Workshop on Astrophysics of Dark Matter

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The *Astrophysics of Dark Matter* focus week, held at the Kavli IPMU on October 13 - 16, 2015 brought together particle physicists and astrophysicists to discuss one of the most intriguing mysteries in the universe, the mystery of dark matter.

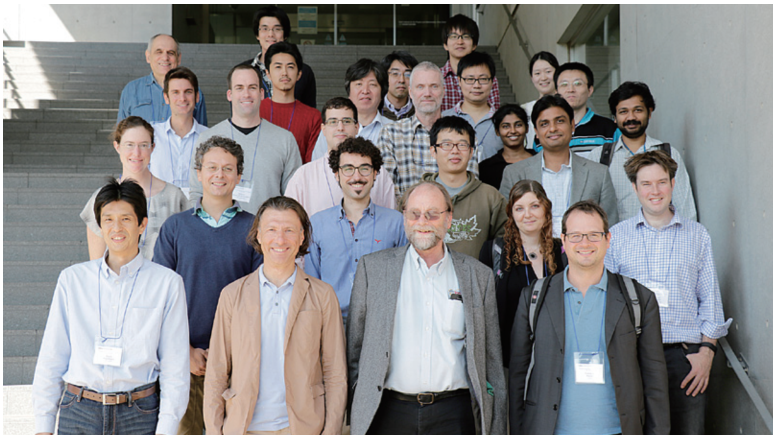
Most of the matter in the universe is dark matter; it is not composed of ordinary atoms, but, rather, of new, yet undiscovered particles. The presence of dark matter is seen by its gravity. Dark matter mass can be measured in several ways. First, gravitational lensing observations, using the bending of light by massive objects, can determine the masses of the "lenses" composed of dark matter. Second, the temperature of gas in clusters of galaxies, inferred from x-ray observations, can be used to determine the depth of the potential well containing this gas. Third, the spectrum of temperature fluctuations in the cosmic microwave background radiation left from Big Bang can be used to measure the ratio of all gravitating matter to ordinary matter, which, unlike dark matter, feels the pressure of photons. Finally, the measured speeds of galaxies in clusters and of stars in galaxies tell us about the gravitational pull of the mass in those objects. All of these independent measurements converge on the same number: dark matter outweighs ordinary matter by more than a factor five.

However, the composition of dark matter remains a mystery. One can show that none of the particles discovered so far can make up dark matter, and, therefore, identification of dark matter will be a discovery of at least one new particle, taking science in a new direction beyond the standard model of particles and interactions.

To solve the mystery of dark matter, one must understand any non-gravitational interactions it might have because these interactions may allow us identify the dark matter particles. Astrophysics can probe the nature of dark matter in several ways.

Dark matter has played a leading role in forming structures we see in the universe today, such as galaxies, clusters of galaxies, etc. The smallest possible structures in the universe depend on whether dark matter is cold or warm, that is, how fast the dark matter particles were moving at the dawn of structure formation. The density profiles of dark matter halos can also be affected by self-interactions of dark matter particles with each other. Observations of dwarf spheroidal galaxies, and the determinations of the dark matter profiles of galaxies and clusters can shed light on the properties of dark matter particles.

Several recent developments made the workshop timely and exciting. The possibility that a reported 3.5 keV X-ray line originates from decay of dark matter, coupled with some anomalies of structure formation on sub galactic scales were at the focus of discussion. Recent breakthroughs in N-body simulations of dark matter, which allow a better description of dark matter (cold and warm), as well as baryons, promise to provide better tools for relating small-scale structure to the properties of dark matter. The proliferation of particle physics models with self-interacting dark matter raises new questions in connection with astrophysical manifestations of microscopic properties of dark matter particles, from halo shapes and triaxiality, to density profiles, to cluster collisions, to supermassive black hole formation. N-body simulations are reaching new levels of understanding of dark matter and baryonic matter; observational techniques using gravitational lensing are maturing. All of these developments made it timely to bring together astrophysicists and particle physicists for a productive discussion.



TeV Particle Astrophysics (TeVPA) 2015

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The conference "TeV Particle Astrophysics (TeVPA) 2015" was successfully conducted at the Kashiwa-no-ha Conference Center October 26–30, 2015. It was organized by the Kavli IPMU and the Institute for Cosmic Ray Research of the University of Tokyo. Having a conference dedicated to the current situation and future prospects of TeV particle astrophysics was an important and timely idea for the following reasons. First, the origin of cosmic rays is now being resolved thanks to great strides in the development of particle astrophysics. These include the observations of gamma rays (at HESS, etc.), high energy neutrinos from outside the earth's atmosphere (at IceCube, etc.), and various cosmic-ray species with unprecedented accuracy (at AMS-02, etc.). Second, TeV particle astrophysics provides us with precious data to search for dark matter, in particular, when its mass is of the order of TeV rather than the electroweak scale, for such heavy dark matter is difficult to detect in collider experiments in the near future.

All of these topics were covered in great depth at the conference, which included fifteen plenary talks and four parallel sessions (dark matter, neutrino, cosmic-ray, and gamma-ray sessions). Concerning neutrino physics, data on high energy neutrinos were accumulated and their origin was discussed in plenary and contributed talks. The future prospects of neutrino observations were also discussed. Another important subject in the conference was ultra-high energy cosmic rays whose spectrum, compositions, and anisotropy were attracting great interest from participants. Gamma-ray astronomy has been developing with large Cherenkov detectors and is expected to reveal the acceleration mechanism of cosmic rays and properties of source objects. Thus, many aspects of gamma-ray astronomy were covered and intensively discussed in the conference.

On the other hand, concerning dark matter studies, most of the plenary and contributed talks were devoted to indirect searches for dark matter. Since particle astrophysics and astronomical observations are steadily being developed and as a result we will obtain in the near future very precise data of dark matter such as distributions in our galaxy and satellite galaxies, all participants were interested in the impact of the observations on indirect dark matter searches. These aspects were thoroughly covered and discussed in the talks, and participants could clearly understand the current situation and future prospects of the searches, and got a glimpse of promising future directions on this subject.

This conference was originally not planned to be a large one, but the number of participants was much more than expected. We had almost 200 participants in total! This means that the topic of the conference is now regarded as the most important one by almost all researchers in particle physics, cosmology, and astronomy. Having a similar workshop again at the Kavli IPMU in near future would be important.

PFS-SSP Galaxy Survey Workshop 2015

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There is a wide variety of galaxies in the Universe. How did they form? One way to explore this astronomical question is to reveal the past appearance of distant galaxies. Spectroscopic observations are a common way to determine the nature of the galaxy in detail. Distant galaxies, however, tend to be generally faint, and spectroscopic observation becomes difficult compared to nearby galaxies. Therefore, spectroscopic observation with larger telescopes is indispensable. Furthermore, multi-object spectroscopy to observe as many galaxies as possible is important for an efficient survey of faint galaxies.

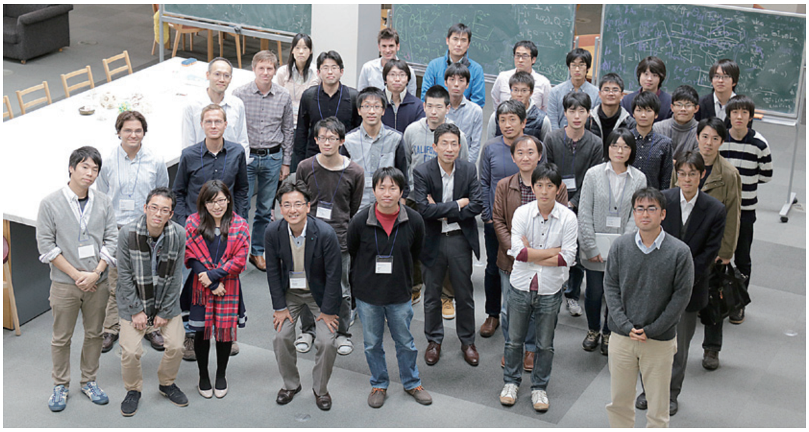
Prime Focus Spectrograph (PFS) on the Subaru Telescope, which is now being promoted by the Kavli IPMU, is a fiber type spectrograph that can simultaneously obtain spectra of up to 2400 objects in a field of view of 1.3 degrees, covering a wide wavelength range from visible to near-infrared. Using this powerful instrument, we are now preparing for a large galaxy spectroscopic survey. Since PFS is an international collaboration, the survey plan is being discussed by researchers all around the world. On November 13, 2015, about 40 Japanese researchers who are interested in the galaxy formation and evolution gathered at the Kavli IPMU and discussed specific scientific cases using PFS.

The PFS galaxy survey targets galaxies at redshift of around 2 (age of the Universe of about 30 billion years), when the galaxies are in the most active phase, to make statistical studies of the nature of galaxies. However, since the observable wavelength of PFS is wide, it is possible to observe objects such as galaxies and active galactic nuclei (AGN) at various redshifts from ~1 (age of the Universe of 60 billion years) to ~7 (age of the Universe of 800 million years). In this workshop, we discussed what kind of scientific cases will become clear by using PFS and how to arrange the survey strategy. In addition, the importance of the role of PFS in this field was also discussed from the theoretical point of view.

At this time, the expectations for PFS of galaxy formation and evolution researchers in Japan are becoming clearer. Although PFS is a project based on international collaboration, the Japanese community is expected to take leadership on the survey. In addition to the discussion on specific scientific themes, some researchers who will lead the individual topics were determined.

In the future, researchers in the PFS collaboration will gather and discuss various topics related to the project. The results of the discussions in this workshop will be reported in the collaboration meeting, and consistency with the other surveys will be discussed. We expect to start the actual observations from the second half of 2019. We will continue to hold similar scientific workshops on a regular basis, and the discussion will be input into the survey plan in order to successfully achieve the goals related to galaxy formation and evolution with unprecedented results.

We are grateful to the staff of the Kavli IPMU for their hard work, as well as to the graduate students of the University of Tokyo for their help.



Categorical and Analytic Invariants in Algebraic Geometry 1 & 2

Alexey Bondal
Kavli IPMU Principal Investigator

The year 2015 saw the start of the Japanese-Russian bilateral project on Categorical and Analytic Invariants in Algebraic Geometry. It was jointly financed by JSPS and the Russian Foundation for Basic Research (RFBR). The project is governed by Kyoji Saito and Alexey Bondal.

The aim of the project is to bring together the best Japanese and Russian experts actively working in the area of algebraic and analytic geometry, homological algebra and string theory, in order to get an insight on the structure of complex varieties and certain interrelated invariants thereof, such as derived categories, semi-infinite Hodge structures, topological correlators and quantum motives, which reflect the properties of these varieties relevant to mirror symmetry.

The first conference, "Categorical and Analytic Invariants in Algebraic Geometry 1," under the auspices of this project, took place at the Steklov Institute in Moscow on September 14—18. Several members of the Kavli IPMU participated, as well as mathematicians from the Graduate School of Mathematical Sciences, The University of Tokyo, from Kyoto University, Osaka University, Tokyo Metropolitan University, the Steklov Institute in Moscow, the Higher School of Economics in Moscow.

The new workshop, "Categorical and Analytic Invariants in Algebraic Geometry 2," took place at the Kavli IPMU during the week of 16–20 November, 2015. More experts on the subject of the project from both Russia and Japan as well as from several other countries attended.

From the mathematical perspective, mirror symmetry is understood as a mysterious duality between the complex and symplectic worlds, where branes, the boundary conditions for strings, are interpreted in a non-mixed way either as complexes of coherent sheaves or as Lagrangian submanifolds. For that reason, the project has two sides, symplectic and complex, and many talks of the workshop were devoted to study of one of the sides of the mirror or to comparison of the two.

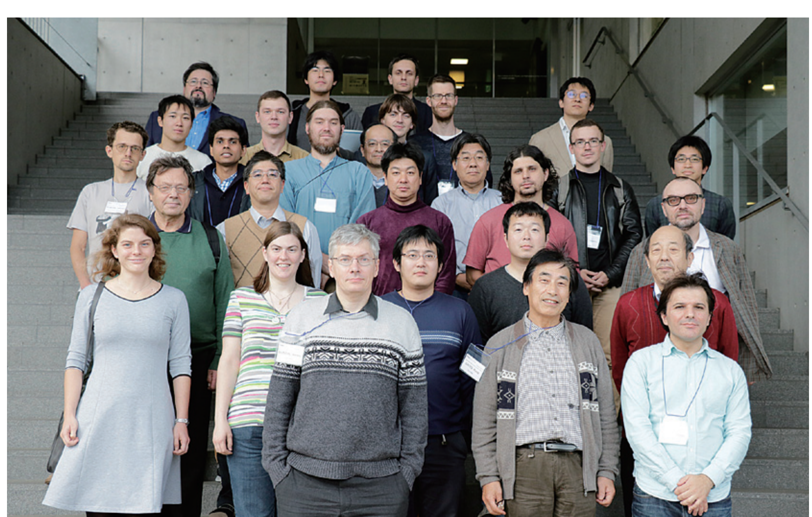
Since the subject of the study of the project is inspired by mirror symmetry, which was a discovery of physics, it was crucial to give the microphone to physicists. The first speaker of the workshop was Kentaro Hori, a string physicist at the Kavli IPMU, who outlined an approach from the perspective of Gauged Linear Sigma Models.

An interpretation of the Fukaya categories of Lagrangian cycles in terms of the categorification of special topological constructible complexes of sheaves, called perverse sheaves, was presented by Mikhail Kapranov. He described a vast categorical and topological landscape of this new theory and gave an explicit description for the case of punctured Riemann surfaces by means of the Waldhausen construction.

An application of K. Saito's Frobenius structures related to singularities of functions to the physical problem of the computation of the correlation numbers in the theory of 2-dimensional Minimal Liouville gravity was reported by the famous Russian physicist Alexander Belavin. In a conjectural picture proposed by the speaker, the choice of primitive form was of crucial importance.

Another attempt to have a look behind the both sides of the mirror was the talk given by Hiroshi Iritani on mirror symmetry of toric stacks. The consistency of behavior of analytic and categorical invariants of toric stacks under mirror symmetry transformation was scrutinized with delicacy.

All the other talks at the workshop were devoted to the most modern and advanced study of either categorical or analytic invariants on one of the side of the mirror, i.e. in complex and algebraic geometry or in symplectic geometry. The excellent expertise of the participants has guaranteed that the level of the reported research was far beyond what one might expect in the boundaries of two countries; it was truly world class. That is why the workshop attracted the attention of some prominent foreign researchers.



Workshop Report

B Mode from Space

Hajime Sugai
Kavli IPMU Associate Professor

The workshop “B Mode from Space” was held at the Kavli IPMU Lecture Hall from Thursday, December 10 to Wednesday, December 16, 2015, with 130 participants (http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=72). The research goal of the participants is to reveal the inflation era before the Big Bang. In the period immediately after the beginning of the universe, the universe is believed to have expanded exponentially and to have produced the primordial gravitational wave. We aim to detect the footprint of this wave on the Cosmic Microwave Background (CMB) in a form of polarization pattern called B mode. The CMB has its emission peak at millimeter wavelengths. It is essential to separate it from the foreground galactic emission including the synchrotron and the dust emission.

In this workshop, we intensively discussed the developments of foreground removal methods over the course of a whole day, including talks on the dust emission mechanism itself. We have also discussed other scientific motivations of CMB polarization experiments, e.g., the understanding of the reionization era of the universe and the narrowing down of the neutrino mass limit.

Based on the direct involvement of participants in past, present and future CMB polarization projects, various kinds of approaches have been reported. These include ground-based experiments such as SPT, ACT, POLARBEAR/Simons Array, ABS, QUIJOTE, and CMB-S4; balloon experiments such as EBEX and PIPER, which are shorter-time scale experiments but are relatively free from atmospheric absorption / radiation; and satellite experiments such as Planck, LiteBIRD, and PIXIE, which carry out long-term measurements without suffering from the atmosphere. Through this workshop, a major movement towards next-generation CMB polarization experiments has emerged, as mentioned in the conference banquet by Jan Tauber, who was responsible for the Planck satellite (which followed COBE/WMAP CMB satellites).

In the second half of the workshop, technical aspects of CMB experiments were reported and discussed, including compact optics for satellites, polarization modulators with a half wave plate, cooling systems including adiabatic demagnetization refrigerators which go down to 100mK, and TES/MKID superconductor detectors and their readout systems. The Kavli IPMU is one of the core institutions of LiteBIRD (Light satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection), and I presented on its optics designing. The LiteBIRD will carry out three-year measurements of linear polarization of the CMB in the whole sky, covering the wide frequency range of 35GHz to 450GHz.

About 40%, 30%, and 30% of the participants, were respectively from Japan, the USA, and Europe; these regions are leading this research field of CMB experiments. The local organizing committee, led by Nobu Katayama, consisted of Masaya Hasegawa, Masashi Hazumi, Hirokazu Ishino, Tomotake Matsumura, Yutaro Sekimoto, and Sugai. We thank the Kavli IPMU office, particularly Ms. Kohama, for their management support, as well as students from Japanese universities.