIT. After two years of research at the Kavli IPMU, he was appointed as a tenure-track assistant professor at Tsukuba University.
2. Another case is a new idea to stimulate the researcher's mobility, based on the agreement between TRIUMF and the Kavli IPMU. For the first five years, an applicant can work in the both laboratories with a certain job effort as a tenure-track. After five years, an applicant can choose one of the laboratories for a permanent position. In 2013, one prominent postdoc won this new

position and started research under the condition of 75% at the Kavli IPMU and the rest at TRIUMF.

We also actively compete for additional resource from funding agencies to support our young researchers to obtain experience and exposure abroad. One program from JSPS provided ¥86M to send 88 members abroad, and 16 among them stayed abroad longer than two months.

5. Organizational Reforms (within 3 pages)

5-1. Decision-making system in the center

Describe the strong leadership that the director is giving the Center's operation and its effect, and the division of roles and authority between the Center and its host institution.

The Director continues to uplift the Kavli IPMU by recruiting very best scientists from all over the world, and promoting the science that is carried out at the Kavli IPMU in both scientific community and public sector. Toward achieving this goal, the Director receives advice at different levels from the Executive Board (EB), Steering Committee (SC), Scientific Advisory Committee (SAC), and External Advisory Committee (EAC).

The EB, consisting of the Director, two Deputy Directors, Associate Director and the Administrative Director, is held regularly, typically once a month, to ensure smooth operation and swift decision making on daily matters. The members of the EB also take an important role when the Director makes direct access to the office of the University President.

The SAC members are two Deputy Directors, Associate Director and five PIs. They advise the Director on hiring new faculty, budgeting for research, and setting research strategies of the Kavli IPMU. The EAC members, consisting of seven internationally well-known outstanding experts, meet at least once a year, and provide valuable advice to the University President on the activities and achievement at the Kavli IPMU.

In January 2011, the Todai Institutes for Advanced Study (TODIAS) was established and the Kavli IPMU became the first institute (5-3. System reforms advanced by WPI program and their ripple effects). This introduced no difference in the decision-making system of the Kavli IPMU. The SC, consisted by members of the EB and a couple of PIs, serves as the personnel committee for faculty and reports the decisions to the TODIAS Steering Committee.

On February 1, 2014, the Office for Research Strategies was opened, with the support UTokyo, reporting directly to the Director in order to strengthen the research activities by pursuing the external funds. A new university research administrator (URA) was hired to start the office activities.

5-2. Arrangement of administrative support staff and effectiveness of support system

Describe the assignment of the Center's administrative support staff who have English language and other specialized skills, effort made in establishing the support system, and the system's effectiveness.

From the beginning, the Director eagerly desired to establish a "Utopia for researchers" to make the environment where international researchers could devote all their attention to research. Many bilinguals were hired as administrative supporting staff to help international researchers to start their lives in Japan.

In 2013, the number of administrative staff is 40, of which 30 are in the category of research support staff of the Kavli IPMU, in contrast with the 9 staff that belong to the administrative bureau of the University. The daily administrative matters are handled by the administrative division that is supervised by the Administrative Director with the help of the General Manager. There are 11 staff members in the general affairs section (including 2 public relation specialists, one URA and one secretarial staff), three in the accounting section, nine in the international relations section (including one in charge of conference and one Japanese instructor), three in the financing section, four in the purchasing section, three in the Kamioka Satellite office, two for computing and website, one for the library and two for documentation.

Out of 40, a half of staff members are bilingual (two of them trilingual), and three have background in particle physics. This team handles all logistics for newly arriving staff and visitors, in particular those from abroad. The team helps organizing international conferences and workshops, and filing research grant applications and other paperwork. They are also responsible for organizing various public outreach activities such as public lectures, publication of the Kavli IPMU NEWS magazine, and updating the Kavli IPMU website covering a wide variety of information.

The public relation officers manage press releases and press conferences in a timely fashion with a good relationship with the public relation office of UTokyo. We built a system to work with international media outlets. We became a member of interactions.org, an international organization of major particle physics laboratories that acts as an outlet to international media. Through the Kavli

Foundation, we can post press releases to EurekAlert in the US managed by AAAS and AlphaGalileo in Europe.

Three staff members have skills in computing support including managing servers. One staff member is an artist helping scientists with visualization for publications and press release material. Another staff member is a musician and organizes a chamber orchestra for our members. A member has background in finances with very good human skill and works with donors to attract private donations.

As proposed by the Director at the beginning of the Kavli IPMU, the daily teatime at three o'clock is now a "healthy" habit of the Kavli IPMU residents encouraging informal and interdisciplinary discussions among them. The administrative staff assists a systematic arrangement for this activity every day. Discussions during the teatime often stimulate the researcher to publish interdisciplinary papers.

5-3. System reforms advanced by WPI program and their ripple effects

Concisely itemize the system reforms made to the Center's research operation and administrative organization, and describe their background and results. Describe the ripple effects that these reforms have on the host institution. (Describe the ripple effects on other institutions.)

It must be stressed that TODIAS is a quite crucial system reform stimulated by the WPI program. In January 2011, UTokyo established the TODIAS and approved the Kavli IPMU as the first member institute within this new and permanent organization. This was the drastic organizational reform since 1949 at UTokyo. It was established as a university-wide organization and comprises research institutes, each demonstrating its function as a world-leading center of knowledge, aiming to enhance the University's academic excellence as a whole and further advance its internationalization.

The TODIAS structure enabled the Kavli IPMU to request operating funds from MEXT, giving the Kavli IPMU a means to acquire resources to sustain itself permanently. In fiscal year 2014, the TODIAS received four permanent posts to guarantee the outstanding research and education in the research division.

When launched by WPI program in October 2007, the (Kavli) IPMU was given a status of "special district" within UTokyo where top-down management, flexible hiring system and merit-based salary system had been made possible. Inspired by the WPI program and stimulated by real experiences inside the Kavli IPMU, UTokyo have intensified the following system reforms to make the Kavli IPMU a world-leading institute:

- Merit-based salary scale
- Joint (split) appointments
- Tenured position with non-traditional external funding
- *Nenpo* system (no traditional bonus or retirement benefit with higher pays and mobility)
- Flexible management of positions
- Assist by bilingual administrative staff

Director Murayama is actually the first example of a split appointment with an institution outside Japan, as well as of a merit-based salary. For example, one professor started a split appointment between the Faculty of Science and the Kavli IPMU with split effort of 60/40%. Also another professor made a joint appointment between KEK and the Kavli IPMU with split effort of 80/20%. A tenure track assistant professor was hired under a newly established joint TRIUMF-Kavli IPMU agreement as briefly mentioned in 4-4.

All these reforms give high mobility for faculty, which could be a possible catalyst for destructing the compartmentalization in the university. The impact of this change will be felt not only in UTokyo but also across the nation with other institutions likely to make similar changes.

5-4. Support by Host Institution

The following two items concern the support that the host institution provides the Center, including those items of support that it committed to at the time of the initial project proposal submittal or in its revised commitment following the project's interim evaluation. Describe the functional measures that the host institution has taken to sustain and advance the Center's project.

5-4-1. Record of host institution support and its effects

- *In Appendix 5, describe the concrete measures being taken by the host institution.*

At the time of the original proposal, UTokyo made many exceptions to the Kavli IPMU as a "special district" within the University: flexible salary system, longer appointments than traditional fixed-term positions, moving some PIs with advantageous arrangements with retirements from traditional departments, appointments beyond the retirement age, etc. UTokyo also committed to build the main research building specifically for the Kavli IPMU, and a new international lodge near the Kashiwa campus, a main residential facility for international researchers who have moved to the Kavli IPMU and short-term visitors. After the Kavli IPMU was established, it also provided extra assistant professor positions to aid PIs to be freed from duties to be involved in research at the Kavli IPMU. President Hamada made a decision to accept Kavli donation despite some concerns and oppositions within the University.

As described in the previous section 5-3, the creation of TODIAS in 2011 is outstanding support providing a permanent place for the Kavli IPMU within the University. Under this structure, the TODIAS requested funding to MEXT to sustain the activity and won four permanent positions in TODIAS in 2013. Following the interim evaluation, UTokyo made several measures to make the Kavli IPMU sustainable. The University has agreed to provide the Kavli IPMU with nine tenure positions of the President's discretion by the end of FY 2016. Already five positions have been secured. The University secures 9 people from the administrative bureau of the University.

More details on the concrete measures are described in Appendix 5.

5-4-2. Position of the Center within the host institution's mid-term plan

- *To Appendix 5, attach the cover sheets of the host institution's "Mid-term objectives" and/or "Mid-term plan" and parts of these documents related to the WPI Center.*

In 2007, UTokyo's "first phase" mid-term research objectives included a statement, which says, "Actively promote the establishment and development of a core research facility". The accompanying medium-term plan says "At the world's top level research center, the 'Institute for the Physics and Mathematics of the Universe', intensively develop organizations to investigate the origin and evolution of the Universe through the collaborations of mathematics, physics and astronomy."

In 2010, the university's "second phase" mid-term research objectives and mid-term plan was issued (revised partially in 2014). The action plan is much more general and says, "specifically, promote international research collaboration in the field of advanced astronomical scientific research, as well as develop the environment for education by inviting world-class researchers."

Also, based on the President's Action Scenario FOREST2015, the University founded TODIAS in 2011 as a university-wide organization for the pursuit of academic excellence and globalization of research environment, and placed the Kavli IPMU in TODIAS. Under this action scenario, UTokyo is taking any means necessary to support the Kavli IPMU.

In addition to the annual review by the WPI program committee, the University reviews us with an External Advisory Committee every year. The committee consists of world-leading scientists, currently chaired by Steve Kahn (Stanford, Director of Particle Physics and Astrophysics of SLAC) together with John Ellis (King's College London, former Head of Theory Group at CERN), Young-Kee Kim (Chicago, former Deputy Director of Fermilab), Sadayoshi Kojima (TITECH), David Morrison (University of California at Santa Barbara), Sadanori Okamura (Hosei University, former Vice President for Research of UTokyo), Nigel Smith (Director, Snolab). Their report is transmitted to the President and Vice President of the University.

5-5. Others

Describe efforts advanced to foster young researchers (e.g., start-up funding, autonomous research environment) and to enlist female researchers.

- *In Appendix 5, give the transition in the number of female researchers.*

All postdoctoral fellows receive annual research fund of 500,000 yen from the Kavli IPMU. Researchers at or above professor rank receive startup fund according to their needs. Effective startup of their research activity is expected to win the Grant-in-Aid sooner to develop the research drastically. The Kavli IPMU organizes an instructing guidance how to win the Grant-in-Aid especially for the international researchers.

To enlist female researchers, the Director, Deputy Directors, PIs and faculty members are making effort to showcase the excellent research environment and promising future in the Kavli IPMU on many occasions. In FY2013, A. Leauthaud, previously a Kavli IPMU postdoc, was appointed as an assistant professor, the first female faculty member. In addition, we now have four female postdocs and one support scientist (A. More, M. Bersten, M. Ishigaki, C. Lackner, B. Vulcani and T. Iwashita, as well as a graduate student, H. Niikura. In the case of A. More, a JSPS postdoctoral fellow, her husband S. More was also hired as a faculty member at the Kavli IPMU. However, there is still only one woman PI (M. Nojiri). Continuous efforts to search for a new woman PI and to increase the number of female faculty members as well as the number of female researchers have been kept through every opportunity, e.g., international conferences, workshops, advertising our fascinating intellectual environment and the research activities.

6. Others

- *In addition to the above 1-5 evaluation items, only if there is anything else that deserves mention regarding the center project's progress, please note it.*

In 2012, IPMU was named after Mr. Fred Kavli by accepting a donation from the Kavli Foundation of the United States and establishing an endowment. The motivation to bear Kavli name was two-fold: endowment and prestige. Because of the steady and flexible endowment income that can be carried over fiscal years, it already allowed us to overstretch our finances to go aggressively after postdoc candidates and research objectives. The stable endowment income also allows us to acquire loan from UTokyo to help with cash flow in our research projects. The prestige factor is difficult to quantify, but it appears to have made a big splash within the community that the WPI institute was now recognized internationally with this donation. This is the first research center in Japan named after a donor of endowment, a symbol of system reform. Fortunately, in FY 2014, the TODIAS won four permanent posts to guarantee the outstanding research and education in the TODIAS. The Kavli Foundation regards this progress as a result of vigorous support by UTokyo, and they decided to increase a donation as an effective matching fund.

For UTokyo, of course, there has been no previous experience to accept endowment from a foreign foundation, so that it provided an opportunity for UTokyo to reexamine and reform the systems for managing donated funds.

One more activity resulting strengthened global visibility of the Kavli IPMU is following. In 2012, UTokyo has signed an agreement to deliver courses through online education provider Coursera, a rapidly growing Massive Open Online Course (MOOC) provider that offers courses online for anyone to take, for free. H. Murayama was chosen to be the first instructor of the MOOC courses to be provided by UTokyo. H. Murayama's course was popular and signed up by nearly 50,000 people from more than 140 countries worldwide.

As a measure of our international visibility, we studied citation counts. The citation record obtained from Thomson Reuters' Web of Science, of the science and technology papers that the Kavli IPMU has produced since its launch in 2007 to 2013, shows, for instance, 117 (114) papers with more than 50 citations, and the number of citations per paper of 24.35 (17.77), with (without) the famous *Review of Particle Properties*. These numbers are comparable to or better than those of world-leading institutes covering the similar research areas as our Institute, such as Institute for Advanced Study (Princeton), the Kavli Institute for Theoretical Physics (Santa Barbara), Yukawa Institute for Theoretical Physics (Kyoto), Perimeter Institute (Canada), and International Center for Theoretical Physics (Trieste), in the same period.

7. Center's Response to Results of FY2013 Follow-up (including Site Visit Results)

** Describe the Center's Response to Results of FY2013 Follow-up. Note: If you have already provided this information, please indicate where in the report.*

・The Kavli IPMU should look beyond the 10-15 year period, and seriously consider what it will do in science and organization to evolve from a world top level institute to a world leading institute in the physics and mathematics of the Universe. (Follow-up)

We believe we have started to produce signature results. To name a few: Y. Toda's results on algebraic geometry inspired by interaction with physicists, T. Yanagida's proposal on pure gravity mediation culminated based on many past works by our members, results by K. Hori and H. Ooguri on string theory inspired by interaction with mathematicians, major focus on dark matter science with gravitational lensing by M. Takada, A. Leauthaud, M. Oguri, world-leading experimental limits from KamLAND-Zen and XMASS, H. Murayama's results on condensed matter physics inspired by condensed matter physicists and helped by mathematicians. The R&D work on gadolinium-loading in Water Cherenkov detectors by M. Vagins also has a great promise. SuMIRe project is a world-leading astronomical survey well known in the community, highlighted in recent US Snowmass study for the future planning. These are truly "made in the Kavli IPMU" which leads science in these areas, and were made possible by the interdisciplinary simulation at the Institute. Now with major projects coming into the data-taking phase, we hope to produce even more world-leading results.

・Particularly at this crucial time in the history of the Kavli IPMU, it is important to focus resources on a few areas of unique scientific promise to guarantee the Kavli IPMU status. (Follow-up)
・It was pointed out that the Kavli IPMU should consider focus areas so that it can evolve from a world-class player to a world leader. There was no response to this from the Kavli IPMU in the presentations. (sitevisit)

We proposed to study fundamental and broad questions, such as how the Universe started, what it is made of, what its fate is, what are its fundamental laws, and why we exist in it. Because of the breadths of the questions, we had to cast a wide net initially to understand what research directions would be the most fruitful. During the initial phase of the Institute, these questions have crystallized into a few pillars, which we will focus on in the extension period:

(1) Development of fundamental theory and mathematics

(2) Test of fundamental theory with experiments/observations

Dark matter, dark energy, inflation

(3) Preparations for future opportunities

In the research fields we are involved in, projects take a long time to plan, build, and execute. Therefore, we need a staggered approach to have projects at different stages, data-taking, construction, and planning. In the initial phase, big projects such as SuMIRe had to be still built and planned. Therefore, we needed to quickly delve ourselves into projects in the data-taking phase so that we can learn lesson to formulate future directions.

During the initial phase of the Institute, it became clear what the science goals of relevant projects are. Based on what we have learned so far, we have a big convergence, a new challenge, and preparations for future opportunities.

SuMIRe, which combines imaging (HSC) and spectroscopy (PFS) on the Subaru telescope, has three major science goals: (1) cosmology (dark energy, test of gravity, neutrino mass), (2) galaxy evolution (stellar formation, chemical evolution, black holes), (3) galactic archaeology (distribution and nature of dark matter). We lined up projects that will converge on these topics. SDSS-III/BOSS and SDSS-IV/eBOSS lead to (1). iPTF leads to (2). SDSS-IV/MaNGA leads to (3) Therefore, all of these projects converge on SuMIRe during the extension period. It covers major aspect of dark matter and dark energy science. On the other hand, we will review progress of XMASS to see how much we continue to invest in its future.

We found a new exciting challenge. For testing the paradigm of inflation and connecting it to the fundamental theory of quantum gravity, LiteBIRD is a new project born out of our small involvement in POLARBEAR. Working closely with KEK and JAXA/ISAS, we developed the science case that is becoming a realistic opportunity in the extension period and beyond. Given the situation with BICEP2 data, it is crucial to perform a full-sky survey.

On the other hand, we need to have our eyes on new major opportunities on the horizon. Because we do not know whether they will materialize, we keep the effort somewhat small, capitalizing on synergies with nearby institutions with close contact. Hyper-Kamiokande will be a major opportunity in Japan, and we are strategically involved in the physics of the beam (T2K) and Gd-loading (EGADS), working closely with ICRR. ILC is another major opportunity in Japan, and we took on a major responsibility in Silicon Vertex Detector (SVD) in the Belle II experiment, working closely with KEK and Hongo.

Note that we chose our research objectives carefully not to dilute ourselves too thin. We did focus in the areas of algebraic, differential, arithmetic geometry and representation theory among vast subareas in mathematics. We did not venture into exoplanets despite our access to the Subaru telescope. We did not get involved in cosmic-ray experiments despite their relevance to dark matter. We decided to stay away from the LHC experiment because we would make little impact at this stage. Instead, we developed framework to collaborate to other institutions involved in these areas to maintain our intellectual interest.

・Focusing is especially important for SuMIRe beyond data pipeline software in the areas of software for cosmology data analysis and cosmological simulations. Full collaboration with other similar efforts already underway should be pursued. The Kavli IPMU could leverage advances in data mining and informatics by collaborating with computer scientists and statisticians outside the Kavli IPMU jointly with National Astronomical Observatory of Japan. (Follow-up)

・ In the 2011 report, urgent need for capabilities to handle terascale data analysis was pointed out. We did not see a clear strategy to handle such a large data. (sitevisit)

For the purpose of data pipeline software for HSC and PFS, we are in close collaboration with Princeton effort led by Robert Lupton, who is also developing software for LSST. Our own new hire N. Suzuki is developing pipeline for SDSS-IV/eBOSS which can be regarded as a precursor for the PFS cosmology program. In addition, we started a discussion with the Institute of Statistical Mathematics (Tachikawa, Tokyo) to propose a major new initiative to develop the area of common interest.

・The number of on-site PI’s should be increased. Especially we hope to see more progress on making joint appointments for mathematics and theoretical physics PI’s at other Japanese institutions. (Follow-up)

・*It was pointed out that leadership role and power should be granted to associate professors if he/she so desires. There was no response to this from the Kavli IPMU in the presentations. (sitevisit)*
・*The necessity to reduce the number of kennin theorists and mathematicians has been pointed out from the beginning of the Kavli IPMU. With the establishment of joint appointment system, some effort to reduce this number has been made. But joint appointment between UT mathematician and the Kavli IPMU is not progressing. (sitevisit)*

It is indeed clear that the Kavli IPMU became an excellent career path for young researchers. Most recent appointments at Yukawa Institute and Department of Physics at UTokyo are from the Kavli IPMU. At the same time, we need to stabilize the core membership. Given the five* President's discretionary positions to us so far and four from MEXT, we are making progress (name them for the proposal).
(*revised in the final version)
We shied away from appointing our on-site members to PIs to avoid conflict between their unstable employment and responsibilities for the Institute. Now that some of our members are moving to permanent positions, we can appoint them to PIs.
The joint appointments are not easy to achieve, as the partner institution needs to agree with the arrangements. University of Tokyo made a joint appointment a part of the system only in 2013. But most other institutions in Japan have not developed a similar system, which is still a major roadblock. At the same time, UTokyo made joint appointments within the University possible in 2014 only for TODIAS, and we already could attract N. Yoshida back from Physics Department for a 40% effort. We will pursue similar appointments with Astronomy and Mathematics.

・*We applaud the hiring of the first female faculty member Alexie Leauthaud. The number of women remains extremely low. Three post docs, one faculty member, and one PI. During the twenty short poster talks there was not a single woman presenting. In fact Alexie Leauthaud was the only female presenter during the site visit. (sitevisit)*

The pool of female researchers in mathematics and theoretical physics is particularly small, not just in Japan, but also worldwide. We took the strategy to hire couples at the early stages of their career within the areas of our interest. This strategy is bearing fruit. We hired four couples, in one case competing with tenured offers from UK. Yet more effort is needed.

・*The lack of students, mentioned repeatedly in previous reports, continues to be worrisome. A center of this kind should ideally be filled with graduate students writing their Ph.D. thesis under the supervision of the many assistant, associate, and full professors. In this respect there is a striking difference to e.g. a German Max-Planck-Institute, which abounds with students. There the solution of the "granting-the-degree" problem is that students are formally assigned to "official advisors" (which may or may not be members of the institute, but are eligible to have students, i.e., are "real" professors at a university), and then are for practical purposes supervised by junior staff (officially not eligible to have students). We urge the Kavli IPMU and UT to work out such a scheme, to think about funding for graduate students, and to, last not least, provide office space for graduate students. There needs to be a "critical mass" for students, such that they can organize their own journal clubs and student seminars, where they are not afraid to ask questions. The daily teatime would be a perfect meeting place for the students, local faculty, and visiting experts. (sitevisit)*

We completely agree that working with graduate students is an indispensable aspect of successful research institution. Access to graduate students is at mercy of traditional departments, which can grant degrees and decide who can supervise graduate students. So far we have four faculty members admitted to Physics, and three to Mathematical Sciences.
One of the major difficulties has been the lack of tenure at our institution. The traditional departments did not view our fixed-term faculty members suitable to supervise the graduate students. We believe this view will change as many of our full and associate professors move to permanent positions thanks to the commitment by the President Hamada as well as additional resource to TODIAS from MEXT.
We will make a serious attempt to create a graduate school of our own. From the initial exploration, it appears feasible to create our own graduate school. There are many hurdles to overcome, but it does not appear impossible. In the extension period, as we will see more permanent structure to the Institute, we propose to make a major attempt to create *Kavli Graduate School for the Physics and Mathematics of the Universe*. We envision it to be a highly selective student body, completely international, following the systems in the US universities.

World Premier International Research Center Initiative (WPI)

1. FY 2013 List of Principal Investigators

NOTE:
・Underline names of investigators who belong to an overseas research institution.
・In case of researchers not listed in the latest report, attach "Biographical Sketch of a New Principal Investigator".

<Results at the end of FY2013>

Principal Investigators Total:18

Name (Age)	Affiliation (Position title, department, organization)	Academic degree, specialty	Working hours (Total working hours: 100%)				Starting date of project participation	Status of project participation (Describe in concrete terms)	Contributions by PIs from overseas research institutions
			Work on center project		Others				
			Research activities	Other activities	Research activities	Other activities			
Center director Hitoshi Murayama (50) (*)	Kavli IPMU (Director), University of California, Berkeley (Professor, Physics Dept)	Ph.D. particle theory, cosmology	45%	40%	0%	15%	10/1/2007	Stays 70% at Kavli IPMU, and 30% at UC Berkeley of which a half of the time at Kavli IPMU Berkeley satellite. Joins videoconference 4 times a week.	Sending 2 young scientists (2 weeks each) and 2 senior scientists (1 week each). Accepting 5 young scientists (2 weeks each).
Yoichiro Suzuki (64) (*)	Kavli IPMU (Deputy Director), UTokyo (Professor, ICRR)	Ph.D. astroparticle physics	70%	5%	5%	20%	10/1/2007	Usually stays at Kamioka Branch. Joins videoconference once a week	
Hiroaki Aihara (58)(*)	Kavli IPMU (Deputy Director), UTokyo (Professor, Physics Dept)	Ph.D. high energy physics	45%	5%	0%	50%	10/1/2007	Stays at Kavli IPMU once a month. Joins videoconference once a week.	
Alexey Bondal (52) (*)	Steklov Mathematical Institute (Professor), Kavli IPMU (Professor)	Ph.D. mathematics	40%	0%	40%	20%	10/1/2007	Stays at Kavli IPMU 6 months a year. Joins videoconference once a week for the rest of 6 months.	Sending 1 senior scientist (2 weeks).

Kunio Inoue (48) (*)	Tohoku University (Director, Professor, RCNS)	Ph.D. astroparticle physics	45%	0%	5%	50%	10/1/2007	Stays at Kamioka Branch once a week.	
Takaaki Kajita (55) (*)	UTokyo (Director, Professor, ICRR)	Ph.D. astroparticle physics	40%	0%	0%	60%	10/1/2007	Stays at Kamioka Branch once a month. Usually stays at ICRR which is right next to Kavli IPMU.	
Stavros Katsanevas (60) (*)	University of Paris 7 (Professor, Physics Dept)	Ph.D. astroparticle physics	20%	0%	10%	70%	10/1/2007	Stays at Kavli IPMU once a year. Joins videoconference once a month.	Sending 1 young scientist to Kavli IPMU (3 weeks).
Toshiyuki Kobayashi (51) (*)	UTokyo (Professor, Graduate School of Mathematical Sciences)	Ph.D. mathematics	70%	0%	8%	22%	6/1/2011	Stays at Kavli IPMU once a month. Joins videoconference once a month.	
Toshitake Kohno (58) (*)	UTokyo (Professor, Graduate School of Mathematical Sciences)	Ph.D. mathematics	70%	0%	8%	22%	10/1/2007	Stays at Kavli IPMU once a week. Joins videoconference once a week.	
Masayuki Nakahata (54) (*)	UTokyo (Professor, ICRR)	Ph.D. astroparticle physics	85%	0%	9%	6%	10/1/2007	Usually stays at Kamioka Branch.	

Mihoko Nojiri (51) (*)	KEK (Professor)	Ph.D. particle theory	40%	0%	40%	20%	10/1/2007	Stays at Kavli IPMU twice a week.	
Ken'ichi Nomoto (67) (*)	Kavli IPMU (Professor)	Ph.D. cosmology	70%	0%	12%	18%	10/1/2007	Stays at Kavli IPMU full time.	
Hirosi Ooguri (52) (*)	California Institute of Technology (Professor, Physics Dept and Mathematics Dept), Kavli IPMU (Professor)	Ph.D. string theory	66%	0%	3%	31%	10/1/2007	Stays at Kavli IPMU 3 months a year. Joins videoconference once a week for the rest of 9 months.	Sending 1 young scientist (2 weeks). Accepting 2 young scientists (2 weeks each).
Kyoji Saito (69) (*)	Kavli IPMU (Professor)	Ph.D. mathematics	80%	20%	0%	0%	10/1/2007	Stays at Kavli IPMU full time.	
David Spergel (53) (*)	Princeton University (Professor, Dept of Astrophysical Sciences)	Ph.D. cosmology	55%	0%	5%	40%	10/1/2007	Stays at Kavli IPMU once a year. Joins videoconference once a week.	Sending 1 professor (1 month), 4 young scientists (2 weeks each).
Henry Sobel (70) (*)	University of California Irvine (Professor, Physics Dept)	Ph.D. astroparticle physics	50%	0%	13%	37%	10/1/2007	Stays at Kamioka Branch 4 times a year. Joins videoconference once a week.	Sending 7 young scientists t (3 weeks each).

Naoshi Sugiyama (52) (*)	Nagoya University (Professor, Physics Dept)	Ph.D. cosmology	47%	0%	3%	50%	10/1/2007	Stays at Kavli IPMU once a month. Joins videoconference once a week.	
Tsutomu Yanagida (65) (*)	Kavli IPMU (Professor)	Ph.D. particle theory	90%	0%	0%	10%	10/1/2007	Stays at Kavli IPMU full time.	

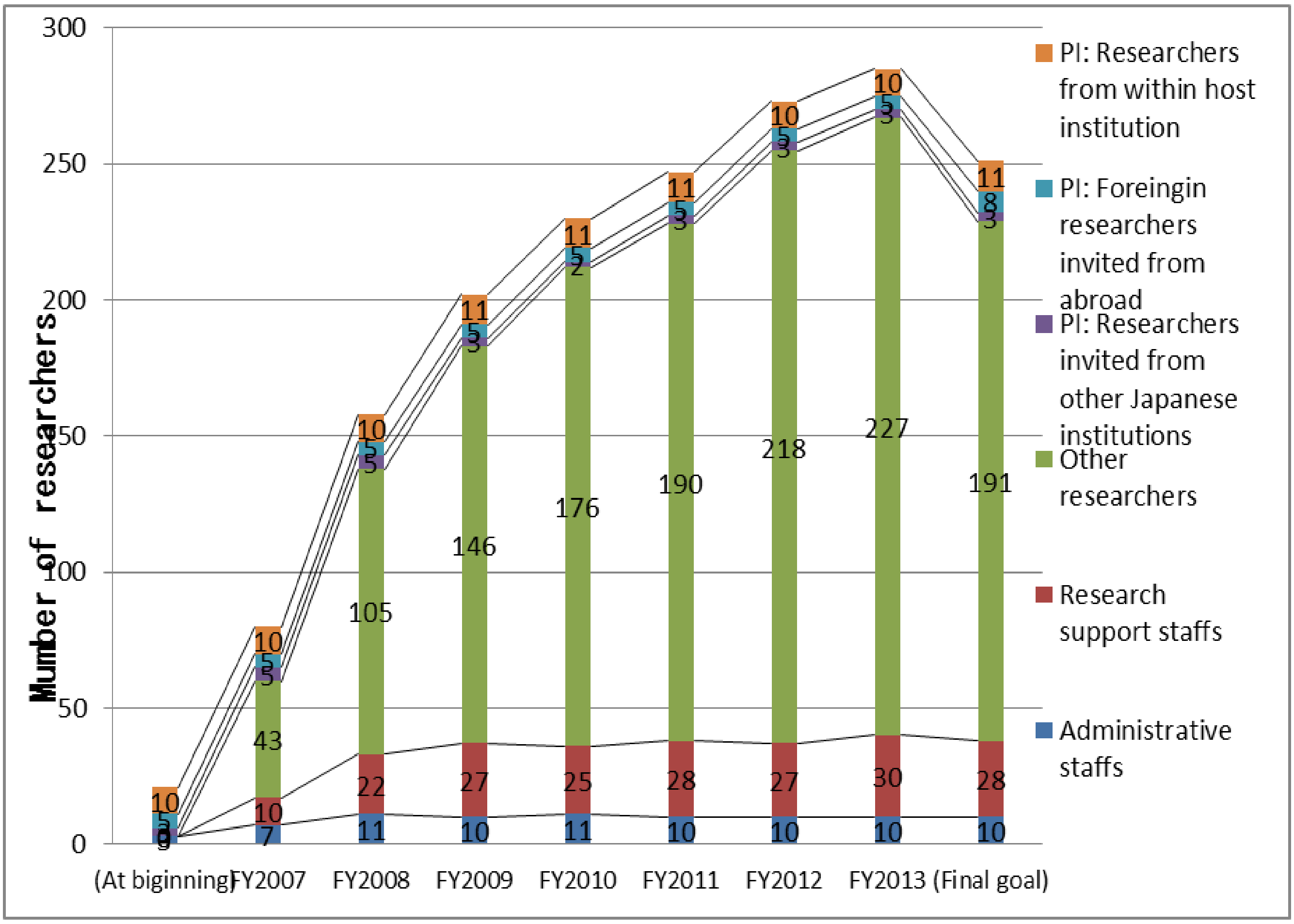
Researchers unable to participate in project in FY 2013

Name	Affiliation (Position title, department, organization)	Starting date of project participation	Reasons	Measures taken

World Premier International Research Center Initiative (WPI)

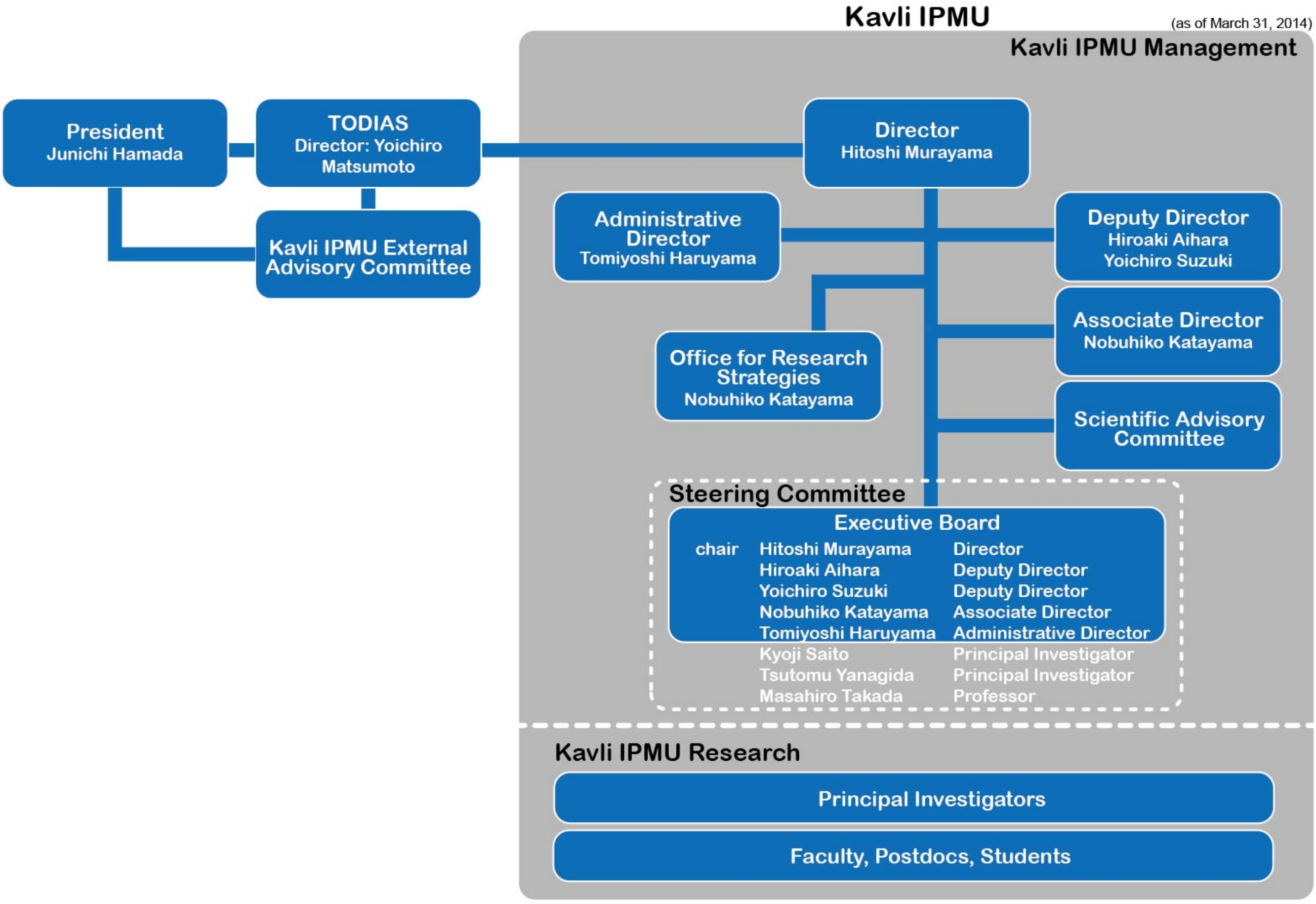
2. Annual transition in the number of Center personnel

**Make a graph of the annual transition in the number of center personnel since the start of project.*



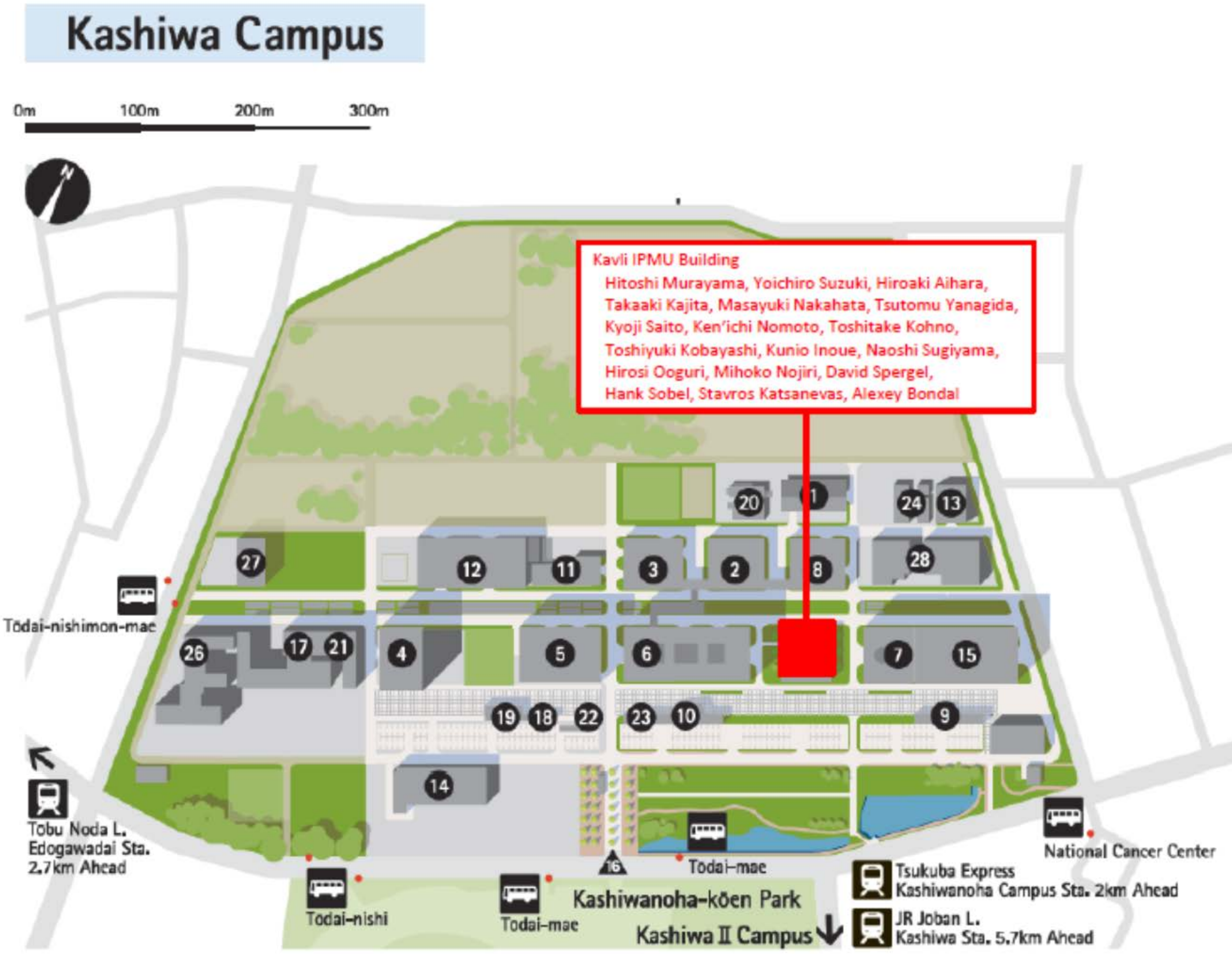
World Premier International Research Center Initiative (WPI)

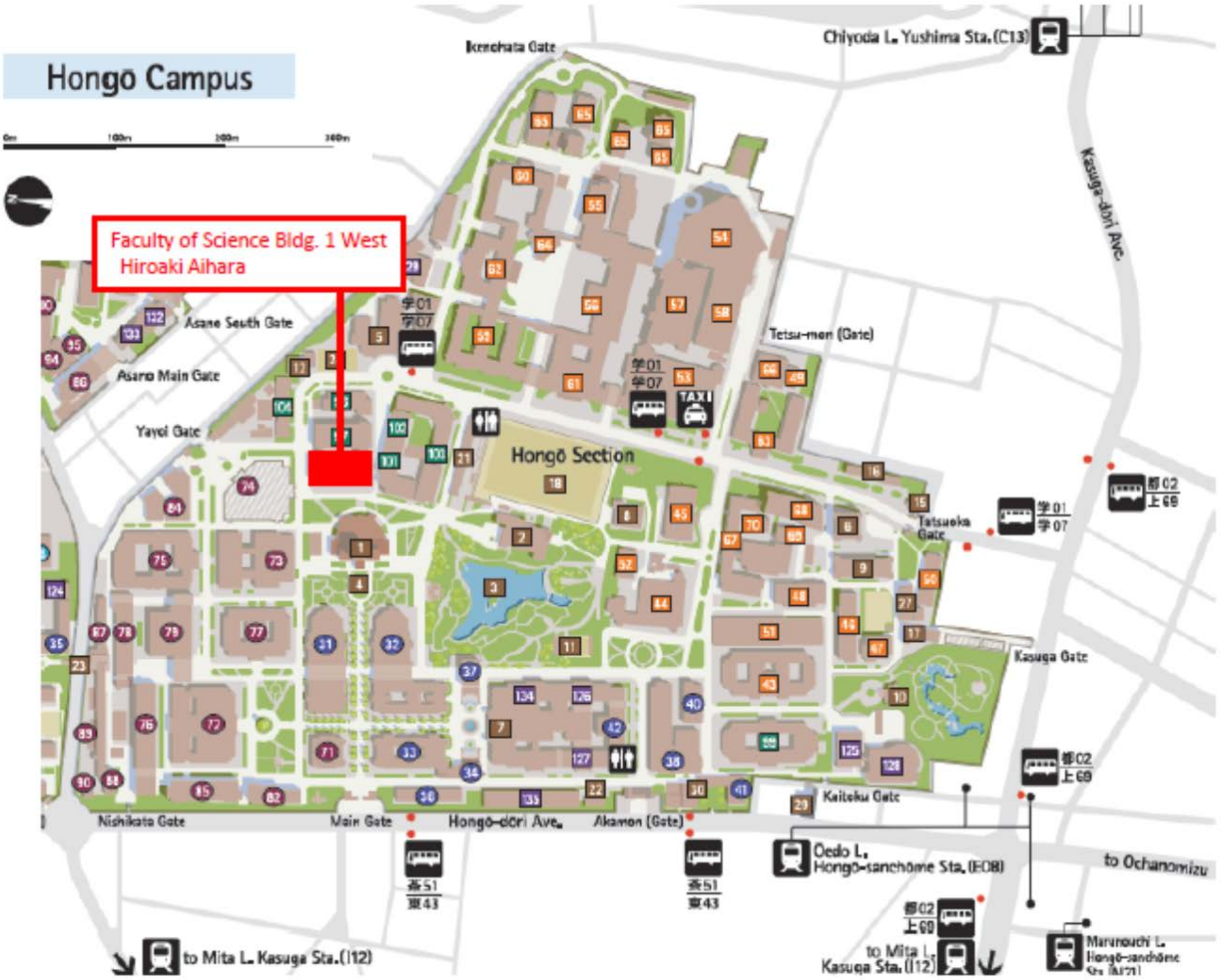
3. Diagram of management system

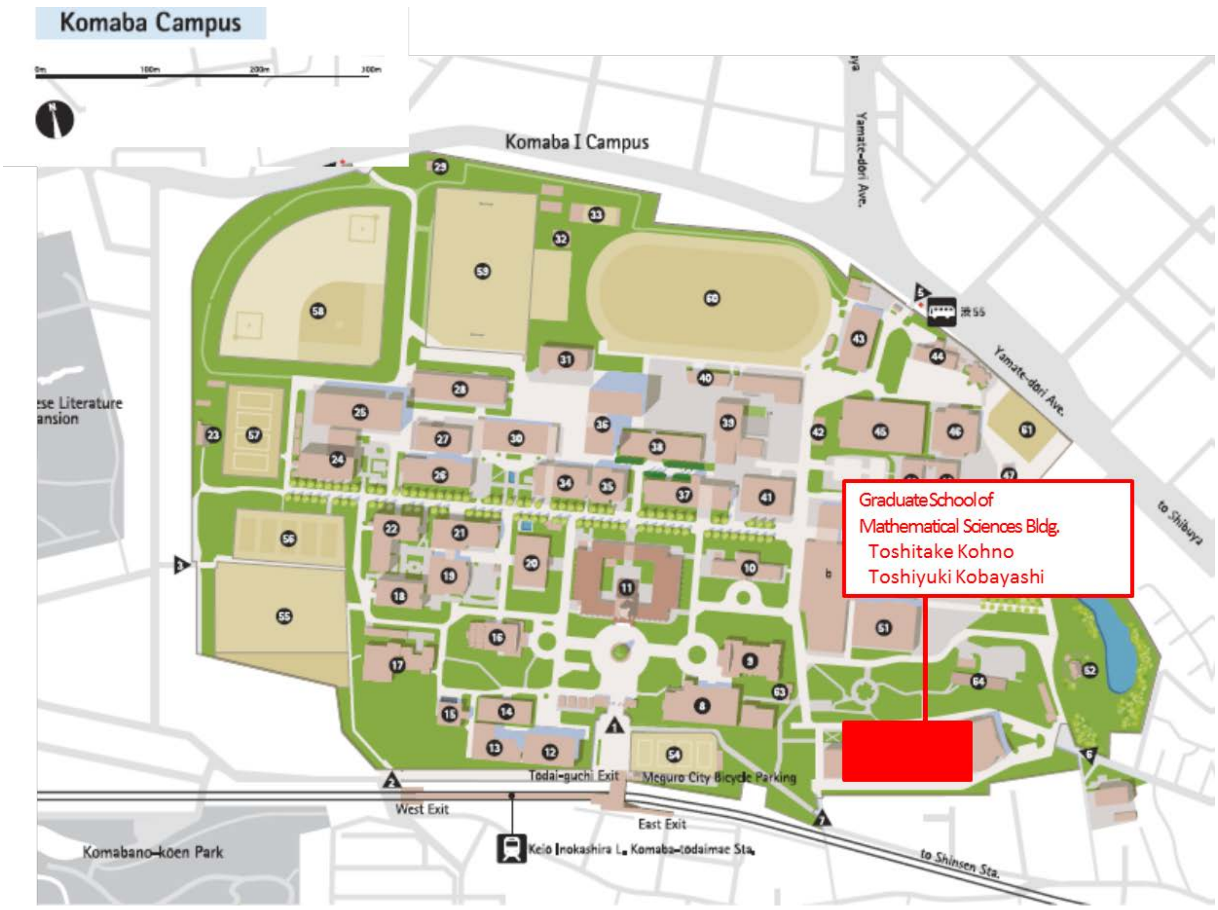


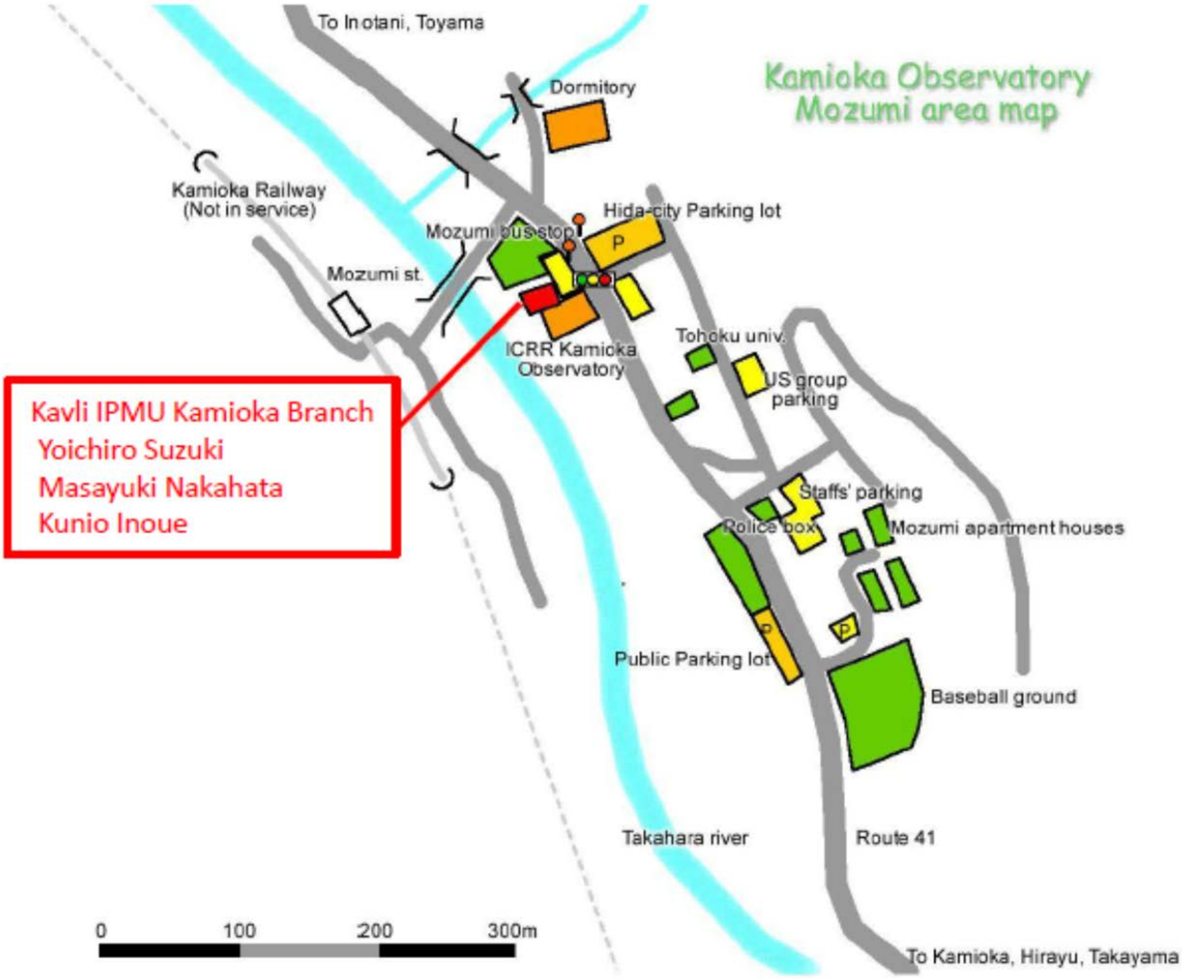
World Premier International Research Center Initiative (WPI)

4. Campus map


Kashiwa Campus
0m
100m
200m
300m
Kavli IPMU Building
Hitoshi Murayama, Yoichiro Suzuki, Hiroaki Aihara,
Takaaki Kajita, Masayuki Nakahata, Tsutomu Yanagida,
Kyoji Saito, Ken'ichi Nomoto, Toshitake Kohno,
Toshiyuki Kobayashi, Kunio Inoue, Naoshi Sugiyama,
Hirosi Ooguri, Mihoko Nojiri, David Spergel,
Hank Sobel, Stavros Katsanevas, Alexey Bondal
Tōdai-nishimon-mae
Tobu Noda L.
Edogawadai Sta.
2.7km Ahead
Tōdai-nishi
Tōdai-mae
Kashiwanoha-kōen Park
Kashiwa II Campus
Tsukuba Express
Kashiwanoha Campus Sta. 2km Ahead
JR Joban L.
Kashiwa Sta. 5.7km Ahead
National Cancer Center


Hongo Campus
Faculty of Science Bldg. 1 West
Hiroaki Aihara
Ikenohata Gate
Chiyoda L. Yushima Sta.(C13)
Kasuga-dori Ave.
Asano South Gate
Asano Main Gate
Yayoi Gate
Tetsu-mon (Gate)
Hongō Section
Tatsuoka Gate
Kasuga Gate
Kaitoku Gate
Nishikata Gate
Main Gate
Hongo-dori Ave.
Akamon (Gate)
Oedo L. Hongo-sanchome Sta.(E08)
to Ochanomizu
to Mita L. Kasuga Sta.(I12)
to Mita L. Kasuga Sta.(I12)
TAXI

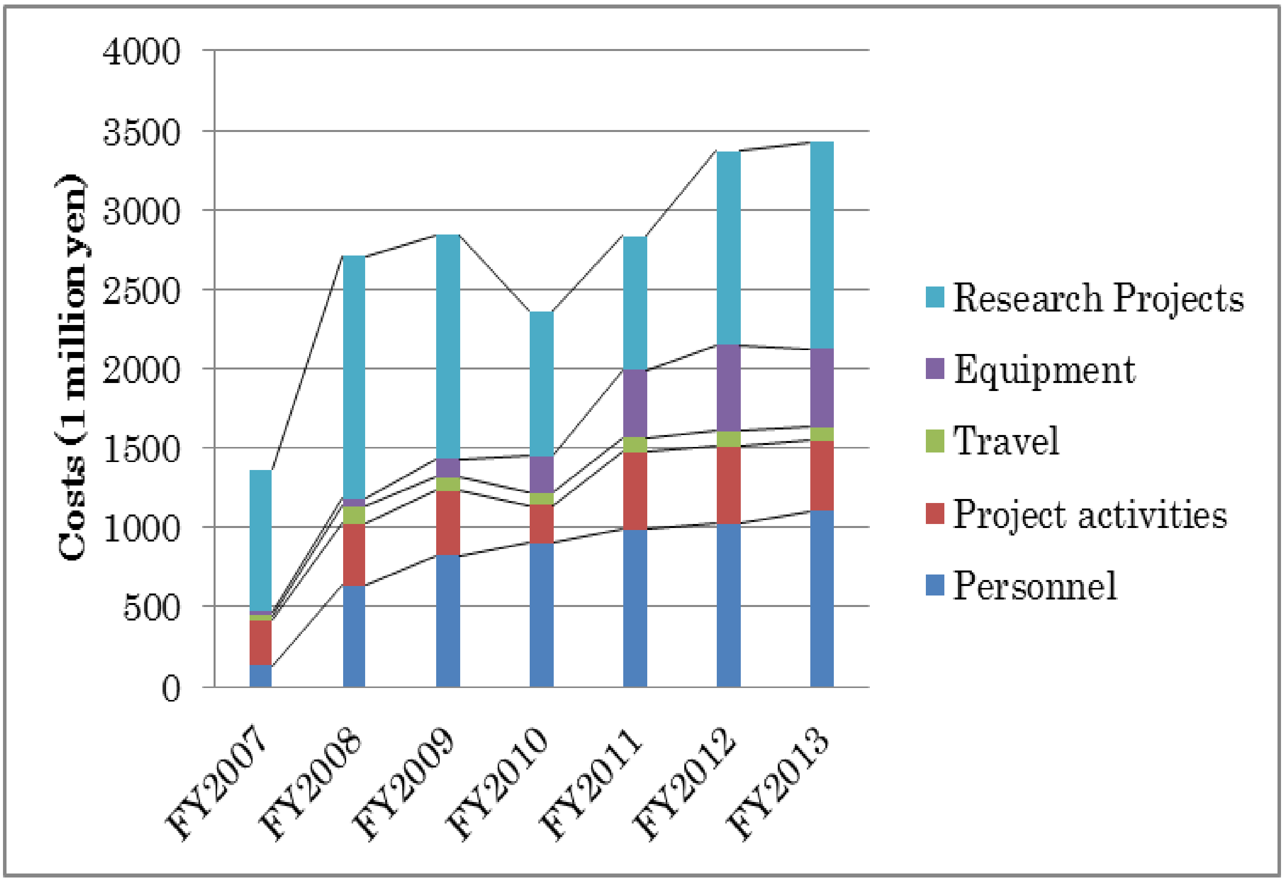

Komaba Campus
Komaba I Campus
Yamate-dori Ave.
Graduate School of Mathematical Sciences Bldg.
Toshitake Kohno
Toshiyuki Kobayashi
to Shibuya
Todai-guchi Exit
Meguro City Bicycle Parking
West Exit
East Exit
Keio Inokashira L. Komaba-todaimae Sta.
to Shinsen Sta.
Komabano-koen Park


Kamioka Observatory
Mozumi area map
To Inotani, Toyama
Dormitory
Kamioka Railway
(Not in service)
Mozumi st.
Mozumi bus stop
Hida-city Parking lot
P
ICRR Kamioka
Observatory
Kavli IPMU Kamioka Branch
Yoichiro Suzuki
Masayuki Nakahata
Kunio Inoue
Tohoku univ.
US group
parking
Staffs' parking
Police box
Mozumi apartment houses
Public Parking lot
Baseball ground
Takahara river
Route 41
0
100
200
300m
To Kamioka, Hirayu, Takayama

World Premier International Research Center Initiative (WPI)

5. Annual transition in the amounts of project funding

**Make a graph of the transition in the number of overall project funding.*



	FY2007	FY2008	FY2009	FY2010	FY2011	FY2012	FY2013
Research Projects	896	1524	1410	911	846	1225	1301
Equipment	25	48	117	231	425	538	488
Travel	25	112	88	80	92	96	90
Project activities	288	388	404	234	486	486	444
Personnel	132	635	825	906	987	1027	1101

6. FY2013 Project Expenditures (the exchange rate used: 1USD= 103.2365JPY)

i) Overall project funding

Cost Items	Details	Costs (10,000 dollars)
Personnel	Center director and Administrative director	30
	Principal investigators (no. of persons): 10	95
	Other researchers (no. of persons): 126	774
	Research support staffs (no. of persons): 30	97
	Administrative staffs (no. of persons): 9	71
	Total	1067
Project activities	Gratuities and honoraria paid to invited principal investigators (no. of persons): 19	25
	Cost of dispatching scientists (no. of persons): 1	2
	Research startup cost (no. of persons): 57	34
	Cost of satellite organizations (no. of satellite organizations): 1	9
	Cost of international symposiums (no. of symposiums): 16	2
	Rental fees for facilities	216
	Cost of consumables	59
	Cost of utilities	29
	Other costs	55
	Total	431
Travel	Domestic travel costs	9
	Overseas travel costs	34
	Travel and accommodations cost for invited scientists (no. of domestic scientists):38 (no. of overseas scientists):174	34
	Travel cost for scientists on secondment (no. of domestic scientists):1 (no. of overseas scientists):21	9
	Total	86
Equipment	Depreciation of buildings	43
	Depreciation of equipment	431
	Total	474
Other research projects	Projects supported by other government subsidies, etc.	468
	Commissioned research projects, etc.	0
	Grants-in-Aid for Scientific Research, etc.	792
	Total	1260
Total		3318

Ten thousand dollars

WPI grant		0
Costs of establishing and maintaining facilities		0
Establishing new facilities (Number of facilities: , m²)	Costs paid:	
Repairing facilities (Number of facilities: , m²)	Costs paid:	
Others		
Cost of equipment procured		12
Name of equipment: Germanium semicondoctor detector Number of units: 1	Costs paid:	8
Name of equipment: Liquid Nitrogen supplier Number of units: 1	Costs paid:	1
Others		3

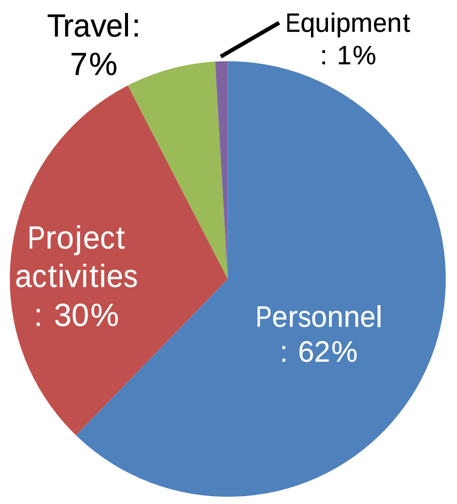
ii) Costs of Satellites and Partner institutions

Cost Items	Details	Costs (10,000 dollars)
Personnel	Principal investigators (no. of persons): 0	
	Other researchers (no. of persons): 2	
	Research support staffs (no. of persons): 0	
	Administrative staffs (no. of persons): 0	
	Total	8
Project activities		0
Travel		1
Equipment		1
Other research projects		0
Total		10

7. FY2013 WPI Grant Expenditures (the exchange rate used: 1USD= 103.2365JPY)

i) Overall expenditures

Cost Items	Details	Costs (10,000 dollars)
Personnel	Center director and Administrative director	30
	Principal investigators (no. of person): 4	51
	Other researchers (no. of person): 83	556
	Research support staffs (no. of person): 30	97
	Administrative staffs (no. of person): 9	71
	Total	805
Project activities	Gratuities and honoraria paid to invited principal investigators (no. of person): 19	25
	Cost of dispatching scientists (no. of person): 1	2
	Research startup cost (no. of person): 57	34
	Cost of satellite organizations (no. of satellite organization): 1	9
	Cost of international symposiums (no. of symposiums): 15	2
	Rental fees for facilities	216
	Cost of consumables	54
	Cost of utilities	3
	Other costs	45
	Total	390
Travel	Domestic travel costs	9
	Overseas travel costs	34
	Travel and accommodations cost for invited scientists (no. of domestic scientists): 38 (no. of overseas scientists): 168	34
	Travel cost for scientists on secondment (no. of domestic scientists): 1 (no. of overseas scientists): 21	9
	Total	86
Equipment	Cost of equipment procured	12
	Total	12
Total		1,293



ii) Costs of Satellites and Partner institutions

Cost Items	Details	Costs (10,000 dollars)
Personnel	Principal investigators (no. of person): 0	
	Other researchers (no. of person): 2	
	Research support staffs (no. of person): 0	
	Administrative staffs (no. of person): 0	
	Total	8
Project activities		1
Travel		1
Equipment		0
Total		10

World Premier International Research Center Initiative (WPI)

1. List of papers underscoring each research achievement

** List papers underscoring each research achievement listed in the item 2-1 "Research results to date" (up to 40 papers) and provide a description of the significance of each (within 10 lines).*
** For each, write the author name(s); year of publication; journal name, volume, page(s), and article title. Any listing order may be used as long as format is the same. If a paper has many authors, underline those affiliated with the Center.*
** If a paper has many authors (say, more than 10), all of their names do not need to be listed.*
** Place an asterisk (*) in front of those results that could only have been achieved by a WPI center.*

Research results 1: Modified Gravity

[1]. S. Mukohyama, "Scale-inariant cosmological perturbations from Hořava-Lifshitz gravity without inflation", *Journal of Cosmology and Astroparticle Physics*, **0906** (2009) 001
DOI: 10.1088/1475-7516/2009/06/001

Based on the renormalizable theory of gravitation proposed by Hořava, this paper proposed a simple scenario to generate almost scale-invariant, super-horizon curvature perturbations. The anisotropic scaling with dynamical critical exponent z=3 implies that the amplitude of quantum fluctuations of a free scalar field generated in the early epoch of the expanding universe is insensitive to the Hubble expansion rate and, thus, scale-invariant. Those fluctuations are later converted to curvature perturbations by the curvaton mechanism or/and the modulated decay of heavy particles/oscillating fields. This scenario does not require inflation. Also, this scenario does not rely on any additional properties and thus works in any versions of the theory. This paper attracted more than 190 citations in INSPIRE database.

*Research results 2: B-mode Polarization of Cosmic Microwave Background

The objective of the LiteBIRD satellite mission is to test cosmic inflation and quantum gravity theories with unprecedented precision. With the mission's full success, it can discover the direct evidence of the cosmic inflation in any models within a broad class called "large field" model and prove that the primordial gravitational wave originates in quantum fluctuations in the gravitational field. The Science Council of Japan selected the LiteBIRD project as one of the twenty-seven projects in the "Master Plan of Important Large Projects 2014". It has received the "A" rating from MEXT for both importance and urgency categories in the roadmap 2014 for promoting the large research projects. To realize this exciting mission, the Kavli IPMU, Japan Aerospace Exploration Agency (JAXA) and High Energy Accelerator Research Organization (KEK) have recently agreed that the Kavli IPMU leads the scientific team and coordinates the effort to build the mission instrument while the project manager resides at JAXA and coordinates the LiteBIRD satellite project.

*Research results 3: Pure Gravity Mediation and Theories of the Higgs Boson

*[2]. M. Ibe and T. T. Yanagida, "The Lightest Higgs Boson Mass in Pure Gravity Mediation Model", *Physics Letters*, **B709** (2012) 374-380
DOI: 10.1016/j.physletb.2012.02.034

The Pure Gravity Mediation (PGM) was proposed just after when the strong evidence of the Higgs boson was discovered at the LHC in December 2011. This is the first paper of the PGM, in which it was shown that the observed Higgs boson mass about 125 GeV is naturally explained in the model. Furthermore, it was also stressed that there is no phenomenological and cosmological problems in the PGM. Because of its simple and beautiful structure of the SUSY breaking and mediation mechanism and its consistency with all experimental results, this PGM model has been widely accepted as the most motivated and interesting scenario beyond the standard model in the particle physics community. In fact, there are a lot of follow up papers. For example, the paper by Princeton group (N. Arkani-Hamed *et al.*, arXiv:1212.6971) is one of them. The PGM provides now a strong motivation for the future 100 TeV hadron collider discussed seriously at CERN.

note: One of the authors, T. T. Yanagida is mistakenly affiliated with ICRR in this article, but his correct affiliation is the Kavli IPMU.

*[3]. M. Ibe, S. Matsumoto, and T. T. Yanagida, "Pure Gravity Mediation with $m_{3/2}$ = 10-100 TeV", *Physical Review D*, **85** (2012) 095011
DOI: 10.1103/PhysRevD.85.095011

This is the second paper of the Pure Gravity Mediation (PGM), in which it is shown that the neutral wino is the unique candidate for dark matter in the model. It was pointed out that the wino of $O(1)$ TeV mass will be tested in future cosmic gamma-ray experiments. This is a crucial observation, since the PGM model naturally predicts the wino mass in this range. (If the thermal leptogenesis is the correct origin of the observed baryon asymmetry in the universe, the wino mass is predicted smaller than 1 TeV.) Matsumoto is now studying more details of the gamma-ray detection and developing experimental methods together with astrophysics experimental group at the Kavli IPMU. This is one of important interdisciplinary works possible at the Kavli IPMU.

*Research results 4: Dark Matter Distribution

*[4]. N. Okabe, M. Takada, K. Umetsu, T. Futamase, G. P. Smith, "LoCuSS: Subaru Weak Lensing Study of 30 Galaxy Clusters", *Publications of the Astronomical Society of Japan*, **62** (2010) 811-870
DOI: 10.1093/pasj/62.3.811

The prime focus camera of the 8.2m Subaru Telescope is currently the best-available facility for weak gravitational lensing measurements thanks to its wide field-of-view and exquisite image quality. In this paper the authors used the Subaru imaging data for 30 X-ray luminous galaxy clusters at $0.15<z<0.3$ to carry out a detailed weak lensing study of the mass distribution in a cluster region. They revealed that the average mass distribution is in a remarkably good agreement with the prediction seen in N-body simulations for a Λ-dominated, cold dark matter model. In a series of their papers, they have compared the weak-lensing-based mass estimates with other cluster observables such as X-ray and Sunyaev-Zel'dovich effects in order to derive a well-calibrated proxy relation of cluster mass and observables. Their results give a proof that Subaru data is powerful to obtain robust estimates on the cluster mass and density profile, which is crucial for cluster-based cosmology.

*[5]. M. Oguri, M. Takada, N. Okabe, G. P. Smith, "Direct measurement of dark matter halo ellipticity from two-dimensional lensing shear maps of 25 massive clusters", *Monthly Notices of the Royal Astronomical Society*, **405** (2010) 2215-2230
DOI: 10.1111/j.1365-2966.2010.16622.x

In this paper, the authors present new measurements of dark matter distributions in 25 X-ray luminous clusters by making a full use of the two-dimensional (2D) weak-lensing signals obtained from high-quality Subaru imaging data. Their approach to directly compare the measured lensing shear pattern with elliptical model predictions allows them to extract new information on the mass distributions of individual clusters, such as the halo ellipticity and mass centroid. By combining the 2D fitting results for a subsample of 18 clusters, the elliptical shape of dark matter haloes is detected at significance level. The mean ellipticity is found to be $e=0.46\pm0.04$ (68% C.L.), which is in excellent agreement with a theoretical prediction based on the standard collisionless cold dark matter (CDM) model. Their results give independent, quantitative information on dark matter properties at cluster scales.

*Research results 5: Dark Matter Detection

*[6]. K. Abe *et al.* (XMASS collaboration including K. Hiraide, Y. Kishimoto, K. Kobayashi, S. Moriyama, M. Nakahata, H. Ogawa, H. Sekiya, Y. Suzuki, A. Takeda, M. Yamashita, J. Liu, K. Martens, Y. Takeuchi), "Light WIMP search in XMASS", *Physics Letters*, **B719** (2013) 78
DOI: 10.1016/j.physletb.2013.01.001

Since little energy is deposited by light WIMPs, the low-energy threshold of the XMASS detector is advantageous for detecting them. The 300-eV-electron-equivalent energy threshold of the XMASS-I detector is determined by four hits, which are required to trigger the detector. Without fiducialization the XMASS collaboration analyzed all events in 835kg of liquid xenon after a cut to reduce Cherenkov events that occur in the quartz windows of photomultiplier tubes. To examine light WIMPs in the parameter space allowed by other experiments, they compared the expected energy spectrum for light WIMPs with the observed energy spectrum, and excluded part of the parameter space including the region where DAMA/LIBRA group claimed that they have seen an annual time variation in their accumulated data for the last 13 years. This demonstrated the advantage of the large target mass and lower energy threshold.

*[7]. K. Abe *et al.* (XMASS collaboration including K. Hiraide, Y. Kishimoto, K. Kobayashi, S. Moriyama, M. Nakahata, H. Ogawa, H. Sekiya, Y. Suzuki, A. Takeda, M. Yamashita, J. Liu, K. Martens, Y. Takeuchi), "Search for solar axions in XMASS, a large liquid-xenon detector", *Physics Letters*, **B724** (2013) 46
DOI: 10.1016/j.physletb.2013.05.060

The strong CP problem is a longstanding problem in the quantum chromo-dynamics. The axion is a hypothetical particle predicted by the Peccei–Quinn solution to the problem. The search for axions as well as axion-like particles (ALPs) can be conducted by considering the Sun as a source of these hypothetical particles. Because ALPs should be generated in the core of the Sun, their typical energy of a few keV corresponds to the temperature of the core. These particles can couple to electrons, which cause the axio-electric effect, and deposit their total energy in the detector. To search for such particles, the XMASS collaboration used the data from the search for light WIMPs. By requiring the expected spectra not to exceed the observed energy spectrum, they derived an improved limit on the axion-electron-electron coupling constant g_{aee}.

*Research results 6: Theory of Dark Energy and Modified Gravity

*[8]. A. D. Felice and S. Mukohyama, "Towards consistent extension of quasidilaton massive gravity", *Physics Letters*, **B728** (2014) 622-625
DOI: 10.1016/j.physletb.2013.12.041

This paper presented the first example of a unitary theory of Lorentz-invariant massive gravity, with all degrees of freedom propagating on a strictly homogeneous and isotropic, self-accelerating de Sitter background. The theory is a simple extension of the quasidilaton theory, respecting the symmetry of the original theory but allowing for a new type of coupling between the massive graviton and the quasidilaton scalar. The extended quasidilaton theory provides an explicit example evading the previous no-go result for homogeneous and isotropic, stable solutions in massive gravity.

*Research results 7: New Observational Constraint on Dark Energy

*[9]. M. Oguri, N. Inada, M. A. Strauss, C. S. Kochanek, I. Kayo, M-S. Shin, T. Morokuma, G. T. Richards, C. E. Rusu, J. A. Frieman, M. Fukugita, D. P. Schneider, D. G. York, N. A. Bahcall, R. L. White, "The Sloan Digital Sky Survey Quasar Lens Search. VI. Constraints on Dark Energy and the Evolution of Massive Galaxies", *The Astronomical Journal*, **143** (2012) 120
DOI: 10.1088/0004-6256/143/5/120

This is the final cosmological result from the SQLS, a large survey of gravitationally lensed quasars in the Sloan Digital Sky Survey (SDSS). The team has discovered nearly 50 new quasar lenses from ~100,000 spectroscopic quasars in the SDSS. A clean subsample of 19 quasar lenses selected from 50,836 source quasars is used for the statistical analysis to constrain dark energy. For the flat universe case, the non-zero cosmological constant is detected at 6 sigma level. Significant amount of dark energy is required even if the team allows the redshift evolution of the galaxy velocity function, which robustly confirm the accelerated cosmic expansion independently of type Ia supernovae.

This paper was selected as '2013 AJ highlights Collection'.

*Research results 8: SuMIRe

*[10]. M. Takada, *et al.* (including H. Aihara, K. Bundy, S. More, H. Murayama, J. D. Silverman, D. N. Spergel, H. Sugai), "Extragalactic science, cosmology, and Galactic archaeology with the Subaru Prime Focus Spectrograph", *Publications of the Astronomical Society of Japan*, **66** (2014) 1
DOI: 10.1093/pasj/pst019

This paper summarizes the science cases of PFS in terms of provisional plans for Subaru 300 nights, highlighting three topics. (1) Cosmology: Constrain the nature of dark energy via a survey of emission line galaxies in the redshift range $0.8<z<2.4$. Measure precise cosmological distances via the baryonic acoustic oscillation scale, and the structure growth via redshift-space distortion. (2) Galactic archaeology: Clarify the past assembly histories of spiral galaxies Milky Way and Andromeda galaxy and the structure of their dark matter halos by measuring radial velocities and chemical abundances of 10^6 stars. (3) Galaxy/AGN evolution: Conduct a color-selected survey of $1<z<2$ galaxies and AGN over 16 deg^2 to $J\simeq23.4$, yielding a fair sample of galaxies with stellar masses above $10^{10}M_\odot$ at $z\simeq2$. It is extremely rare that science cases are published in astronomy before the instrument is actually built, and this represents a practice more common in particle physics, while it also this demonstrates the deep interests of researchers on the PFS project.

*Research results 9: Derived Category of Coherent Sheaves and Counting Invariants

[11]. Y. Toda, "Curve counting theories via stable objects I. DT/PT correspondence", *Journal of the American Mathematical Society*, **23** (2010), no. 4, 1119-1157
DOI: 10.1090/S0894-0347-10-00670-3

In this paper, Y. Toda proved (Euler characteristic version of) Pandharipande-Thomas (PT) conjecture relating rank one DT invariants counting curves on Calabi-Yau 3-folds and invariants counting stable pairs. The PT conjecture relates two kinds of curve counting invariants on Calabi-Yau 3-folds, and drew much attention when they proposed in 2007. The PT conjecture was proved by introducing the spaces of weak stability conditions on Calabi-Yau 3-folds, and applying Joyce's wall-crossing formula. This paper was a pioneering paper for the further developments on wall-crossing arguments in DT theory. The arguments in this paper have been developed and led to the proofs of several other properties on DT theory, e.g., MNOP rationality of the generating series of rank one DT invariants, flop formula of DT invariants, *etc*.

*[12]. Y. Toda, "Bogomolov-Gieseker type inequality and counting invariants", *Journal of Topology,* **6** (2013), no. 1, 217-250
DOI: 10.1112/jtopol/jts037

M. Yamazaki informed Y. Toda that the paper by Denef-Moore, 'Split states, Entropy Enigmas, Holes and Halos,' hep-th/0702146 in string theory may be related to his work on DT invariants. K. Hori helped him to understand the paper. He could finally translate it into a mathematical language and found that they claimed a very interesting mathematical conjecture which relates DT invariants counting two dimensional torsion sheaves inside Calabi-Yau 3-folds and rank one DT invariants counting curves on them. In this paper, Y. Toda proved that the conjectural Bogomolov-Gieseker type in 'Bridgeland stability conditions on 3-folds I: Bogomolov-Gieseker type inequalities, A. Bayer and E. Macri and Y. Toda, *J. Algebraic Geom.* **23** (2014), 117-163'' implies Denef-Moore's conjecture. This was surprising since the above inequality conjecture was derived from a pure mathematical argument, and its relationship with Denef-Moore's conjecture was not expected. Y. Toda was invited to give a talk at the 2014 International Congress of Mathematicians.

*[13]. A. Bayer, E. Macri and Y. Toda, "Bridgeland stability conditions on 3-folds I: Bogomolov-Gieseker type inequalities", *Journal of Algebraic Geometry*, **23** (2014) 117-163
DOI: 10.1090/S1056-3911-2013-00617-7

Although Bridgeland stability condition is an important notion in mirror symmetry, its existence for projective Calabi-Yau 3-folds is still an open problem. In this paper, the authors constructed candidates of Bridgeland stability conditions on any projective 3-fold via double tilting of the category of coherent sheaves. Their construction led to the conjectural inequality evaluating the third Chern characters of certain two term complexes of sheaves on 3-folds. Their inequality is interpreted to be the generalization of the classical Bogomolov-Gieseker inequality for algebraic surfaces, which have been desired for algebraic geometers for more than 30 years. Their inequality conjecture turned out to imply Fujita's conjecture for 3-folds, a classical and open problem in algebraic geometry.

Research results 10: Langlands Correspondence and p-adic Cohomology Theory

[14]. T. Abe, "Langlands correspondence for isocrystals and existence of crystalline companion for curves",

arxiv.org:1310.0528, Preprint

In this paper, the LC for p-adic theory is established and Deligne's conjecture on the existence of crystalline companion is proven in the curve case, which completes the research program T. Abe proposed a couple of years ago. The main difficulty is to construct a framework of p-adic cohomology theory. We already had "good" cohomology theory so called rigid cohomology by Berthelot. However, this theory is not sufficient since we need "variation theory". This is the same situation that in many applications, Hodge theory is not enough and Hodge modules are needed. For this, Berthelot introduced arithmetic $\mathcal{D}$-module theory. Thanks to works by Berthelot, Caro, Kedlaya, and others, this theory was almost satisfactory for quasi-projective varieties. In this paper, Abe removed this limitation and made it work over certain algebraic stacks, which was indispensable to apply Lafforgue's technique to our situation.

[15]. T. Abe and D. Caro, "Theory of weights in p-adic cohomology",
arxiv.org:1303.0662 Preprint

This paper is devoted to establish the "yoga of weights" for p-adic cohomology theory. The concept of weights was introduced by Grothendieck in the course of attacking to the Weil conjecture. There were mainly two theories that realize his yoga: étale cohomology and Hodge theory. That for étale cohomology was established by Deligne in "Weil II" paper, and for Hodge theory was fully developed by M. Saito modeled on Deligne's theory later generalized vastly by T. Mochizuki. In this paper, the authors have added yet another theory, p-adic cohomology, in the list, which had been expected under the philosophy of LC, and also needed to construct LC. As a by-product, they also established p-adic intersection cohomology, which used to be technically difficult even to define.

*Research results 11: Primitive Forms and Mirror Symmetry

*[16]. T. Milanov, "Analyticity of the total ancestor potential in singularity theory", *Advances in Mathematics*, **255**, no. 1 (2014) 217-241
DOI: 10.1016/j.aim.2014.01.009

The total ancestor potential in singularity theory is defined via Givental's higher genus reconstruction formalism applied to the flat (or Frobenius) structure of K. Saito. A priori, the definition makes sense only at semi-simple points. However, it was conjectured by Givental that in the settings of singularity theory his definition extends analytically to the entire deformation space. By definition, the total ancestor potential satisfies several copies of Virasoro constraints. In Milanov's earlier work he proved that the Virasoro constraints can be solved by a method proposed by Eynard and Orantin which is known as the topological Eynard-Orantin recursion. The main result in this paper is that the recursion can be extended to generic non-semisimple points. As a corollary, using also the Hartog's extension theorem, he obtained a proof of Givental's conjecture.

[17]. C. Li, S. Li, K. Saito, Y. Shen, "Mirror Symmetry for Exceptional Unimodular Singularities",
arXiv:1405.4530, Preprint

In this paper, the authors prove the LG-LG-mirror symmetry conjecture for the super-potential functions which may have the negatively weighted deformation parameters in the irrelevant directions. Based on an idea of a previous work of the authors (arXiv:1311.1659), K. Saito and his colleagues perturbatively determine the primitive form and the flat coordinates for one F of the exceptional unimodular singularities. Using Witten-Dijkgraaf-Verlinde-Verlinde-equation, they show that only the 4-point corelators determine the pre-potential function. By generalizing the mirror map of Krawits from the flat deformation parameter space of F to the space of states in Fan-Jarvis-Ruan-Witten (FJRW) theory for the Berglund-Huebsh dual polynomial F^T, they compare the Tayler coefficients of the pre-potential function up to the degree 4 in the flat coordinate system with the corresponding FJRW invariants, and confirm that the conjecture holds.

*[18]. B. Bakalov and T. Milanov, "W-constraints for the total descendant potential of a simple singularity", *Compositio Mathematica*, **149** (2013) 840-888
DOI: 10.1112/S0010437X12000668

Using the period integrals of a primitive form the authors construct a twisted representation of the lattice vertex algebra corresponding to the Milnor lattice in singularity theory. Furthermore they define a W-algebra as a vertex subalgebra determined by a set of screening operators corresponding to the vanishing cycles. In the case of simple singularities, their definition coincides with the definition of a W-algebra for simple Lie algebras of type ADE. Their main result is that the total ancestor potential is a highest weight vector for the W-algebra. For simple singularity the structure of the W-algebra is understood to some extent. In particular, it was proved recently by S. Q. Liu and Y. Zhang that their constraints determine uniquely the total descendant potential. In general, it is still unknown if their construction can be generalized, in a sense that it is very hard to determine the kernel of the screening operators.

*Research results 12: Discovery of New Connection between Finite Group and Calabi-Yau Geometry

*[19]. T. Eguchi, H. Ooguri and Y. Tachikawa, "Notes on the *K3* Surface and the Mathieu Group M_{24}", *Experimental Mathematics* **20** (2011) 91-96
DOI: 10.1080/10586458.2011.544585

In this paper, H. Ooguri with T. Eguchi and Y. Tachikawa pointed out that the elliptic genus of the *K3* surface has a natural decomposition in terms of dimensions of irreducible representations of the Mathieu group M_{24}. These dimensions appear as coefficients of the expansion of the elliptic genus in terms the characters of the N=4 superconformal algebra associated to the non-linear sigma-model whose target space is the *K3*. Their discovery has been mathematically proven by Terry Gannon in 2013. Their result suggests that M_{24} acts as symmetry on the elliptic cohomology.

*[20]. H. Ooguri and M. Yamazaki, "Emergent Calabi-Yau Geometry", *Physical Review Letters*, **102** (2009) 161601
DOI: 10.1103/PhysRevLett.102.161601

In this paper, H. Ooguri and M. Yamazaki showed how the smooth geometry of Calabi-Yau manifolds emerges from the thermodynamic limit of the statistical mechanical model of crystal melting. In particular, they showed that that the thermodynamic partition function of molten crystals is equal to the classical limit of the partition function of the topological string theory by relating the Ronkin function of the characteristic polynomial of the crystal melting model to the holomorphic 3-form on the corresponding Calabi-Yau manifold.

*Research results 13: Supersymmetric Gauge Theories

*[21]. O. Chacaltana, J. Distler and Y. Tachikawa, "Nilpotent orbits and codimension-two defects of 6d N=(2,0) theory", *International Journal of Modern Physics*, **A28** (2013) 1340006
DOI: 10.1142/S0217751X1340006X

The Alday-Gaiotto-Tachikawa's conjecture was originally for the group *SU(N)*. To extend it to a more general group, there appear many subtle points that did not show up for *SU(N)*. In the *SU(N)* version, physical objects labeled by a Young diagram with N boxes played an extremely important role. In the more general case, Young diagrams are replaced by so-called nilpotent orbits, which are known to be very important mathematically. Nilpotent orbits, however, have not appeared very prominently in the theoretical physics literature. In this paper, Y. Tachikawa, together with collaborators O. Chacaltana and J. Distler, spelled out how various basic features of nilpotent orbits manifest themselves in this newly-found physical setup. Almost all of the concepts that can be found in a mathematical textbook on the nilpotent orbits naturally appears. In addition, it was found that a few cutting-edge results on the nilpotent orbits, found in the last decade in the mathematical literature, are also required to understand the system.

*[22]. O. Aharony, N. Seiberg, and Y. Tachikawa, "Reading between the lines of four-dimensional gauge theories", *Journal of High Energy Physics*, **1308** (2013) 115
DOI: 10.1007/JHEP08(2013)115

It has been long known that every gauge theory on a flat spacetime has two continuous parameters, the gauge coupling constant and the theta angle. But the subtle behavior of gauge theories on nontrivial spacetime topology always confused researchers. In this paper, it was pointed out that on general spacetime manifolds, there are additional discrete parameters necessary to specify a gauge theory completely. These parameters control what kind of line operators are available in this gauge theory, and are best described by the cohomology of classifying spaces, a concept known in mathematics for a long time but having not much applications in physics until this paper came out. Discussions with mathematicians at the Kavli IPMU, and having an access to the library at the Kavli IPMU that comprehensively covers books in all areas of mathematics, both old and new, were essential to the completion of the paper.

*Research results 14: Methods in Quantum Field Theory and String Theory --- Duality

*[23]. K. Hori, "Duality In Two-Dimensional (2,2) Supersymmetric Non-Abelian Gauge Theories", *Journal of High Energy Physics*, **1310** (2013) 121
DOI: 10.1007/JHEP10(2013)121

The paper studies the low energy behaviour of $\mathcal{N}$=(2,2) supersymmetric gauge theories in 1+1 dimensions. Theories with small numbers of matter representations are shown to exhibit supersymmetry breaking. For large numbers of matters, duality between theories with different gauge groups and matter contents is discovered. It is a two-dimensional analog of Seiberg duality in four dimensional $\mathcal{N}$=1 gauge theories. The result is applied to gauged linear sigma models, which flow to families of superconformal field theories that can be used for superstring compactifications, with corners corresponding to three-dimensional Calabi-Yau manifolds. This work is motivated by recent mathematical discoveries concerning equivalences of derived categories. The result provides a unifying scheme to understand the discoveries and offers a systematic way to generalize them. For the author, communication with A. Bondal was essential. A mathematical question (without answer!) helped him discover the duality that yields a natural construction of the double cover.

*[24]. K. Hori and M. Romo, "Exact Results In Two-Dimensional (2,2) Supersymmetric Gauge Theories With Boundary",
arXiv:1308.2438, Preprint

The partition function on the hemisphere of a class of two-dimensional (2,2) supersymmetric field theories including gauged linear sigma models is computed via supersymetric localization. The result provides a general exact formula for the central charge of the D-brane placed at the boundary. It takes the form of Mellin-Barnes integral and the question of its convergence leads to the grade restriction rule concerning branes near the phase boundaries. Expressions in various phases is found, including the large volume formula in which a characteristic class called the Gamma class shows up. The two sphere partition function factorizes into two hemispheres glued by the inverse to the annulus. The result can also be written in a form familiar in mirror symmetry, and suggests a way to find explicit mirror correspondence between branes.

*Research results 15: *F*-Theory: Its Phenomenology Applications and Duality

*[25]. H. Hayashi, R. Tatar, Y. Toda, T. Watari and M. Yamazaki, "New Aspects of Heterotic-*F* theory duality", *Nuclear Physics*, **B806** (2009) 224-299
DOI: 10.1016/j.nuclphysb.2008.07.031

String theory has several different formulations, and *F*-theory is known to be the most promising one in order to study the origin of flavor structure of the standard model particles. There had been a few problems left unsolved in the formulation of *F*-theory, however, because of high-level mathematics involved, and further progress using *F*-theory had been blocked for more than a decade. The team of physicists and a mathematician at the IPMU and other institutes solved these problems, and this article has become one of a few foundational papers that enabled explosive progress in 2008-2010. Aside from solving theoretical problems in the formulation of *F*-theory, this article also discovered that matter fields are described by smooth wavefunctions (without singularity) in internal space, which also has immediate consequence in the enhancement factor of proton decay.

*[26]. R. Tatar, Y. Tsuchiya and T.Watari, "Right-handed Neutrinos in *F*-theory Compactifications", *Nuclear Physics*, **B823** (2009) 1-46
DOI: 10.1016/j.nuclphysb.2009.07.020

This article uses the theoretical formulation of *F*-theory developed in [25] and other articles, to show that complex structure moduli fields of *F*-theory compactifications have trilinear coupling with Higgs and charged leptons. A number of important consequences follow from this result; i) complex structure moduli fields can be identified with right-handed neutrinos, ii) there are likely to be many right-handed neutrinos, iii) the typical mass scale of right-handed neutrinos are that of complex structure moduli, which is some orders of magnitude below the unification scale. The consequence (iii) provides an explanation for the energy scale 10^{15}GeV of the dimension-five operator inferred from the atmospheric neutrino oscillation experiments.

*Research results 16: Application to Condensed Matter Physics

*[27]. N. Ogawa, T. Takayanagi and T. Ugajin, "Holographic Fermi Surfaces and Entanglement Entropy", *Journal of High Energy Physics*, **1201** (2012) 125
DOI: 10.1007/JHEP01(2012)125

One unsolved problem in condensed matter systems is the analysis of Fermi surfaces in strongly interacting systems, *e.g.*, the strange metal phase of high T_c superconductors. In this paper, the authors gave a systematic study of Fermi surfaces by using the entanglement entropy in AdS/CFT correspondence for the first time. The analysis of entanglement entropy remarkably fixes the form of metric in the gravity description in a very strongly way. This powerful analysis leads to the conclusion that any strongly coupled and large N quantum systems should have an anomalous specific heat which clearly differs from the Landau Fermi liquids but agrees with the strange metal phase. They also found a condition for the presence of Fermi surfaces in terms of the metric of gravity dual.

*[28]. H. Watanabe and H. Murayama, "Unified Description of Nambu-Goldstone Bosons without Lorentz Invariance", *Physical Review Letters*, **108** (2012) 251602
DOI: 10.1103/PhysRevLett.108.251602

Nambu-Goldstone bosons arise from the concept of spontaneous symmetry breaking that applies to all areas of physics and even chemistry and biology. Yet no consistent and universal theory existed for more than half a century. Together with a condensed matter physicist H. Watanabe, H. Murayama discovered such a unified description that provides correct counting of degrees of freedom, dispersion relations, as well as their interactions. It relies on a relatively obscure area of mathematics called presymplectic geometry, which allows for a complete classification of possibilities. This paper opened up a research area that led to many other works including three more *Physical Review Letters* by the same authors including the one below. This paper has been selected as an "Editor's suggestion" and highlighted in synopsis of "*Physics*" of APS.

*[29]. H. Watanabe and H. Murayama, "Noncommuting Momenta of Topological Solitons", *Physical Review Letters*, **112** (2014) 191804
DOI: 10.1103/PhysRevLett.112.191804

Given H. Watanabe and H. Murayama's improved understanding of the theory of Nambu-Goldstone bosons in non-Lorentz-invariant systems, here they applied it to the properties of topological solitons. They proved that their momenta do not commute due to topological numbers, akin to Witten-Olive central extension of supersymmetry algebras by magnetic charges. It has an immediate experimental consequence that the soliton always moves sideways with respect to the exerted force. It generalizes to arbitrary Kähler manifolds as the target space. The first referee complained it was too mathematical for *Physical Review Letters*, while the other referee supported it saying "The authors use some sophisticated mathematics, but it is mathematics that in recent years has become a standard part of the condensed matter physics toolkit."

*Research results 17: Neutrino Properties

*[30]. A. Gando *et al.* (KamLAND-Zen Collaboration including K. Inoue, M. Koga, K. Nakamura, A. Kozlov, S.J. Freedman, B.K. Fujikawa, Y. Efremenko, S. Enomoto, M.P. Decowski), "Limit on Neutrinoless ββ Decay of ^{136}Xe from the First Phase of KamLAND-Zen and Comparison with the Positive Claim in ^{76}Ge", *Physical Review Letters*, **110** (2013) 062502
DOI: 10.1103/PhysRevLett.110.062502

Neutrinos are the only known particles that may not be distinguished from their anti-particles. This nature is thought to be a key to unravel big mysteries in particle physics and cosmology, particularly 'Matter dominance in the universe' and 'Light but finite mass of neutrinos'. So far, the only viable experimental approach to the nature is a search for 'neutrino-less double beta decay ($0\nu\beta\beta$). KamLAND-Zen utilizes the established and existing large ultra-low radioactivity environment of KamLAND. It holds the world largest amount of ββ nuclei (320 kg of 90% enriched ^{136}Xe) as xenon-loaded liquid scintillator in a mini-balloon suspended. The obtained lower limit for the half-life, 1.9×10^{25} yr at 90% C.L. (the world best) or 3.4×10^{25} yr if combined with the EXO-200 result, can be converted to the effective Majorana neutrino mass of 120-250 meV as an upper limit. It resulted in the 97.5% C.L. exclusion of the previous claim for 0νββ signal with a ^{76}Ge detector.

[31]. A. Gando *et al.* (KamLAND Collaboration including K. Inoue, M. Koga, K. Nakamura, A. Kozlov, A. Piepke, B.K. Fujikawa, B.E. Berger, Y. Efremenko, W. Tornow, S. Enomoto, M.P. Decowski), "Reactor on-off antineutrino measurement with KamLAND", *Physical Review D*, **88** (2013) 033001
DOI: 10.1103/PhysRevD.88.033001

KamLAND is surrounded by nuclear power reactors and their effective distance of about 180km provided a unique opportunity to measure neutrino oscillations involving first and second neutrino mass eigenstates. KamLAND detect these electron-type anti-neutrinos from the nuclear reactors via the inverse beta decay reaction of hydrogen atoms. KamLAND observed two cycles of neutrino disappearance and reappearance very clearly as a smoking-gun evidence of the neutrino oscillation and measurement of the cycle brought very precise determination (2.4%) of neutrino mass-squared difference. It is the most precise measurement of neutrino mass information ever. A recent shutdown of Japanese reactors also made the KamLAND Collaboration possible to investigate the whole picture of their background model. Observed anti-neutrino event rate perfectly correlated with the consequential variation of anti-neutrino creation at nuclear reactors and thus the firm base of the precise measurement is confirmed.

*[32]. S. Saito, M. Takada, A. Taruya, "Neutrino mass constraint from the Sloan Digital Sky Survey power spectrum of luminous red galaxies and perturbation theory", *Physical Review D*, **83** (2011) 043529
DOI: 10.1103/PhysRevD.83.043529

In this paper, the authors compare the model power spectrum, computed based on the perturbation theory of structure formation, with the power spectrum of luminous red galaxies measured from the SDSS DR7 data. The model included the effects of massive neutrinos, nonlinear matter clustering and nonlinear, scale-dependent galaxy bias in a self-consistent manner. They first test the perturbation theory model by comparing the model predictions with the simulation results for a cold dark matter model without massive neutrinos. In combination with the WMAP constraints, they derive an upper bound on the sum of neutrino masses, given as $m_{\nu,\mathrm{tot}}<0.81$ eV (95% C.L.), marginalized over other parameters including nonlinear bias parameters as well as dark energy equation of state parameter. The neutrino mass limit is improved by a factor of 1.85 compared to the limit from the WMAP alone, $m_{\nu,\mathrm{tot}}<1.5$ eV.

*Research results 18: Evolution of Galaxies

*[33]. A. Leauthaud, J. Tinker, K. Bundy, *et al.*, "New Constraints on the Evolution of the Stellar-to-dark Matter Connection: A Combined Analysis of Galaxy-Galaxy Lensing, Clustering, and Stellar Mass Functions from z = 0.2 to z =1", *The Astrophysical Journal*, **744** (2012) 159
DOI: 10.1088/0004-637X/744/2/159

Using data from the COSMOS survey, the authors perform the first joint analysis of galaxy-galaxy weak lensing, galaxy spatial clustering, and galaxy number densities, with aid of *N*-body simulations for a ΛCDM model. The joint analysis provides constraints on the relationship between galaxies and their host dark matter halos. Then, by combining the constraints with the stellar mass estimates for a sample of galaxies, they derive strong constraints on the shape and redshift evolution of the stellar-to-halo mass relation (SHMR) from z=0.2 to 1. They show that the dark-to-stellar ratio, M_h/M_*, varies from low to high masses, reaching a minimum of $M_h/M_*\sim27$ at $M_*=4.5\times10^{10}$ M_{sun} and $M_h=1.2\times10^{12}$ M_{sun}. This minimum is important for models of galaxy formation because it marks the mass at which the accumulated stellar growth of the central galaxy has been the most efficient. This paper was tied for the 9th most highly cited paper in the field of astrophysics in 2012.

*[34]. J. D. Silverman, *et al.* (including M. Tanaka), "The Impact of Galaxy Interactions on Active Galactic Nucleus Activity in zCOSMOS", *The Astrophysical Journal*, **743** (2011) 2
DOI: 10.1088/0004-637X/743/1/2

Close encounters between galaxies are expected to be a viable mechanism, as predicted by numerical simulations, by which accretion onto supermassive black holes can be initiated. To test this scenario, J. D. Silverman and his collaborators construct a sample of 562 galaxies (M_{*}>2.5×10^{10} M_{sun}) in kinematic pairs over the redshift range 0.25<z<1.05 that are more likely to be interacting than a well-matched control sample of 2726 galaxies not identified as being in a pair, both from the zCOSMOS 20k spectroscopic catalog. Galaxies that harbor an active galactic nucleus (AGN) are identified on the basis of their X-ray emission ($L_{0.5\text{-}10\ keV}$ > 2×10^{42} erg s^{-1}) detected by Chandra. They find a higher fraction of an AGN in galaxies in pairs relative to isolated galaxies of similar stellar mass.

*[35]. B. Ménard, R. Scranton, M. Fukugita, R. Gordon, "Measuring the galaxy-mass and galaxy-dust correlations through magnification and reddening", *Monthly Notices of the Royal Astronomical Society*, **405** (2010) 1025-1039
DOI: 10.1111/j.1365-2966.2010.16486.x

In this paper, the authors present a simultaneous detection of gravitational magnification and dust reddening effects due to galactic haloes and large-scale structure. The measurement is based on correlating the brightness of ~85000 quasars at z > 1 with the position of 24 million galaxies at z ~ 0.3 derived from the SDSS data and is used to constrain the galaxy-mass and galaxy-dust correlation functions up to cosmological scales. The presence of dust is detected from 20 kpc to several Mpc, and they find its projected density to follow: Σ_{dust} ~ $r_p^{-0.8}$, a distribution similar to mass. On large scales, its wavelength dependence is described by R_V = 4.9±3.2, consistent with interstellar dust. This, in turn, implies a cosmic dust density of Ω_{dust} ~5 × 10^{-6}, roughly half of which comes from dust in haloes of ~ $L\star$ Lgalaxies.

*Research results 19: Formation of First Stars and Black Holes

*[36]. T. Hosokawa, K. Omukai, N. Yoshida, H. W. Yorke, "Protostellar feedback halts the growth of the first stars in the universe", *Science*, **334** (2011) 1250-1253
DOI: 10.1126/science.1207433

The paper presents the results from radiation-hydrodynamics simulations of the evolution of a first star. The simulations show, for the first time, how a primordial protostar stops its growth by emitting intensely ultra-violet radiation. The results resolve a long-standing puzzle that the observed elemental abundance patterns of Galactic metal-poor stars do not show the signatures of the so-called pair-instability supernovae that are triggered when very massive stars die. It is suggested that a majority of the first stars did not have the monstrous masses because of the feedback effect.

*Research results 20: Supernovae and Evolution of Chemical Elements

*[37]. K. Maeda, *et al.* (including K. Nomoto, M. Tanaka), "An asymmetric explosion as the origin of spectral evolution diversity in type Ia supernovae", *Nature*, **466** (2010) 82-85
DOI: 10.1038/nature09122

Type Ia supernovae form an observationally uniform class of stellar explosions, in that more luminous objects have smaller decline-rates. This one-parameter behavior allows type Ia supernovae to be calibrated as cosmological "standard candles", and led to the discovery of an accelerating Universe. Recent investigations, however, have revealed that the true nature of type Ia supernovae is more complicated. Here the authors report that the spectral diversity is a consequence of random directions from which an asymmetric explosion is viewed. Their findings suggest that the spectral evolution diversity is no longer a concern when using type Ia supernovae as cosmological standard candles. Furthermore, this indicates that ignition at an offset from the center is a generic feature of type Ia supernovae.

[38]. N. Tominaga, N. Iwamoto, and K. Nomoto, "Abundance Profiling of Extremely Metal-Poor Stars and Supernova Properties in the Early Universe", *The Astrophysical Journal*, **785** (2014) 98
DOI: 10.1088/0004-637X/785/2/98

To explore the origin of "non-dark matter," *i.e.*, the ordinary elements, is one of the important tasks of the Kavli IPMU, along with exploring the nature of dark matter and dark energy. This paper takes the approach to analyze the elemental abundance patterns observed in stars whose iron content is extremely small and compare them with the theoretically predicted abundance patterns produced by supernova explosions of the first stars. This paper shows that this approach is very successful to reveal the nature of the first stars in the Universe. To explain the very distinct abundance patterns of the iron-poor stars, such as very large ratios of CNO elements over Fe, the first stars have masses 20-50 solar masses and their explosions undergo large amount of fallback onto the black hole. The results are very useful to infer the typical mass and the explosion property of the first stars in the Universe.

*[39]. K. Bays *et al.* (Super-Kamiokande Collaboration including Y. Hayato, S. Moriyama, M. Nakahata, M. Shiozawa, Y. Suzuki, T. Kajita, K. Kaneyuki, K. Martens, M. Vagins, E. Kearns, J.L. Stone, M.B. Smy, H.W. Sobel, K. Scholberg, C.W. Walter, K. Nakamura, Y. Takeuchi, T. Nakaya), "Supernova relic neutrino search at Super-Kamiokande", *Physical Review D*, **85** (2012) 052007
DOI: 10.1103/PhysRevD.85.052007

A search for supernova relic neutrinos (SRN) was conducted using the Super-Kamiokande (SK) detector. The SRN signal is a diffuse neutrino background originating from all past supernovae. This signal has not been detected, but it is expected to lie in the 10-30 MeV energy range, in the gap between the energy of reactor and atmospheric neutrinos. In this paper, positron signals from anti-neutrino interactions were searched without tagging neutrons. In such case, the most copious background in this energy range is the spallation background and solar neutrinos. In order to reduce them as much as possible, analysis methods have been improved such as taking into account the longitudinal correlation between muons and beta decay products for spallation background. As a result, energy threshold of the analysis was lowered to 16 MeV. The search was conducted using 2853 live days' data taken from 1996 to 2008 at SK. No significant excess of signals was observed and flux upper limit was obtained for various model predictions.

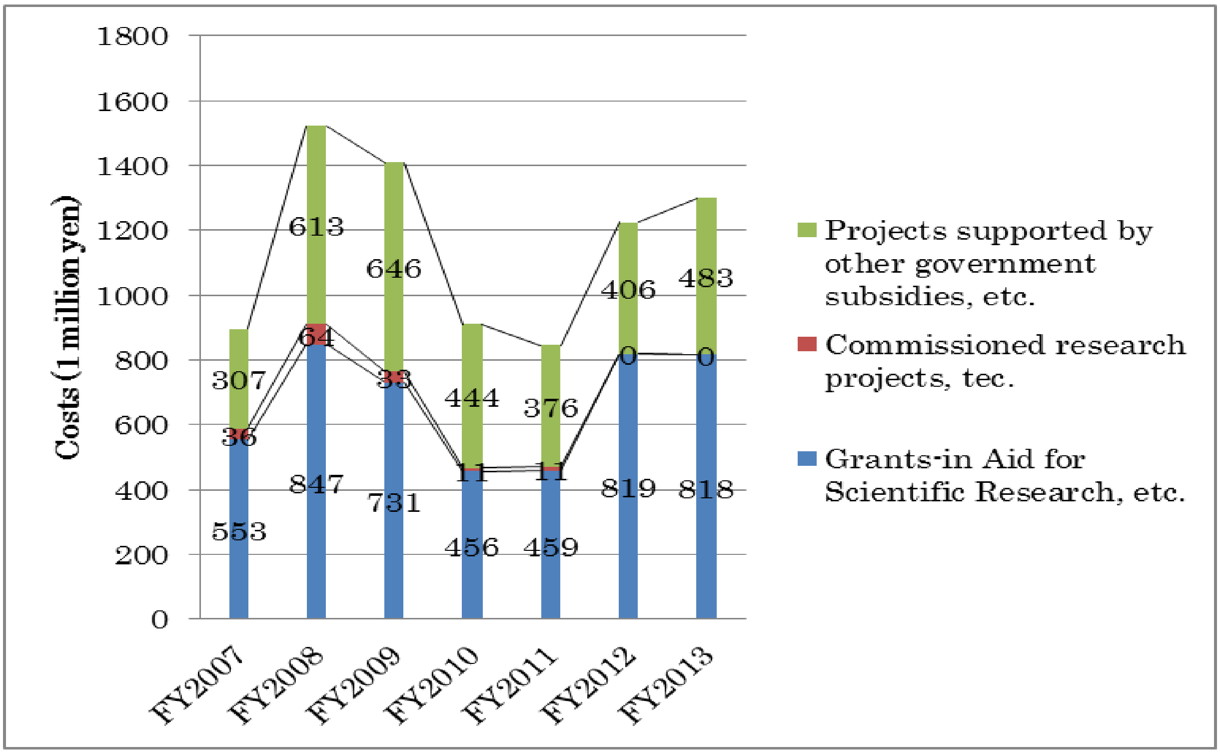
*[40]. S. M. Adams, C.S. Kochanek, J. F. Beacom, M. R. Vagins, and K.Z. Stanek, "Observing the Next Galactic Supernova", *The Astrophysical Journal*, **778** (2013) 164
DOI: 10.1088/0004-637X/778/2/164

In this paper, the authors model the distance, extinction, and magnitude probability distributions of a Galactic core-collapse supernova (ccSN), its shock breakout radiation, and its massive star progenitor. They find, at very high probability (~100%), that the next Galactic SN will easily be detectable in the near-IR and that near-IR photometry of the progenitor star very likely (~92%) already exists in the 2MASS survey. Most ccSNe (~98%) will also be easily observed in the optical. The benefits of neutrino detection experiments quickly disseminating a likely position (~3 deg) are discussed, coupled with a review of the process by which neutrinos from a Galactic ccSN would be detected and announced. They describe the Kavli IPMU's newly-operational, gadolinium-based EGADS detector and its currently unique potential for providing instant, independent, high-confidence supernova neutrino alerts to the world.

2. Annual transition in non-WPI project funding (grants)

**Make a graph of the annual transition in non-WPI project funding (grants).*
**Describe external funding warranting special mention.*

[External funding warranting special mention]



[External funding warranting special mention]

*Grant-in-Aid for Scientific Research (A) (JSPS) FY2014, (XMASS) the world largest liquid Xenon detector in order to make an observation of Dark Matter: 6.4MY, Creative Scientific Research (JSPS) FY2009-12, (XMASS) Study of Dark Matter: 225.2MY

* Grant-in-Aid for Scientific Research (S) (JSPS) FY2009-13, Search for Supernova Relic Neutrinos: 51.2MY

*Grant-in-Aid for Specially Promoted Research (JSPS) FY2010-14, KamLAND detector and set limits on the lifetimes of neutrino less double beta decays: 567MY

*FIRST (Funding Program for World-Leading Innovative R&D on Science and Technology) FY2011-14, SuMIRe (Subaru Measurement of Image and Redshifts): 2,161MY

*Grant-in-Aid for Scientific Research on Innovative Areas (JSPS) FY2013-14, EGADS (Evaluating Gadolinium's Action on Detector Systems): 15MY

3. Major Awards, Invited Lectures, Plenary Addresses (etc.) (within 2 pages)

3-1. Major Awards

** List main internationally-acclaimed awards received announced in order from the most recent.*
** For each, write the recipient's name, name of award, and year issued. In case of multiple recipients, underline those affiliated with the center.*

1. Yuji Tachikawa, Hermann Weyl Prize, 2014
2. Yukinobu Toda, Spring Prize of the Mathematical Society of Japan (MSJ), 2014
3. Takaaki Kajita, Julius Wess Award, 2013
4. Toshitake Kohno, Geometry Prize of the Mathematical Society of Japan (MSJ), 2013
5. Yoichiro Suzuki, Giuseppe and Vanna Cocconi Prize, 2013
6. Hitoshi Murayama, Elected to member of the American Academy of Arts and Sciences, 2013
7. Eiichiro Komatsu, Lancelot M. Berkeley - New York Community Trust Prize for Meritorious Work in Astronomy, 2013
8. Hirosi Ooguri, Fellow of the American Mathematical Society, 2013
9. Kunio Inoue, Nishina Memorial Prize, 2012
10. Yukinobu Toda, Geometry Prize (Mathematical Society of Japan), 2012
11. Twenty six members of the WMAP (Wilkinson Microwave Anisotropy Probe) team including <u>David Spergel</u> and <u>Eiichiro Komatsu</u>, Gruber Cosmology Prize, 2012
12. Hirosi Ooguri, Simons Investigator Award, 012
13. Takaaki Kajita, Japan Academy Prize, 2012
14. Brice Ménard, Sloan Research Fellowship, 2012
15. Kyoji Saito, Mathematical Sciety of Japan Geometry Prize, 2011
16. Tomoyuki Abe, Mathematical Sciety of Japan Takebe Prize, 2011
17. Serguey Petcov, Bruno Pontecorvo Prize, 2011
18. Yoichiro Suzuki, Bruno Pontecorvo Prize, 2011
19. Toshiyuki Kobayashi, Inoue Science Prize, 2011
20. Ken'ichi Nomoto, Institut d'Astrophysique de Paris Medal, 2010
21. David Spergel, Charles L Bennett, Lyman A Page Jr, Shaw Prize, 2010
22. Katsuhiko Sato, Japan Academy Prize, 2010
23. Henry Sobel, Bruno Pontecorvo Prize, 2010
24. Masayuki Nakahata, Inoue Science Prize, 2009
25. Hirosi Ooguri, Nishina Memorial Prize, 2009
26. Shigeki Sugimoto, Yukawa-Tomonaga Memorial Prize, 2009
27. Hirosi Ooguri, Humboldt Research Award, 2008
28. Eiichiro Komatsu, IUPAP Young Scientist Prize in Computational Physics, 2008
29. Naoki Yoshida, IUPAP Young Scientist Prize in Computational Physics, 2008

30.Hirosi Ooguri, Eisenbud Prize, American Mathematical Society, 2008

3-2. Invited Lectures, Plenary Addresses (etc.) at International Conferences and International Research Meetings

** List up to 20 main presentations in order from most recent.*
** For each, write the lecturer/presenter's name, presentation title, conference name and date(s)*

1. Masayuki Nakahata, "Neutrino Physics", the 33rd International Cosmic Ray Conference (ICRC2013), July 2-9, 2013
2. Mihoko Nojiri, "Theoretical Results on Physics Beyond the Standard Model 30'", 2013 Lepton Photon Conference, June 24-29, 2013
3. Hitoshi Murayama, "Future Experimental Programs", Invited lecture at Nobel Symposium on the LHC results, May 13-17, 2013
4. Mark Robert Vagins, "Astrophysical Neutrino Forecast - Mostly Sunny, with a Good Chance of Supernovas", American Association for the Advancement of Science (AAAS) 2013 Annual Meeting, February 16, 2013
5. Shigeki Sugimoto, "Holographic QCD -Status and perspectives for the future-", Xth Quark Confinement and the Hadron Spectrum, October 8-12, 2012
6. Hirosi Ooguri, "Conference Summary", Strings 2012 Conference, July 23-28, 2012
7. Toshitake Kohno, "Homological representations of braid groups and KZ connections", 6th European Congress of Mathematics, July 2-6, 2012
8. Shinji Mukohyama, "Modified Gravity", The Thirteenth Marcel Grossmann Meeting, July 1-7 2012
9. Kunio Inoue, "Results from KamLAND-Zen", The 25th International Conference on Neutrino Physics and Astrophysics (Neutrino 2012), June 3-9, 2012
10. Masahiro Takada, "Weak lensing: Gaussianity and non-Gaussianity", Astronomical Data Analysis VII IESC, May 14-18, 2012
11. Kyoji Saito, "On primitive forms and associated period maps", 2011 Geometry Prize, The Mathematical Society of Japan, March 28, 2012
12. Tsutomu T. Yanagida, "The Origin of Matter", HERTZ LECTURE (DESY Lecture on Physics 2011), September 2011
13. Tadashi Takayanagi, "Holographic Entanglement Entropy and its New Developments", Strings 2011, June 27-July 1, 2011
14. Kentaro Hori, "Duality in Two-dimensional (2,2) Supersymmetric Non-Abelian Gauge Theories", String-Math 2011, June 6-11, 2011
15. Yukinobu Toda, "Curve counting invariants via stable objects I, II, III", Derived categories of Algebro-Geometric Origin and Integrable Systems, December 19-24, 2010
16. Naoki Yoshida, "Chemistry in the Early Universe", 41st Annual Conference on Atomic, Molecular, and Optical Physics of the American Physical Society, May 27, 2010
17. Yoichiro Suzuki, "Solar and Atmospheric Neutrinos", XXIV International Symposium on Lepton and Photon Interactions at High Energies (LP09), August 17-22, 2009
18. Takaaki Kajita, "Status and prospect of atmospheric neutrinos and long baseline studies", The eleventh international conference on Topics in Astroparticle and Underground Physics (TAUP 2009), July 1-5, 2009
19. Ken'ichi Nomoto, "The Cosmic Explosions: The Violent Supernovae", The Opening Ceremony of the International Year of Astronomy, January 15-16, 2009
20. Taizan Watari, "Heterotic--F Theory Duality Revisited", String Phenomenology 2008, May 29, 2008

4. List of Achievements of Center's outreach activities

** Using the table below, show the achievements of the Center's outreach activities from FY2011 through FY2013 (number of activities, times held).*

Activities	FY2011 (number of activities, times held)	FY2012 (number of activities, times held)	FY2013 (number of activities, times held)
PR brochure, pamphlet	6	7	6
Lectures, seminars for general public	11	13	12
Teaching, experiments, training for elementary and secondary school students	8	7	6
Science cafe	4	3	3
Open houses	1	1	1
Participating, exhibiting in events	2	3	4
Press releases	25	33	33

5. List of Media Coverage of Projects carried out between FY 2011 – 2013
(within 2 pages)

** Select main items of press releases, media coverage, and reports between FY2011-2013 (especially overseas)*

1) Japan

No.	Date	Type media (e.g., newspaper, magazine, television)	Description
1	2014.3.27	Mainichi (newspaper)	What is 'primitive gravitational wave'? * Notation about POLARBEAR/LiteBIRD
2	2013.12.10	Newton Special Edition (magazine)	Expanding Universe, Extra Dimension * Supervision: Shinji Mukohyama
3	2013.10.9-13	Mainichi/Sankei/Asahi/Yomiuri (newspaper)	Nobel Prize in Physics: Higgs Particle * Comments by Hitoshi Murayama
4	2013.7.19	NHK (tv)	New Finding by T2K Experiment * Comments by Hitoshi Murayama
5	2013.6.6	NHK (tv)	Cosmic Front: Mystery in A.D.775 * Marcus Werner appears
6	2013.5.30	NHK (tv)	News on UTokyo Massive open online course (MOOC) * Interview with Hitoshi Murayama
7	2013.4.24-5.20	Nikkei/Denki /Mainichi /Asahi (newspaper) Jiji.com/Nikkei Web/Astro Arts/Mynavi News/Excite News (web)	'Standard Candle' Supernova Extraordinarily Magnified by Gravitational Lensing
8	2013.4.11	NHK (tv)	Cosmic Front: Approaching to the fate of the Universe * Comments by Hitoshi Murayama
9	2013.3.14	NHK (tv)	Cosmic Front First Star *Dr. Naoki Yoshida & the Kavli IPMU are addressed.
10	2012.9	Newton Special Edition (magazine)	Higgs boson - world of particle physics - *Director Murayama supervises the issue.
11	2012.7.19	NHK (tv)	Close Up Gendai: Discovery of a century - Higgs Boson - *Comments by Hitoshi Murayama
12	2012.7.5	Mainichi/Asahi/Sankei/Nikkei/Yomiuri (newspaper)	Murayama talks about the discovery of Higgs boson-like particle
13	2012.5.10	Mainichi/Asahi/Sankei/Nikkei/Yomiuri (newspaper)	Hitoshi Murayama and Mr. Fred Kavli visited Japanese Prime Minister, Yoshihiko Noda.
14	2012.4.5	Yomiuri (newspaper)	Exploration – Particle physics theory challenges the mystery of Dark Matter *Interviewing with Director Murayama
15	2012.2.9	NHK (tv)	Bakumon Gakumon: Take us to the edge of the Universe! * Comments by Hitoshi Murayama
16	2011.11.26	NHK (tv)	Science Zero: Red supergiant star, Betelgeuse, is about to blow?
17	2011.10.9	TV Asahi (tv)	Miracles in the Earth: Genius in Japan - Addressing deep mystery of the Universe
18	2011.9	Newton (magazine)	Special report- Birth of the Universe and its future

19	2011.6.28	NHK (tv)	Cosmic Front: About explode? -Red giant star, Betelgeuse-
20	2011.4.19	NHK (tv)	Cosmic Front: Challenges the mystery of Dark matter

2) Overseas

No.	Date	Type media (e.g., newspaper, magazine, television)	Description
1	2014.2.24-26	IHEP web/CAS web/Lailook/Optics Journal/Tsinghua univ news (web)	Nine world leading physicists had face-to-face discussions at Tsinghua University, Beijing on Feb 23
2	2013.8.6	Science Daily/Mynavi News (web)	Stunning Image of Nearby Galaxy M31
3	2013.7.31 -8.3	NHK (tv) Nikkei/Mainichi/Asahi/Yomiuri/Sankei/ Fukui/Ehime/Minaminihon /Chugoku (newspaper) CNET/BruDirect/Telegraph/SPACE.com/Gizmag/SEPA MAS/Pijama Surf (Mexico)/RIA (Russia)(web) Akahata/Mynavi News/Astro Arts/47 web (web)	Hyper-Suprime Cam First Light * Comments by Hitoshi Murayama
4	2013.6.13-14	Pacific News/Newtalk/Business Sandard/Economic Times/Youth Daily News (Taiwan) (web) Mynavi News/Yahoo! News/JAPAN HERALD/Astro Arts (web news)	Cosmic giants shed new light on dark matter
5	2013.5.9-10	Kexue.com/eNews parkForest/SEN (web) Astro Arts/Mynavi News (web)	Joint the Search for 'Space Warps' Volunteers will Power the Search for Warps in Space
6	2013.4.6-8	Red Orbit/Science World Report (web)	New Evidence Of Supernova Progenitor Supernova Explosion of Yellow Supergiant Star in March Confirmed
7	2012.9.13	Hawaii Tribune Herald (newspaper) Yomiuri/Nikkei Sangyo (newspaper) Phys.org/Nature News/Space Daily (web)	Hyper Suprime-Cam ushers in a new era of observational astronomy
8	2012.8.3	Hindustantimes(India)/redOrbit/mail Online/Phys.org (web) Nikkei/Sankei/Yomiuri/Kagaku (newspaper)	Clumpy Structure of Supernova Explosions -- A Subaru view of supernova explosion mechanism * Comments by Maeda and Nomoto
9	2012.7	Highlighting Japan (magazine)	Nurturing global talent * Comments by Hitoshi Murayama
10	2012.2.9	Asahi/Yomiuri/Manichi/Sankei/Nikkei/ Nikkan Kogyo (newspaper) Astrocast.tv/Nonotech-Now/Newwise/ spaceREF/Science Insider/Nature News/Phys.org/Physics World (web)	New Kavli Institute Announced at The University of Tokyo Receives Major Endowment from The Kavli Foundation and Joins Family of Kavli Institutes
11	2011.11.11	NHK (tv) Sankei/Nikkei (newspaper) Nikkei Science (magazine) Space.com/Clarksville Online/ La Canada Flintridge Patch (web)	The first star weighed 40 times the sun

World Premier International Research Center Initiative (WPI)

List of papers of representative of interdisciplinary research activities

** List up to 20 papers that underscoring each interdisciplinary research activity and give brief accounts (within 10 lines).*
** For each, write the author name(s); year of publication; journal name, volume, page(s), and article title. Any listing order may be used as long as format is the same. If a paper has many authors, underline those affiliated with the Center.*
** If a paper has many authors (say, more than 10), all of their names do not need to be listed.*

Collaboration of Astronomy and Mathematics

{1} M. C. Werner, "Gravitational lensing in the Kerr-Randers optical geometry", *General Relativity and Gravitation*, **44** (2012) 3047-3057
DOI: 10.1007/s10714-012-1458-9

A new geometric method to determine the deflection of light in the equatorial plane of the Kerr solution is presented, whose optical geometry is a surface with a Finsler metric of Randers type. Applying the Gauss–Bonnet theorem to a suitable osculating Riemannian manifold, adapted from a construction by Nazım, it is shown explicitly how the two leading terms of the asymptotic deflection angle of gravitational lensing can be found in this way. M. C. Werner has background both in astronomy and geometry, making this interdisciplinary work possible.

{2} G. W. Gibbons, M. C. Werner, N. Yoshida and S. Chon, "On de-Sitter geometry in cosmic void statistics", *Monthly Notices of the Royal Astronomical Society*, **438** (2014) 1603-1610
DOI: 10.1093/mnras/stt2298

A Kavli IPMU mathematician and astrophysicists develop a novel mathematical model for the distribution of cosmic voids. Recent wide-field galaxy surveys show that the large-scale galaxy distribution appears as complex network of filaments of voids of various physical sizes. Kavli IPMU scientists proposed that the geometrical concept of a four-dimensional de Sitter configuration of spheres in Euclidean 3-space can be used to describe the number density of cosmic voids. Their model reproduces the observed number distribution when realistic observational effects owing to survey geometry is taken into account, and thus the model provides a new geometrical perspective on self-similarity in cosmology.

{3} R. M. Quimby, M. C. Werner, M. Oguri, S. More, A. More, M. Tanaka, K. Nomoto, T. J. Moriya, G. Folatelli, K. Maeda, and M. Bersten, "Extraordinary Magnification of the Ordinary Type Ia Supernova PS1-10afx", *The Astrophysical Journal*, **768** (2013) L20
DOI: 10.1088/2041-8205/768/1/L20

The US group Pan-STARRS claimed to have discovered a new and very bright type of supernova PS1-10afx. R. M. Quimby, who had discovered the superluminous supernova, could see immediately that it is not a superluminous supernova, while its spectrum and light curve resembled those of standard type-Ia supernovae, except that it was 30 times brighter. M. C. Werner, who has background in both astronomy and geometry, pointed out that gravitational lensing due to an unobserved galaxy could have magnified its brightness, even though it requires an extraordinary coincidence that the lens is exactly along the line of sight to the host galaxy. M. Oguri, a physicist with experience working with large data set, quickly estimated that such a coincidence is possible in the Pan-STARRS data set. This discussion took place at the daily teatime. This proposed explanation was later confirmed in {4}.

{4} R. M. Quimby, M. Oguri, A. More, S. More, T. J. Moriya, M. C. Werner, M. Tanaka, G. Folatelli, M. C. Bersten, K. Maeda, and K. Nomoto, "Detection of the Gravitational Lens Magnifying a Type Ia Supernova", *Science*, **344** (2014) 396
DOI: 10.1126/science.1250903

By observing the spectrum of the host galaxy of PS1-10afx after it had faded away, they could prove the interpretation proposed in Ref. {3} above. Pan-STARRS team already determined the redshift of the supernova to be 1.39. Their new observation using Low-Resolution Imaging Spectrograph on the

Keck-I telescope also showed [O II] emission doublet is observed with redshift 1.117. Therefore, the latter is the foreground galaxy which acted as the hypothesized lens. This result was covered very widely in media both in Japan (28) and elsewhere (59).

Joint paper by physicists and mathematicians

{5} H. Jockers, V. Kumar, J. M. Lapan, D. R. Morrison and M. Romo, "Two-Sphere Partition Functions and Gromov-Witten Invariants", *Communications in Mathematical Physics*, 325 (2014) 1139
DOI: 10.1007/s00220-013-1874-z

The partition function on the two-sphere of $\mathcal{N}$=(2,2) supersymmetric gauge theories was computed recently by Benini et al. and Doroud et al., via supersymmetric localization. The paper observes that the result for gauged linear sigma model yields the exact Kähler potential on the moduli space of the infrared superconformal fixed points. When the superconformal field theory is used to compactify Type II superstring theory, this provides a direct method to compute the spacetime Kähler potential of the moduli fields, exactly in α'. In the geometric regime where the low energy theory correspond to a Calabi-Yau threefold, the result allows one to compute the genus zero Gromov-Witten invariants of the threefold. These quantities are computed for the quintic and for Rödland's Pfaffian Calabi-Yau threefold and find agreement with existing results in the literature.

Mathematics inspired by Physics

{6} Y. Toda, "Gepner type stability conditions on graded matrix factorizations",
arXiv:1302.6293, Preprint.

Toda introduced the notion of Gepner type Bridgeland stability conditions on triangulated categories, which depends on a choice of an autoequivalence and a complex number. He conjectured the existence of Gepner type stability conditions on the triangulated categories of graded matrix factorizations of weighted homogeneous polynomials. Such a stability condition may give a natural stability condition for Landau-Ginzburg B-branes, and correspond to the Gepner point of the stringy Kähler moduli space of a quintic 3-fold. They showed the conjecture when the variety defined by the weighted homogeneous polynomial is a complete intersection of hyperplanes in a Calabi-Yau manifold with dimension less than or equal to two. Gepner is a physicist who formulated Calabi-Yau target space using the worldsheet formulation of the string theory, and Y. Toda's paper draws heavily from works in physics including that by H. Ooguri, with acknowledgment to K. Hori.

{7} K. Saito, "Limit Elements in the Configuration Algebra for a Cancellative Monoid", *Publications Of The Research Institute For Mathematical Sciences*, **46** (2010) 37-113
DOI: 10.2977/PRIMS/2

Modeling on the classical theory of nearest neighbour Ising models on square lattices where the input data of Botzman weight is replaced by an abstract notion of labels on the wedge of the Cayley graph of a cancellative monoid (Γ,G), he introduces an infinitely generated Hopf algebra to count the configurations in the graph. Then, the space Ω(Γ,G) of all free energies form a compact subset of the algebra. The main theorem states i) an existence of a fibration structure π: $\Omega(\Gamma,G)\rightarrow\Omega(P_{\Gamma,G})$ where the target space $\Omega(P_{\Gamma,G})$ is the space of all opposite sequences to the growth series $P_{\Gamma,G}$ of (Γ,G), and ii) a residual representation of the traces of the fiber of the fibration. This gives a quite new approach to the geometric theory of discrete groups inspired from physics, and some follow-up papers began to appear (*e.g.* http://de.arxiv.org/abs/1311.4450, MR3049573 *J. Algebra* 385 (2013), 314–332).

Physics papers that became possible thanks to latest mathematics

{8} Y. Tachikawa and K. Yonekura, "$\mathcal{N}$=1 curves for trifundamentals", *Journal of High Energy Physics* 1107 (2011) 025
DOI: 10.1007/JHEP07(2011)025

The aim of this work was to generalize Gaiotto's construction to a less supersymmetric setup. With K. Yonekura, who was then a student at the Kavli IPMU, they managed to reduce the physics question into a well-formulated mathematical problem, in the area of algebraic geometry. Thankfully, there are many Kavli IPMU mathematicians who are experts on this mathematical subject. Y. Tachikawa asked Professor A. Bondal, a PI at the Kavli IPMU, who explained to him a way to solve this problem. K. Yonekura, working independently for a while, found a physics way to solve the same problem. Nicely, the two completely independent methods gave the same answer, again illustrating the complementary virtues of theoretical physics and mathematics. A. Bondal is acknowledged in the paper.

{9} C. A. Keller, N. Mekareeya, J. Song and Y. Tachikawa, "The ABCDEFG of instantons and W-algebras", *Journal of High Energy Physics* 1203(2012)045
DOI: 10.1007/JHEP03(2012)045

The Kavli IPMU as a center of mathematics and physics in the Asia-Pacific region was crucial for the existence of this paper. N. Mekareeya, a Thai, and J. Song, a Korean, happened to be invited to the Kavli IPMU on the same date. There, N. Mekareeya explained to Y. Tachikawa an intriguing partial result; Y. Tachikawa immediately noticed that J. Song is an expert on this stuff who can complete this partial result into an interesting relation between the instanton moduli spaces and infinite-dimensional algebras. Together with Keller, who is a coworker of J. Song at his institute, the four authors indeed obtained a new relation, a generalization of the Alday-Gaiotto-Tachikawa relation. A. Bondal and S. Carnahan, both mathematicians at the Kavli IPMU, provided a crucial mathematical step in the derivation of the result, and are acknowledged in the paper.

{10} F. Benini, R. Eager, K. Hori and Y. Tachikawa, "Elliptic genera of 2d N=2 gauge theories", to appear in *Communications in Mathematical Physics*,
arXiv:1308.4896, Preprint

The elliptic genera of general two-dimensional N=(2,2) and N=(0,2) gauge theories are computed via supersymmetric localization. It is given by the sum of Jeffrey-Kirwan residues of a meromorphic form, representing the one-loop determinant of fields, on the moduli space of flat connections on the two-torus. Several examples are presented to illustrate the formula, for theories with Abelian and non-Abelian gauge groups, and for theories that flow to superconformal field theories that can be used as string backgrounds. The formula is used to test a part of the dualities found in [23]. The result can be used to obtain useful information about string compactifications and D-brane dynamics, such as low lying spectra of effective spacetime theories and the degeneracy of BPS states.

{11} H. Ooguri, P. Sulkowski, M. Yamazaki, "Wall Crossing As Seen By Matrix Models", *Communications in Mathematical Physics*, **307** (2011) 429-462
DOI: 10.1007/s00220-011-1330-x

This paper gives interpretation of the Donaldson-Thomas invariants in mathematics based on supersymmetric field theory in physics. The number of BPS bound states of D-branes on a Calabi-Yau (CY) manifold depends on two sets of data, the BPS charges and the stability conditions. For D0 and D2-branes bound to a single D6-brane wrapping a CY 3-fold X, both are naturally related to the Kähler moduli space $M(X)$. They construct unitary one-matrix models, which count such BPS states for a class of toric CY manifolds at infinite't Hooft coupling. The matrix model for the BPS counting on X turns out to give the topological string partition function for another CY manifold Y, whose Kähler moduli space $M(Y)$ contains two copies of $M(X)$, one related to the BPS charges and another to the stability conditions. The two sets of data are unified in $M(Y)$. In addition, the matrix models compute spectral curves and mirror maps relevant to the remodeling conjecture.

{12} H. Ooguri and M. Yamazaki, "Crystal Melting and Toric Calabi-Yau Manifolds", *Communications in Mathematical Physics*, **292** (2011) 179-199
DOI: 10.1007/s00220-009-0836-y

They construct a statistical model of crystal melting to count BPS bound states of D0 and D2 branes on a single D6 brane wrapping an arbitrary toric Calabi-Yau threefold. The three-dimensional crystalline structure is determined by the quiver diagram and the brane tiling which characterize the low energy effective theory of D branes. The crystal is composed of atoms of different colors, each of which corresponds to a node of the quiver diagram, and the chemical bond is dictated by the arrows of the quiver diagram. BPS states are constructed by removing atoms from the crystal. This generalizes the earlier results on the BPS state counting to an arbitrary non-compact toric Calabi-Yau manifold. They point out that a proper understanding of the relation between the topological string theory and the crystal melting involves the wall crossing in the Donaldson-Thomas theory. Y. Toda's clarification based on category of perverse coherent sheaves is specifically acknowledged.

Physics papers that advance mathematics

{13} K. Hori and J. Knapp, "Linear sigma models with strongly coupled phases - one parameter models", *Journal of High Energy Physics*, **1311** (2013) 070
DOI: 10.1007/JHEP11(2013)070

Based on the duality discovered in [23], the paper systematically constructs two-dimensional (2,2) supersymmetric gauged linear sigma models with strongly coupled phases, in which a continuous subgroup of the gauge group is totally unbroken. Relevant properties of the models are studied using the methods developed in [23, 24]. The construction leads to predictions of equivalences of D-brane categories, systematically extending earlier examples. There is another type of surprise. Two distinct superconformal field theories corresponding to Calabi-Yau threefolds with different Hodge numbers, $h^{2,1}=23$ versus $h^{2,1}=59$, have exactly the same quantum Kähler moduli space. The strong-weak duality of (1) plays a crucial rôle in confirming this, and also is useful in the actual computation of the metric on the moduli space. This work partially implements Center's Research objective "enumerate and classify solutions of string theory that will lead to the development of new types of geometries."

{14} P. Braun, Y. Kimura and T. Watari, "On the classifications of elliptic fibrations modulo isomorphism on *K3* surface with large Picard number",
arXiv:1312.4421, Preprint

This paper addresses genuine mathematics problems, which turned out to be well-motivated in a study on string compactification (arXiv:1401.5908, the same authors; accepted by JHEP, which acknowledges mathematician T. Shioda). One of the problems was to determine the modular group of elliptic fibration that a *K3* surface admits precisely. A complete answer to this problem is given in this paper. This problem had to be solved in order to exploit Heterotic-F theory duality. The other problem was to make an estimate of how much classification of elliptic fibration modulo isomorphism is finer relatively to classification of elliptic fibration by the geometry of singular fibres. The former classification corresponds to vacuum classification in physics, while the latter to vacuum classification by their gauge groups. This paper derived an upper bound on how many distinct fibrations modulo isomorphism there can be for a given set of singular fibre geometry.

Condensed matter physics and particle/string theory

{15} H. Ooguri, M. Oshikawa, "Instability in magnetic materials with dynamical axion field", *Physical Review Letters* **108** (2012) 161803
DOI: 10.1103/PhysRevLett.108.161803

H. Ooguri worked with a condensed matter physicist M. Oshikawa on a subject of axion-type particle which is a candidate for dark matter. The detection of axion has been a difficult problem experimentally, while they found an axion-like excitation in condensed matter system. It has been pointed out that axion electrodynamics exhibits instability in the presence of a background electric field. They show that the instability leads to a complete screening of an applied electric field above a certain critical value and the excess energy is converted into a magnetic field. They clarify the physical origin of the screening effect and discuss its possible experimental realization in magnetic materials where magnetic fluctuations play the role of the dynamical axion field.
Chosen as "Editor's Suggestion."

{16} T. Takayanagi, "Holographic Dual of Boundary Conformal Field Theory", *Physical Review Letters*, **107** (2011) 101602
DOI: 10.1103/PhysRevLett.107.101602

The celebrated AdS/CFT correspondence argues that a conformal field theory (CFT) on a manifold is equivalent to string theory (or gravity) on anti de-Sitter space (AdS). In this standard setup of AdS/CFT, the manifold where the CFT is defined, is not allowed to have any boundaries. In this paper, the author extended the construction of AdS/CFT so that the CFT can live on a manifold with boundaries. Especially it was found that the presence of a boundary in CFT corresponds to that in AdS spacetime with the Neumann boundary condition. This formulation has an advantage that we can directly compute the free energy, entanglement entropy and correlation functions. Moreover, this new model has been employed for many applications, such as the proof of g-theorem and holographic construction of quantum Hall effect etc.

{17} H. Watanabe, T. Brauner, and H. Murayama, "Massive Nambu-Goldstone Bosons", *Physical Review Letters*, **111** (2013) 021601
DOI: 10.1103/PhysRevLett.111.021601

When perturbed by explicit symmetry breaking terms, the so-called "pseudo-Nambu-Goldstone bosons" acquire mass which can in most cases be estimated but not exactly predicted. They discovered that exact formula is derived based on Lie algebra only when the perturbation is due to the symmetry generator, such as for the chemical potential. It turned out that this formula has wide-ranging applications to many systems in condensed matter physics and nuclear physics. This paper is written in collaboration with a condensed matter physicist and a nuclear physicist.

{18} H. Watanabe and H. Murayama, "Redundancies in Nambu-Goldstone Bosons", *Physical Review Letters*, **110** (2013) 181601
DOI: 10.1103/PhysRevLett.110.181601

In many systems in condensed matter, nuclear, astro-physics, and cosmology, spacetime symmetries can be spontaneously broken. It has been known that the number of Nambu-Goldstone bosons is reduced in such circumstances. Even though there has been an empirical method to figure out how many modes *can* be reduced, called inverse Higgs mechanism, it was never clear why they *must* be reduced, nor applicable to cases with spontaneously broken translation symmetries. This paper clarified the origin of reduction which they call *Noether constraints*, namely a linear combination of symmetry currents annihilates the ground state. An amazing application of this formulation is the vortex lattice in rotating Bose-Einstein condensate of cold atoms or superfluid. Four symmetries are broken: two translations, one rotation, and one internal $U(1)$ symmetry. Yet there is only one type-A Nambu-Goldstone boson with an unexpected quadratic dispersion relation.

Application of mathematics to cosmology

{19} B. Aazami, G. Cox, "Blowup solutions of Jang's equation near a spacetime singularity", *Classicaland Quantum Gravity* (2014, accepted)
DOI: 10.1088/0264-9381/31/11/115007

They study Jang's equation on a one-parameter family of asymptotically flat, spherically symmetric Cauchy hypersurfaces in the maximally extended Schwarzschild spacetime. The hypersurfaces contain apparent horizons and are parametrized by their proximity to the singularity at $r = 0$. They show that on those hypersurfaces sufficiently close to the singularity, *every* radial solution to Jang's equation blows up. The proof depends only on the geometry in an arbitrarily small neighborhood of the singularity, suggesting that Jang's equation is in fact detecting the singularity. They comment on possible applications to the weak cosmic censorship conjecture.

Application of mathematics to biology

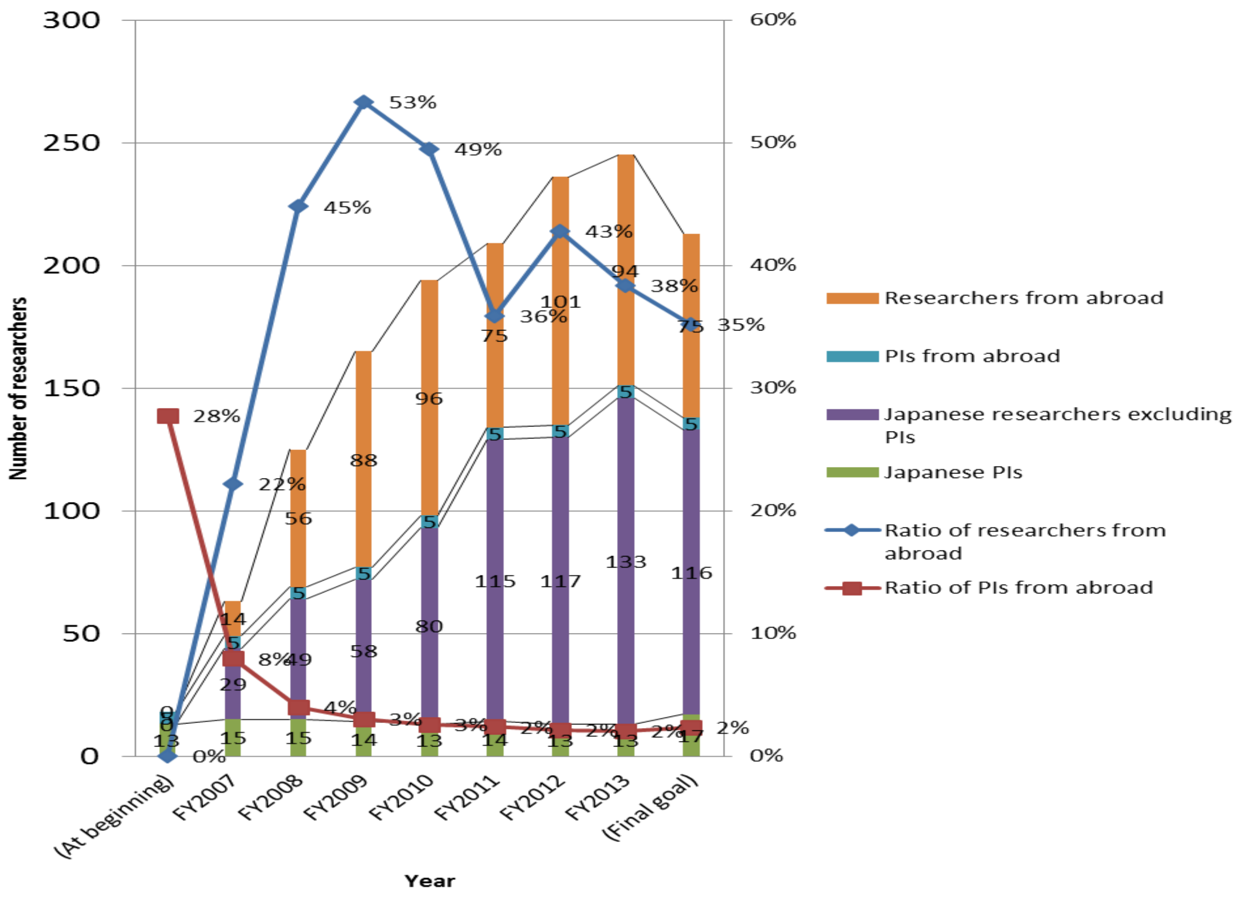
{20} S. Dedeo, D. C. Krakauer, J. C. Flack, "Inductive Game Theory and the Dynamics of Animal Conflict", *Public Library Of Science COMPUTATIONAL BIOLOGY*, **6** (2010) e1000782
DOI: 10.1371/journal.pcbi.1000782

Conflict destabilizes social interactions and impedes cooperation at multiple scales of biological organization, and the causes of turbulent periods of conflict need to be understood. They analyze conflict dynamics in a monkey society model system. They develop a technique, Inductive Game Theory, to extract directly from time-series data the decision-making strategies used by individuals and groups using Monte Carlo simulation. They find individuals base their decision to fight on memory of social factors, not on short timescale ecological resource competition. Furthermore, the social assessments on which these decisions are based are triadic, not pairwise. They show that this triadic decision making causes long conflict cascades and that there is a high population cost of the large fights associated with these cascades. Individual agency has been over-emphasized in the social evolution of complex aggregates, and that pair-wise formalisms are inadequate.

World Premier International Research Center Initiative (WPI)

1. Number of overseas researchers and annual transition

**Make a graph of the transition in the number of overseas researchers since the application.*



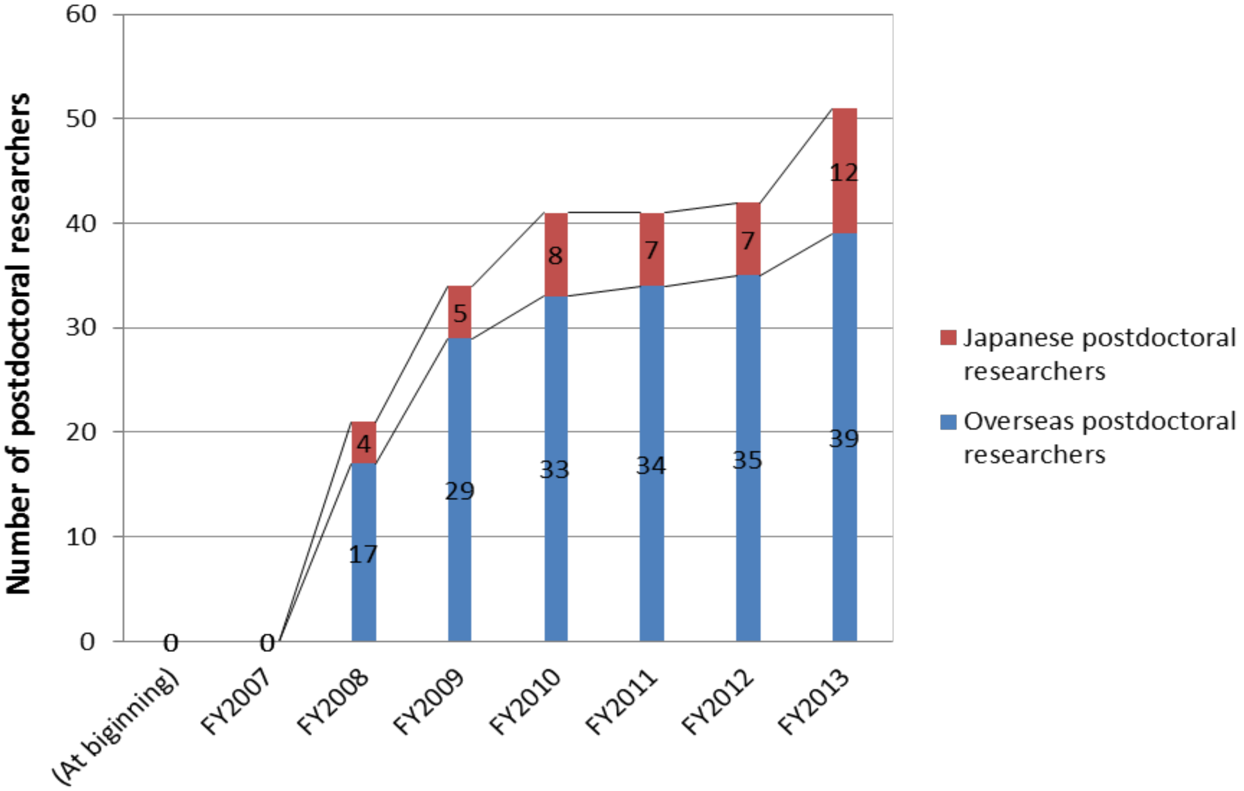
2. Postdoctoral positions through open international solicitations

** In the column of number of applications and number of selection, put the number and percentage of overseas researchers in the < > brackets.*

FY	*number of applications*	*number of selection*
FY2007	481 < 372, 77%>	1 < 0, 0%>
FY2008	527 < 452, 86%>	22 < 16, 73%>
FY2009	726 < 679, 93%>	20 < 16, 80%>
FY2010	794 < 751, 95%>	14 < 10, 71%>
FY2011	811 < 738, 91%>	15 < 14, 93%>
FY2012	664 < 615, 93%>	16 <15, 94%>
FY2013	661 < 607, 92%>	19 < 11, 58%>

3. Number of overseas postdoctoral researchers and annual transition

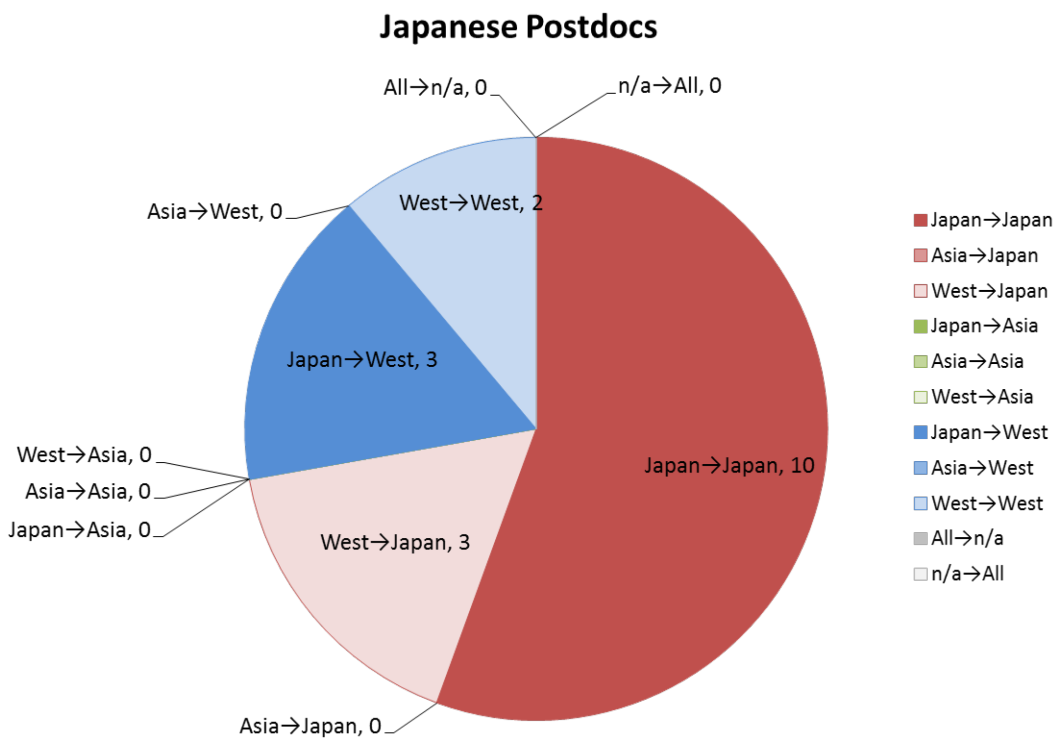
**Make a graph of the transition in the number of overseas postdoctoral researchers since the application.*

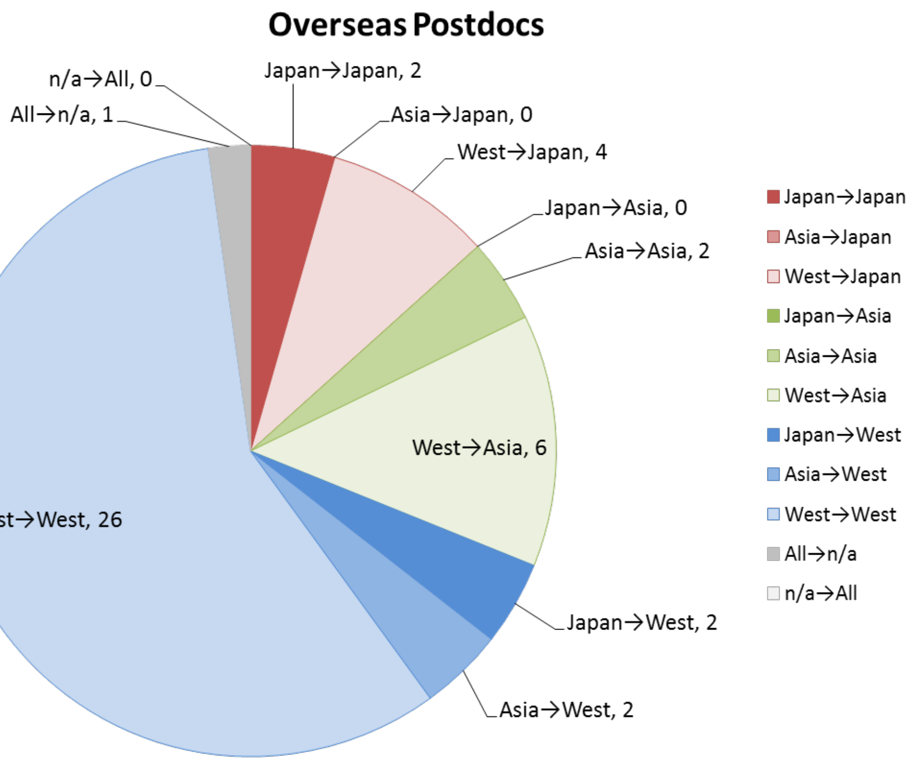


4. Status of postdoc employment at institutions of postdoctoral researchers

・〇〇→△△ indicates that a posdoc has come to the WPI Center from an institute in ○○ and moved to one in △△.

・n/a indicates unknown or resignation for personal reason.





5. List of the cooperative research agreements outside Japan

1. Counterpart of an Agreement: The Astrophysical Research Consortium
   Name of an Agreement: SLOAN DIGITAL SKY SURVEY IV
   MEMORANDUM OF UNDERSTANDING
   Dates of an Agreement: 17 FEB, 2014
   Summary of an Agreement: The Sloan Digital Sky Survey (SDSS) has been in operation since 1998, in three prior phases (termed SDSS, SDSS-II, SDSS-III). It is operated by the Astrophysical Research Consortium (ARC) and uses a dedicated 2.5-m telescope with associated imaging and spectroscopic instrumentation at Apache Point Observatory, in Sunspot.
   The hardware and software systems of SDSS will be unmatched by any other facility for large-scale survey observations for several years to come. The combination of continuing significant scientific impact, the ability to make contributions to diverse fields of astrophysics, and the effectiveness of current and future operations provides the basis to continue for a new phase called SDSS-IV.

2. Counterpart of an Agreement: The Intermediate Palomar Transient Factory (iPTF)
   Name of an Agreement: THE INTERMEDIATE PALOMAR TRANSIENT FACTORY
   A COLLABPRATIVE AGREEMENT (iPTF CA)
   Dates of an Agreement: 23 DEC, 2013
   Summary of an Agreement: Following on from PTF (The Palomar Transient Factory)'s success, this Collaborative Agreement (CA) codifies the Consortium known as The Intermediate Palomar Transient Factory (iPTF). iPTF will be a follow-on survey to PTF that will inherit many of the same assets (wide-filed MOSAIC camera and associated software etc.), but will build upon PTF's success by employing new survey strategies to search for and study transient phenomena poorly measured by PTF.
   *The governing mechanism for the iPTF Consortium is the iPTF Board (the Board). The Board is composed of one representative from each Principal partner institution, plus the Caltech/COO Director in an ex offiio voting capanity.

3. Counterpart of an Agreement: Steklov mathematical Institute, Russian Academy of Sciences
   Name of an Agreement: Memorandum of Understanding
   Dates of an Agreement: 15 SEP, 2013
   Summary of an Agreement: Kavli IPMU and Steklov Mathematical Institute are linked by common academic interests and seek to develop collaborations and exchanges in fields of shared interests and expertise.
   - The principles of Innovation and Collaborations for the advancement of teaching and research in mathematical sciences.

4. Counterpart of an Agreement: Tsinghua university Mathematical Sciences Center
   Name of an Agreement: Memorandum of Understanding
   Dates of an Agreement: 29 MAY, 2013
   Summary of an Agreement: To encourage the development of the following types of activities In the "2011 Project" Proposal from MSC:
   - Visits and exchanges of students, faculty, and scholars in specific areas of education, research and outreach.
   - Organize and hold joint conferences, symposia, or other scientific meetings on subjects of mutual interest.
   - Develop joint research programs and collaborations.
   - Exchange of academic information and materials.

- Other exchange and cooperation programs to which both parties agree.

5. Counterpart of an Agreement: The Astrophysical Research Consortium
   Name of an Agreement: SLOAN DIGITAL SKY SURVEY AS3 ("After SDSS-III") MEMORANDUM OF UNDERSTANDING
   Dates of an Agreement: 25 MAY, 2013
   Summary of an Agreement: The Sloan Digital Sky Survey (SDSS) is a project observationally studying a large area of sky to measure large-scale structure, properties of galaxies, the structure of the Milky Way, and stellar astrophysics. The SDSS was succeeded by the SDSS-III project which extends to 30 June 2014.

6. Counterpart of an Agreement: The Tata Institute of Fundamental Research
   Name of an Agreement: The assembly work of the silicon vertex detector (SVD) layers used in the Belle II experiment
   Dates of an Agreement: 10 MAY, 2013
   Summary of an Agreement: Kavli IPMU and the Tata Institute of Fundamental Research conduct the collaborative research.

7. Counterpart of an Agreement: TRIUMF. The Governors of The University of Alberta, the University of British Columbia, Carleton University, Simon Fraser University, the Governing Council of the University of Toronto and the University of Victoria and such other universities who may become full member universities established pursuant to a contract governed by the laws of the Province of British Columbia operating a Joint Venture known as TRIUMF.
   Name of an Agreement: Memorandum of Understanding Between Kavli IPMU And TRIUMF Concerning Collaboration to Facilitate Joint Appointment
   Dates of an Agreement: OCT, 2012
   Summary of an Agreement: To document the terms governing this joint appointment and to ensure the necessary management elements to facilitate cooperation and the successful exchange of the identified employee.

8. Counterpart of an Agreement: Universidade de São Paulo,California Institute of Technology, JetPropulsion Laboratory,Princeton University, Johns Hopkins University, Laboratoire d'Astrophysique de Marseille, Academia Sinica Institute of Astronomy and Astrophysics
   Name of an Agreement: Memorandum of Understanding among institutions of the PrimeFocusSpectrograph Collaboration
   Dates of an Agreement: 11 AUG, 2012
   Summary of an Agreement: The PFS project aims to survey a large volume of the Universe at an unprecedented depth. It will use thousands of optical fibers each of which can be robotically controlled with hundred milliarcseconds accuracy pointing at a particular galaxy or star of interest. It will be mounted on the Subaru telescope in Hawaii that has a wide field of view. By contributing to the construction of PFS, the collaboration members expect to share observing time on the Subaru telescope, in full partnership with the Japanese astronomical community, under the framework of a Subaru Strategic Program. The contribution and commitment of each institution or consortium of institutions to the project are described.

9. Counterpart of an Agreement: The Scuola Internazionale Superiore di Studi Avanzati (SISSA)
   Name of an Agreement: AGREEMENT BETWEEN THE SCUOLA INTERNAZIONALE SUPERIORE DI STUDI AVANZATI (SISSA) AND THE INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE (IPMU)
   Dates of an Agreement: 24 FEB, 2012

Summary of an Agreement: SISSA and IPMU recognize the value of educational, cultural, and scientific exchanges between international research institutions, and have determined that sufficient interest exists to establish a formal relationship to encourage the exchange of faculty, researchers, and graduate students.

10. Counterpart of an Agreement: Princeton University
Name of an Agreement: AGREEMENT ON ACADEMIC EXCHANGE BETWEEN THE UNIVERSITY OF TOKYO AND PRINCETON UNIVERSITY
Dates of an Agreement: 21 DEC, 2010
Summary of an Agreement: Implement exchanges and other activities in areas of academic research of mutual interest through the following.
(1) Exchange of faculty and administrative staff and researchers.
(2) Exchange of students.
(3) Conducting collaborative research.
(4) Holding joint lectures and symposia.
(5) Exchange of academic information and materials.

11.Counterpart of an Agreement: Unification of Fundamental Forces and Applications (UNIFY)
Name of an Agreement: SEVENTH FRAMEWORK PROGRAMME Marie Curie Actions People International Research Staff Exchange Scheme
Dates of an Agreement: 15 SEP, 2010
Summary of an Agreement: The UNIFY exchange program has two main scientific objectives. One objective is to gain new insights on the quantum mechanical description of the gravitational interaction, an outstanding fundamental problem in theoretical physics, of crucial importance to our understanding of the Universe and of the forces between its basic constituents. The other main objective is to explore recent developments in String Theory and Quantum Gravity in the fields of Cosmology, Black Hole Physics and Gauge Theory. The forthcoming years will bring unprecedented experimental discoveries in these fields of research and are sure to call for new explanations and to shape our attempts to construct an unifying theory of all interactions. UNIFY will achieve its goals by setting a challenging exchange programme that involves world leading universities and institutes (FCUP, HU, Saclay, PI, YITP, IPMU). UNIFY institutions will organize a number of thematic work programmes to push our present knowledge of the law's of nature to its very limit. UNIFY includes in its exchange programme a strong dimension on the training of the next generation of theoretical physicists, as to establish long lasting collaborations between its partners.

12.Counterpart of an Agreement: The University of California, Berkeley
Name of an Agreement: AGREEMENT ON ACADEMIC EXCHANGE BETWEEN THE UNIVERSITY OF TOKYO AND THE UNIVERSITY OF CALIFORNIA, BERKELEY
Dates of an Agreement: 17 DEC, 2009
Summary of an Agreement: Implement exchanges and other activities in areas of academic research of mutual interest through the following.
(1) Exchange of faculty and administrative staff and researchers.
(2) Exchange of students.
(3) Conducting collaborative research.
(4) Holding joint lectures and symposia.
(5) Exchange of academic information and materials.

13.Counterpart of an Agreement: National Taiwan University, Leung Center for Cosmology and Particle Astrophysics (LeCosPA)
Name of an Agreement: Memorandum of Understanding between The University of Tokyo, Institute for Physics and Mathematics of the Universe

Dates of an Agreement: 24 JUN, 2009
Summary of an Agreement: Collaborate on the research topics relating to cosmology and particle astrophysics.

(1) Measurements and analysis of microwave background and related phenomena,
(2) Theory and observation of dark energy and dark matter,
(3) String cosmology,
(4) Large scale structure formation and evolution,
(5) Ultra-high energy cosmic rays and neutrinos and the cosmic accelerator that produces Them,
(6) Gemma ray bursts.

14.Counterpart of an Agreement: Deutsches Elektronen Synchrotron (DESY)
Name of an Agreement: Agreement of Cooperation between Deutsches Elektronen Synchrotron (DESY) and the Institute for the Physics and Mathematics of the Universe (IPMU), University of Tokyo
Dates of an Agreement: 24 JUN, 2009
Summary of an Agreement:

- DESY offers 2-year postdoctoral positions in the frame of its annual fellowship programme.
- DESY, after consultation and only in agreement with IPMU, may offer to a postdoc, who is supposed to work in one of the above mentioned field of common interests, an option of extending the appointment for the another 1-2 years (thus making it into a 3-4 years appointment) with the extra 1-2 years being spent at the IPMU in Tokyo.
- The extra 1-2 years can be chosen by the postdoc him/herself in agreement with the DESY and IPMU theory groups. The stay at IPMU can start after the first year at DESY, with the option to return to DESY to complete the 2 year fellowship.
- During the stay at IPMU the postdoc remains employed at DESY. The salary is paid directly to the postdoc by IPMU instead of DESY during the 1-2 years.
- DESY and IPMU will intensify the already existing collaboration by increasing the exchange of staff, postdocs and graduate students.

15.Counterpart of an Agreement: Garching/Munich Cluster of Excellence on “The Origin and Structure of the Universe”
Name of an Agreement: Memorandum of understanding between Garching/Munich Cluster of Excellence on “The Origin and Structure of the Universe” and Institute for the Physics and Mathematics of the Universe, Tokyo
Dates of an Agreement: 25 FEB, 2009
Summary of an Agreement: Garching Excellence Cluster and IPMU acknowledge the existence of common principles and goals that make it desirable for the two parties to cooperate in scientific collaboration and education.

- Explore the creation of a strong collaboration on these questions related to the formation and evolution of the Universe, the innermost structure of matter, space and time and the nature of the fundamental forces.
- Explore prospects and possibilities to participate in projects of the other party.
- Organize international conferences, workshops, and schools.
- Exchange personnel and organize visit, including the possibility of joint appointment.

16.Counterpart of an Agreement: The Astrophysical Research Consortium
Name of an Agreement: SLOAN DIGITAL SKY SURVEY III MEMORANDUM OF UNDERSTANDING BETWEEN The University of Tokyo and The Astrophysical Research Consortium
Dates of an Agreement: 2 FEB, 2009
Summary of an Agreement: The Sloan Digital Sky Survey (SDSS) is a project observationally studying a large area of sky motivated primarily by extragalactic problems including large-scale structure, properties of galaxies, and other topics. The SDSS was operated by the Astrophysical Research Consortium (ARC) to June 2005, and was succeeded by the SDSS-II project to 30 June 2008. The two SDSS projects included a Japanese

team, which included a number of members from the University of Tokyo. The SDSS-III is a new project that succeeds the SDSS and SDSS-II with new scientific product obtained by the earlier SDSS projects. The continuing significant scientific impact together with the ability to make contributions to diverse fields of astrophysics justifies the SDSS-III.

6. Holding international research meetings

** Give up to twenty examples of the most representative ones of international research conferences or symposiums held between FY2007-2013 using the table below.*

Date	*Meeting title and Place held*	*Number of participants*
March 10-20, 2014	Kavli IPMU-FMSP Workshop: Supersymmetry in Physics and Mathematics Lecture hall, Kavli IPMU	Overseas: 17 Domestic: 25
February 10-14, 2014	Primitive forms and related subjects Lecture hall, Kavli IPMU	Overseas: 41 Domestic: 40
January 27-28, 2014	4th Open Meeting for the Hyper-Kamiokande Project Lecture hall, Kavli IPMU	Overseas: 64 Domestic: 40
December 02-04, 2013	SUSY: Model-building and Phenomenology Lecture hall, Kavli IPMU	Overseas: 12 Domestic: 49
November 18-22, 2013	Workshop: Homological Projective Duality and Quantum Gauge Theory, Kavli IPMU	Overseas: 25 Domestic: 21
May 20-24, 2013	MaNGA Focus Week Lecture hall, Kavli IPMU	Overseas: 22 Domestic: 9
February 18-22, 2013	Kavli IPMU focus week on Gravity and Lorentz violations Kavli IPMU	Overseas: 13 Domestic: 18
November 12-16, 2012	Workshop: Homological Projective Duality and Quantum Gauge Theory, Kavli IPMU	Overseas: 25 Domestic: 21
August 13-16, 2012	PFS 3rd General Collaboration Meeting Kavli IPMU	Overseas: 51 Domestic: 17
June 25-29, 2012	Workshop:Geometry and Physics of the Landau Ginzburg Model, Kavli IPMU	Overseas: 21 Domestic: 37
March 12-16, 2012	IAU Symposium 279: Death of Massive Stars: Supernovae and Gamma-ray Bursts, Nikko	Overseas: 100 Domestic: 59
October 31 - November 4, 2011	Curves and Categories in Geometry and Physics IPMU	Overseas: 15 Domestic: 33
September 27 - October 1, 2010	Horiba International Conference on Cosmology and Particle astrophysics (COSMO/CosPA 2010) Ichijo Hall and other rooms, Hongo Campus	Overseas: 159 Domestic: 135
June 28 - July 2, 2010	CLJ2010: from Massive Galaxy Formation to Dark Energy Media Hall, Kashiwa Campus	Overseas: 107 Domestic: 53
February 8-12, 2010	Focus Week: Condensed Matter Physics Meets High Energy Physics, Lecture Hall, IPMU	Overseas: 40 Domestic: 160
September 28-October 2, 2009	Focus Week: Statistical Frontier of Astrophysics IPMU	Overseas: 19 Domestic: 21
June 22-26, 2009	IPMU International Conference Dark Energy: Lighting up the Darkness!, Media Hall, Kashiwa Campus	Overseas: 55 Domestic: 79
May 18-22, 2009	Focus Week: New Invariants and Wall Crossing Kashiwa Campus	Overseas: 17 Domestic: 61
March 16-20, 2009	Focus Week: Determination of Masses and Spins of New Particles at the LHC Room 633, Research Centers Building, Kashiwa Campus	Overseas: 33 Domestic: 27

March 11-12, 2008	IPMU Opening Symposium Media Hall, Kashiwa Campus	Overseas: 18 Domestic: 119

World Premier International Research Center Initiative (WPI)

1. Host institution's commitment

1-1. Contributions from host institution

(1) Fund, Personnel

(2007-2013)

<Fund> **(million yen)**

Fiscal Year	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**Total**
Personnel	94	258	235	278	229	257	271	295	1,917
- Faculty members (including researchers)	68	150	160	201	229	257	271	295	1,631
Full-time	0	0	10	10	10	24	33	60	147
Concurrent	68	150	150	191	219	233	238	235	1,484
- Postdocs	0	0	0	0	0	0	0	0	0
- RA ect.	0	0	0	0	0	0	0	0	0
- Research support staffs	0	0	0	0	0	0	0	0	0
- Administrative staffs	26	108	75	77	0	0	0	0	286
Project activities	3	18	113	7	23	8	42	15	229
Travel	1	1	2	6	1	1	1	1	14
Equipment	0	0	7	0	3	0	0	0	10
Research projects	290	536	645	503	675	675	560	661	4,545
Total	388	813	1,002	794	931	941	874	972	6,715

<Personnel> **(person)**

Fiscal Year	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**Total**
Personnel	16	38	42	52	44	48	49	52	341
- Faculty members (including researchers)	10	28	31	41	44	48	49	52	303
Full-time	0	0	1	1	1	3	3	5	14
Concurrent	10	28	30	40	43	45	46	47	289
- Postdocs	0	0	0	0	0	0	0	0	0
- RA etc.	0	0	0	0	0	0	0	0	0
- Research support staffs	0	0	0	0	0	0	0	0	0
- Administrative staffs	6(6)	10(10)	11(11)	11(11)	0	0	0	0	38(38)

** Regarding "Fund" entry, describe with reference to the items in the Progress Report(実績報告書,Jisseki-hokoku-sho)based on Article 12 of the Grant Guidelines(交付要綱,Kofu-yoko).*
** Don't include competitive funding obtained by researchers (used as research project funding)*
** Under "Personnel", enter the number of full-time administrative staff within the parenthesis.*

(2) Provision of land and/or building(s), lab space, etc.

The university provides land free at the Kashiwa-Campus for the Kavli IPMU building. It is approximately 1,600 m^2.

1-2. System under which the center's director is able to make substantive personnel and budget allocation decisions

From the beginning, UTokyo developed an innovative scheme to allow the positioning of the Kavli IPMU as an organization directly under the Office of President working in an organic linkage with existing university organizations. In January 2011, UTokyo established the TODIAS and the Kavli IPMU was accepted as its first member institute. Under this scheme, Director of the Kavli IPMU has decision-making power in the operation of the Institute, including the recruitment of researchers.

1-3. Support for the center director in coordinating with other departments at host institution when recruiting researchers, while giving reasonable regard to the educational and research activities of those departments

In order to ensure that education and research activities of the University faculties and institutions from which the researchers are gathered for the Kavli IPMU, the Administration Bureau provided any necessary financial support, such as for personnel expenses of substitute teaching staff, to the concerned university departments and divisions. This allows such departments and divisions to take measurements including securing substitute teaching staff, expecting further improvement in the mobility of researchers within the University.

1-4. Revamping host institution's internal systems to allow introducing of new management methods

(e.g., English-language environment, merit-based pay, cross appointment, top-down decision making unfettered by conventional modes of operation)

As described above, UTokyo has developed an innovative scheme to allow positioning of the Kavli IPMU within TODIAS. Under this scheme, the Kavli IPMU has taken charge in the operation of the organization, including the recruitment of researchers. New special regulations were also established designating the Kavli IPMU as a special zone in which participating researchers and support staff members are allowed a limited exemption from some restrictions under the work rules that are generally applied within the university. Those measures are; English bilingual staff can be easily hired, recruit prominent researchers from all over the world based by paying internationally competitive salary, possible joint appointment between the Kavli IPMU and the foreign universities, and so on.

1-5. Accommodation of center's requirements for infrastructural support

Utilities and other infrastructure support provided by host institution.

*(*In addition to listed in the item 1. Contributions from host institution)*

UTokyo places great importance on the development of an environment to permit excellent researchers from overseas to steadily concentrate on their research activities. Priority allocation of the residences at the opened facility has already been made for researchers invited to the Kavli IPMU from overseas. Top priority has given to the appropriation of land for a research building for the Kavli IPMU and its financing. In 2011, the University built a fancy five-story 'fusion building' for the Kavli IPMU. It is a spiral configuration without any concrete definition of each story. All the researchers, staffs moved from an inconvenient pre-have house to this confortable new building.

1-6. Support for other types of assistance

With the aim of supporting the establishment of an internationally competitive center through the program, UTokyo has set up a committee headed by the board member in charge of the program. The committee, in addition to ensuring university-wide support for the Kavli IPMU, has been worked in close cooperation with the Global COE (Centers of Excellence) Program, the Leading Graduate School Program, and other schemes, as part of its role to produce maximum synergy. The administrative functions of the Administrative Bureau were reorganized in 2007 to intensively support the Kavli IPMU, among other organizations. With these schemes, the University has provided the maximum possible consistent support for the promotion of the Kavli IPMU concept.

[Mid-term Objective and Mid-term Plan of The University of Tokyo (excerpt)]

The First Term (April 1, 2004 – March 31, 2010)

- Objectives on Enhancing the Systems for Research
  Actively promote the establishment and development of a core research facility.
- Measures to Achieve the Objectives on Enhancing the Systems for Research
  - Specific measures on the development of research facilities to function as centers for nationwide and worldwide collaboration
  - Based on institutes, national common use facilities, and university common facilities for education and research, develop centers for national and international research collaboration in the university.
  - At the world's top level research center, the "Institute for the Physics and Mathematics of the Universe", intensively develop organizations to investigate the origin and evolution of the universe through the collaboration of mathematics, physics and astronomy.

The Second Term (April 1, 2010 – March 31, 2016)

- Objectives on Internationalization
  Contribute to society through internationalizing education and research, strengthening the presence of Japan in the world, and creating relationships for international cooperation.
- Measures to Achieve the Other Objectives
  Measures to Achieve the Objectives on Internationalization
  - In order to advance internationalization even more, constantly revise the mid- and long-term strategy for enhancing internationalization and develop and utilize the organization for realizing the objectives.
  - Specifically, promote international research collaboration in the field of advanced astronomical scientific research, as well as develop the environment for education by inviting world-class researchers.

2. Transition in the number of female researchers

Enter the number and percentage of female researchers in the top of each space from 2010 to 2013 and the total number of all the researchers in the bottom.

(Person)

		FY2010	FY2011	FY2012	FY2013	Final goal
Researchers		10, 5%	4, 2%	12, 5%	12, 5%	12, 6%
		194	209	236	250	195
	Principal investigators	1, 6%	1, 5%	1, 6%	1, 6%	2, 9%
		18	19	18	18	22
	Other researchers	9, 5%	3, 2%	11, 5%	11, 5%	10, 6%
		176	190	218	232	173