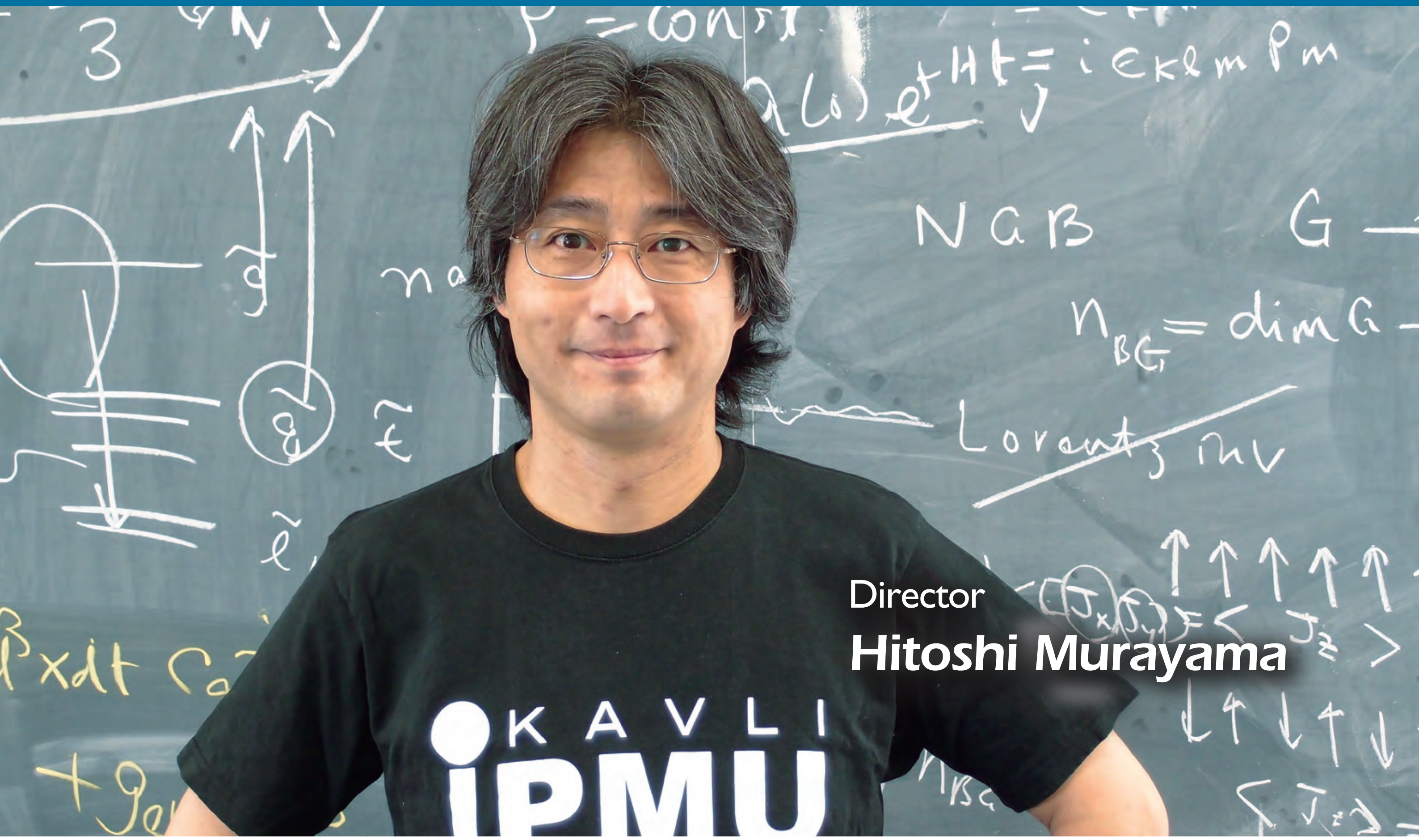
Kavli Institute for the Physics and Mathematics of the Universe



Challenging the mysteries of the Universe through leading collaborations in mathematics, physics, and astronomy

Under the World Premier International Research Center Initiative (WPI), the Institute for the Physics and Mathematics of the Universe was established in 2007. Five years on, the institute received an endowment from The Kavli Foundation, and was renamed the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), The University of Tokyo Institutes for Advanced Study. As of April 2015, the institute includes 85 full time researchers, half of whom are from overseas. In total, about 250 mathematicians, physicists, astronomers, including those with other affiliations, and graduate students are collaboratively engaged in uncovering the mysteries of the Universe.

Research Center's Information (FY 2015)

Center Director: Hitoshi Murayama
Principal Investigators (PI): 19 (including 5 overseas researchers and one female researcher)
Other Researchers: 240 (including 86 overseas researchers and 10 female researchers)
Research Support Staff: 31
Administrative Division:
  Administrative Director: Tomiyoshi Haruyama
  Administrative Staff: 10 (percentage of bilingual staff: 30%)
Satellites and Cooperative Organizations: University of California, Berkeley, USA; Steklov Institute of Mathematics, Russia; TRIUMF, Canada; Princeton University, USA; Laboratoire d'Astrophysique de Marseille, France; ASIAA, Chinese Taipei; and others
URL: http://www.ipmu.jp/en

KAVLI IPMU

Major Research Achievements

1 Subaru unravels the mystery of star explosion observed by Tycho Brahe in 16th Century

By studying the surrounding dust of a supernova remnant, researchers captured the light echoes of star explosion seen by Tycho Brahe, thereby established that it was a Type Ia supernova.

2 Galaxy cluster observation hints at cold dark matter evidence

Observations by Subaru Telescope's Suprime-Cam led to a discovery of new evidence that dark matter distribution around galaxy clusters agree with the prediction of the cold dark matter model.

3 Curve counting theories and derived categories

Using abstract counting theories of objects (derived categories), certain rules that govern curve counting in six dimensions were proved.

4 Discovery of new discrete parameters of gauge theories

Gauge theories were shown to have new discrete parameters hitherto unnoticed, with which the phases and the dualities can be studied in more detail.

5 Nature's magnifying glass playing tricks on a supernova — discovery of a galaxy serving as a gravitational lens —

A supernova appearing 30 times brighter than normal is found to have been magnified by a foreground galaxy acting as a gravitational lens.

6 T2K Experiment shows muon neutrinos transforming into electron neutrinos

Evidence of muon neutrino to electron neutrino transformation is captured for the first time by shooting muon neutrino to a detector 295 km away.

7 New theory suggests that dark matter behaves like Yukawa particle

New theory of SIMP (Strongly Interacting Massive Particle) as candidate of dark matter was proposed. SIMP has properties very similar to the pi meson, often called Yukawa particle.

8 Secondary polytopes and the algebra of the infrared

Mathematical theory of secondary polytopes proposed by Kapranov in 1990s can be used to explain the lower energy limit of physical theories.

Research Paper's Information

Number of Research Papers:	2440
Top 10% Papers:	27.0%
Top 1% Papers:	3.8%
Internationally Collaborative Research Papers:	66.5%

(Database: WoS 2007-2015)

Blackboard in Director Hitoshi Murayama's office at the Kavli IPMU

5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan
Phone : +81-4-7136-4940
Email : inquiry@ipmu.jp

Research Goals

What is the Universe made of? How did the Universe begin? What is the fate of the Universe? What are the rules governing the Universe? Why do humans exist in the Universe? These are the universal questions of mankind. Kavli IPMU is trying to uncover these mysteries of the Universe through the collaboration of mathematicians, physicists, and astronomers (Fig.1).

1 Subaru unravels the mystery of a star explosion observed by Tycho Brahe in the 16th Century

Ken'ichi Nomoto (PI)

An international team of astronomers, including Kavli IPMU, Max-Planck-Institute for Astronomy in Germany, and the National Astronomical Observatory of Japan, carried out spectroscopic analysis of light echoes observed by the Subaru Telescope around a supernova remnant. This analysis established that the light echoes are from the supernova originally seen in 1572 by Danish astronomer Tycho Brahe, and confirmed that it was a typical Type Ia supernova.

A "new star" observed by Tycho Brahe, teacher of Kepler, in detail in 1572 is considered as a supernova. The remains of the explosion are observable today and are referred to as Tycho's supernova remnant. However, the nature of the explosion has been a puzzle.

The international team observed a "dust cloud" about 3 degrees away from the direction of Tycho's supernova remnant using the Subaru Telescope. When the explosion occurred, the emitted light should have flown out in all directions. Some of the light would have traveled directly to Earth to be observed by Brahe 436 years ago. But astronomers have long hypothesized that some of the light may have reflected off nearby dust particles in dust clouds, delaying their observation on Earth. The "cloud" observed by the team precisely correspond to those "echoes" of light.

Nomoto's team also succeeded in analyzing the spectrum of the light echo, and confirmed that the supernova that Brahe had seen was a Type Ia supernova.

O. Krause et al.: Nature, 456, 617, 2008.

2 Galaxy cluster observation hints at cold dark matter evidence

Masahiro Takada (Professor)

An international team of researchers from Academia Sinica of Republic of China (Taiwan), the University of Birmingham, Kavli IPMU and Tohoku University used the Subaru Prime Focus Camera (Suprime-Cam) at the Subaru Telescope to collect observational data of 50 galaxy clusters, and successfully measured the mass density distribution of dark matter in the region of the galaxy clusters. By way of gravitational lensing effect,

Fig. 1. Group photo taken at the Kavli IPMU 9th Anniversary event (credit: Kavli IPMU).

the team determined the dark matter distribution, and found new evidence that it matched the prediction of the cold dark matter model (CDM).

CDM describes dark matter as particles that interact with each other and with other matter only via the force of gravity. Unlike other particles such as neutrinos, these particles have small thermal velocity, thus the name cold dark matter.

There are two quantities which characterize dark matter mass distribution. One is the total mass of dark matter contained in a galaxy cluster. The other is a concentration parameter, which describes how dark matter density changes from its dense center to its lower density edges. Even with galaxy clusters with the same amount of matter, those with the most matter at the center of its cluster will have a higher concentration parameter.

CDM is regarded as the most promising model of dark matter. Observations so far, however, have reported high concentrations of dark matter not compatible with CDM predictions.

According to the new results, the average mass distribution of dark matter has a conspicuous peak at the center, and is symmetrical. The observed mass distribution of the galaxy cluster is well aligned with the prediction of the cold dark matter model.

N. Okabe et al.: ApJL, 769 no.2, 35, 2013

3 Curve counting theories and derived categories

Yukinobu Toda (Associate Professor)

Superstring theory (Fig.2) is based on the idea that our Universe is made up of the familiar 4 dimensions of space and time, and extra dimensions, namely the minute 6-dimensional space. Researchers have wondered how many 2-dimensional curved surfaces exist on the 6-dimensional space. There may be an infinite number of curves, but if we specify the shape and volume, we can regard them as finite sets. It has been conjectured that a certain set of rules must exist that governs the numbers counting such curves. This is an interesting problem for both mathematicians and physicists.

Yukinobu Toda of Kavli IPMU successfully proved the regularity conjecture of the curve counting rule using an abstract notion of mathematics called derived categories.

A derived category can be thought of as a community of objects called sheaves. Derived categories were originally introduced from a technical motivation of pure mathematics, but they are now being studied for their insight into D-branes in superstring theory, and their effect on geometric properties.

Fig. 2. Superstring theory is a popular candidate which may connect the macro world described by Einstein's general theory of relativity, and the micro world described by quantum mechanics (illustration by Tomiyoshi Haruyama).

Using derived categories, it becomes possible to study some peculiar objects. Toda found it was possible to count the number of such objects, and that certain rules govern them. He also linked this 6-dimensional object with a 2-dimensional curved surface, and proved the existence of curve counting regularities.

Thanks to this result, Toda was invited to speak at the International Congress of Mathematicians in South Korea in 2014; they only meet once every four years.

Y.Toda: JAMS, 23 no.4, 1119, 2010

4 Discovery of new discrete parameters of gauge theories

Yuji Tachikawa (Professor)

The four fundamental interactions of nature are i) the electromagnetic force, ii) the force that binds quarks to make protons and neutrons, called the strong force, iii) the force responsible for radioactive decay, called the weak force, and iv) the force that keeps planets in orbit around the Sun, which is gravity. Gauge theories are used to describe the first three, and are specified by a few parameters, including the coupling constant specifying the strength and the theta angle related to its topology. The coupling constants and the theta angles have been known since the 1970s.

In 2013, Yuji Tachikawa at Kavli IPMU, Nathan Seiberg at the Institute for Advanced Study in Princeton, and Ofer Aharony at the Weizmann Institute of Science in Israel found and studied the effects of additional discrete parameters necessary to fully specify a gauge theory. Their research has incorporated the concept of topological phases, which is actively studied in condensed matter physics, into elementary particle theories. An interesting aspect of these works is that they use mathematical techniques already developed in the 1970s but not utilized in theoretical physics until very recently.

O. Aharony et al.: JHEP. 1308, 115, 2013

5 Nature's magnifying glass playing tricks on a supernova – Discovery of a galaxy serving as a gravitational lens

Robert Quimby (Visiting Scientist)

The research team led by Robert Quimby of Kavli IPMU has uncovered how a galaxy acted as a gravitational lens to magnify the brightness of a Type Ia supernova by 30 times (Fig. 3).

Through observations, the team discovered a galaxy located between the supernova, named PS1-10afx, and the Earth. The gravity of this galaxy caused a "gravitational lens effect" which collected light from the supernova, just like a magnifying glass, and this made PS1-10afx appear to shine much brighter than normal supernovae.

When PS1-10afx was first discovered in 2010, its color and light curve matched that of a typical Type Ia supernova, but its brightness was greater than normal. Thus scientists debated two interpretations:I. It was a new type of supernova; II. A gravitational lens was magnifying a Type Ia supernova to make it look brighter. The second interpretation was first suggested by Quimby and his team in 2013. The eventual discovery of the intervening galaxy strengthened this interpretation. It is also the first case documented that shows strong gravitational lensing having such an effect on a Type Ia supernova.

This discovery originated from a tea time discussion between Quimby, an astronomer, and a mathematician and a physicist as described below.

R.M.Quimby et al.: Science, 344(6182), 396, 2014

6 T2K Experiment shows muon neutrinos transforming into electron neutrinos

Mark Hartz (Project Assistant Professor), Mark Vagins (Professor)

The international T2K (Tokai to Kamioka) collaboration has made a definitive observation of muon neutrino to electron neutrino transformation. Their observation was the world first in which they were able to capture a neutrino with a unique flavor that started with a different flavor at its production point.

The T2K experiment (Fig. 4) involves the production of a muon neutrino beam at J-PARC (Japan Proton Accelerator Research Complex), located in Tokai village on the east coast of Japan. The beam is aimed at and detected in the gigantic Super-Kamiokande underground detector (Fig. 5) in Kamioka, 295 km (185 miles) west of Tokai. An analysis of the data from the Super-Kamiokande detector collected between January 2010 and April 2013 showed that, of 532 neutrino candidate events synchronized with the expected arrival time of the J-PARC beam, 28 events produced electrons, indicating the interaction of an electron neutrino. This proves that a fraction of the muon neutrinos in the beam transformed (oscillated) to electron neutrinos over the 295 km distance from Tokai to Kamioka.

Kavli IPMU joined the T2K collaboration in May 2013, which today includes Professor Mark Vagins and Project Assistant Professor Mark Hartz. Hartz has especially played a significant role in analyzing the neutrino oscillation data in this discovery.

T2K Collaboration: PRL, 112, 061802, 2014

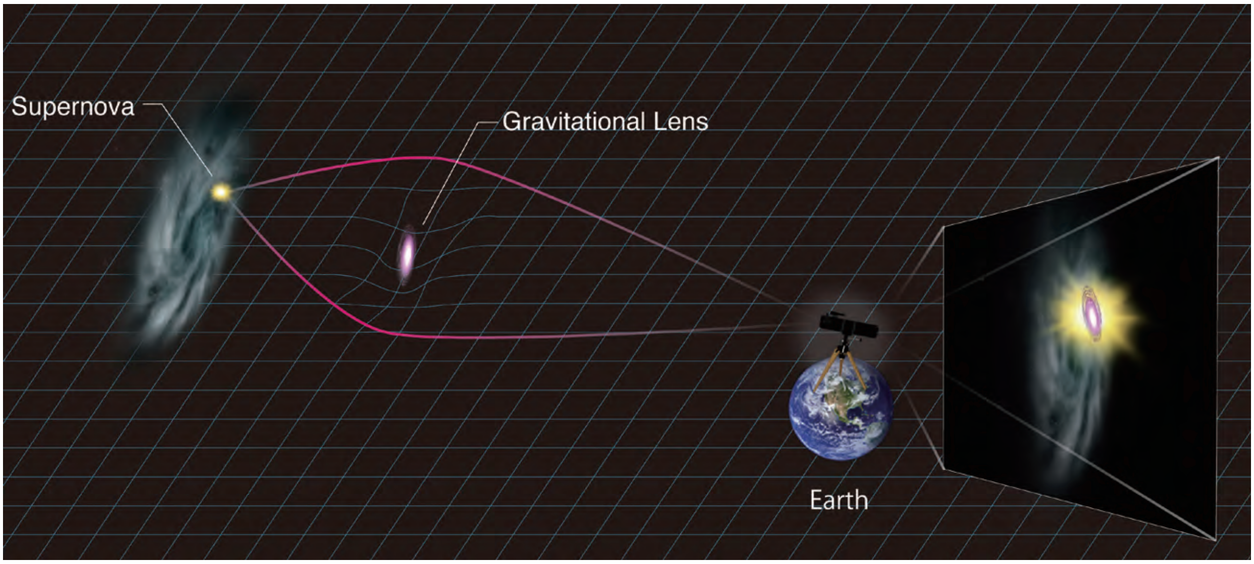


Fig. 3. The gravity of a galaxy situated between a supernova and Earth creates a magnifying glass that makes the supernova appear brighter.

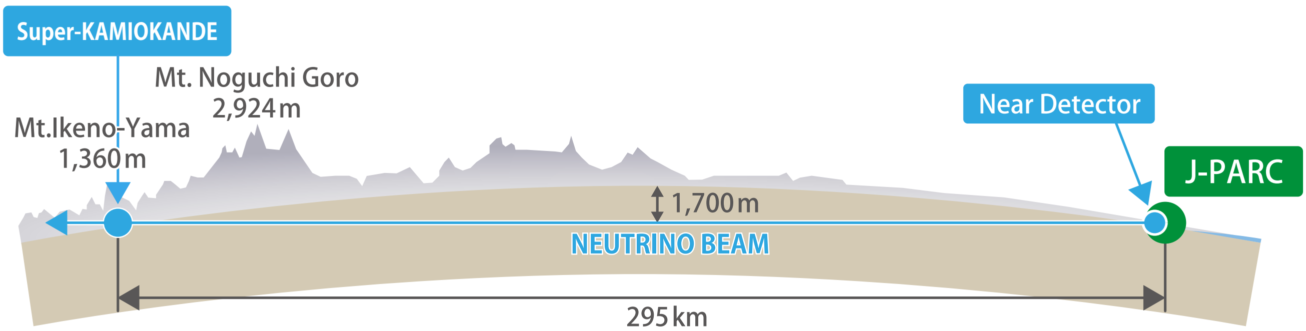


Fig. 4. T2K Experimental set up (diagram courtesy of the T2K Collaboration / KEK)

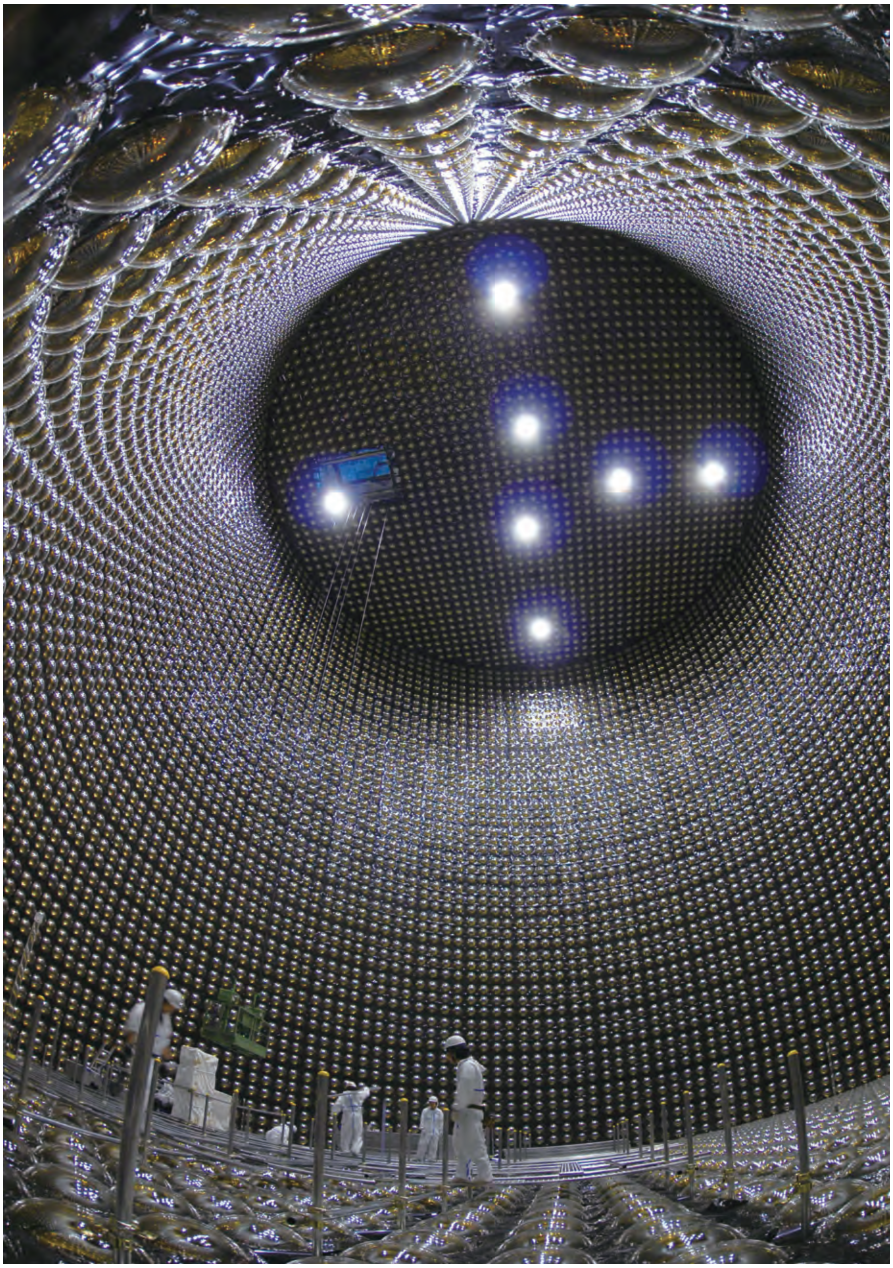
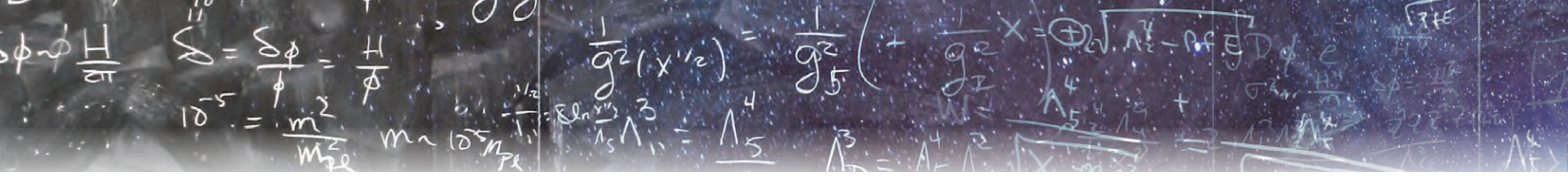


Fig. 5. Inside the Super-Kamiokande detector (Aug 2005 – July 2006). (Photo courtesy of Kamioka Observatory, Institute for Cosmic Ray Research, the University of Tokyo)



7 New theory suggests that dark matter behaves like Yukawa particle

Hitoshi Murayama (PI)

A new theory developed by a team including Director Hitoshi Murayama, Yonit Hochberg of the University of California, Berkeley, and others says that dark matter, which is supposed to occupy 80% of matter in the Universe, acts remarkably similar to the Yukawa particle, a subatomic particle named pi meson and first proposed by Japan’s first Nobel Laureate Hideki Yukawa in 1935.

Dark matter is the agent keeping galaxies, our solar system together. Yet no one has been able to observe it, and it has often been regarded as a totally new exotic form of matter with significantly different properties than particles scientists know about today, such as super-symmetric particles or a particle moving in extra dimensions of space beyond the four predicted by superstring theory.

However, Murayama and his team proposed that dark matter particles are SIMPs (Strongly Interacting Massive Particles), which are similar to pions (Fig. 6).

The properties of pion is precisely described by the concept of "spontaneously broken symmetry" which was proposed by 2008 Nobel Laureate Yoichiro Nambu in 1961. The new theory points out that the properties of Yukawa particles based on Nambu’s theory fit with those of dark matter. This theory also has deep connection with topology in mathematics.

Y. Hochberg et al.: PRL, 115, 021301, 2015

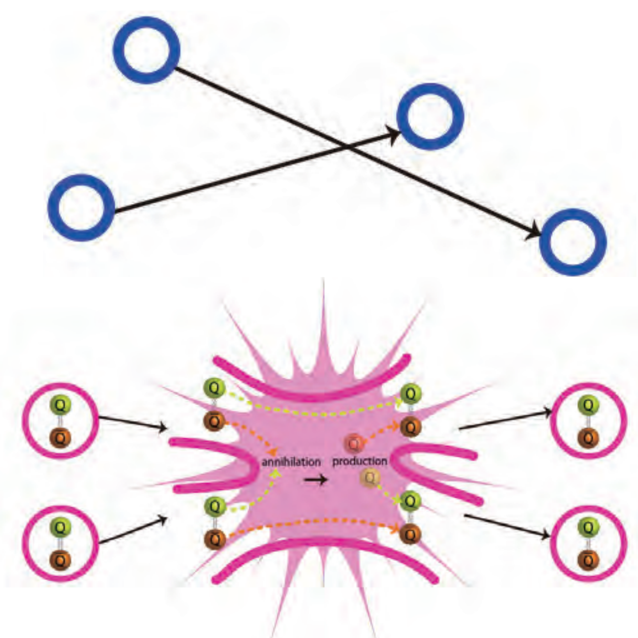


Fig. 6. The difference between dark matter as proposed by conventional theories (upper diagram) that assume dark matter particles pass through one another without affecting the other, and as SIMP (lower diagram) that assume dark matter particles act like pions and do interact with one another upon collision.

8 Secondary polytopes and the algebra of the infrared

Mikhail Kapranov (Professor)

Just as a circle is described by the equation $x^2 + y^2 = 1$, the study of figures given by polynomial equations is called algebraic geometry. On the other hand, geometry which deals with simpler shapes such as polygons, polyhedra and their triangulation is called combinatorial geometry.

By way of a method called tropical geometry, it is possible to obtain combinatorial geometric information from an algebraic geometry problem. Such relations were found by Kapranov et. al. in the study of secondary polytopes of higher dimensional hypergeometric differential equations.

In 2014, Kapranov et.al. found further that such secondary polytopes can be applied to the study of the infrared limit in quantum field theory, e.g., the description of a Lie algebra structure.

M. Kapranov et al.: arXiv: 1408.2673, 2016

Interdisciplinary research and internationalization

Kavli IPMU has a tea time. Every day at 3pm, researchers from different fields and projects take time to relax, and exchange ideas and stories during the tea time (Fig. 7). This, the institute believes, leads to better opportunities for making new discoveries.

A prime example is a tea time discussion between an astronomer, a physicist and a mathematician. Robert Quimby and his fellow researchers followed up by publishing a paper that provided a clear explanation to a recent mystery surrounding a supernova that had appeared 30 times brighter than normal.

In addition to tea time, Kavli IPMU offers a very international environment. As of March 2016, the institute has more than 150 full time researchers, staff and graduate students, as well as more than 100 affiliated researchers. Many of these faculty and postdocs come from overseas. The institute also hosts tens of international scientific meetings every year, attracting 800 visitors for seminars and research discussions annually, half of whom are visiting from overseas.

Kavli IPMU is operated according to international standards; postdoc recruitment is done at the same time as those institutions in the US and Europe; annual salaries are paid by year at the same level. These two factors make Kavli IPMU a competitive choice internationally.

Fig. 7. Tea time inside Kavli IPMU

Hitoshi Murayama speaks at UN Headquarters for Science for Peace and Development Today and Tomorrow

Director Hitoshi Murayama delivered a speech at the "Science for Peace and Development" held at the United Nations Economic Social Council in New York on 20 October 2014. The talk was part of a special event commemorating CERN's 60th anniversary: "CERN: Sixty Years of Science for Peace and Development – The role of science and scientific intergovernmental organizations in bringing people and cultures together," hosted by the United Nations Economic and Social Council, and jointly sponsored by the Permanent Representatives of France and Switzerland (Fig. 8).

Talking after Nobel Laureate Carlo Rubbia and the former Secretary General of United Nations Kofi Annan, Murayama emphasized the need to create places where people can share a common goal in pursuing science. He said this idea was the basis of Kavli IPMU, effectively making the institute known to a worldwide audience.

To read the full speech (English) go to:
http://www.ipmu.jp/en/node/2050

Marina Komori (Kavli IPMU),
Motoko Kakubayashi (Kavli IPMU)

Fig. 8. Director Hitoshi Murayama giving a speech at the UN (photo courtesy of UN Photo / Evan Schneider)