

Yukawa Institute for Theoretical Physics

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Fig. 1: Hideki Yukawa (at the center, front row). A picture taken in 1954 at the entrance of the Yukawa Hall.

HISTORY

The history of the Yukawa Institute for Theoretical Physics goes back to 1949 when Hideki Yukawa of Kyoto University was awarded the Nobel Prize. To commemorate this historic event, the president of Kyoto University immediately proposed the creation of a memorial hall at the campus. In 1950, the Science Council of Japan unanimously resolved a request to the central government to allocate special funding for the promotion of research in theoretical physics. Enthusiastic discussions among physicists from all over the country followed in support of the idea of creating a new institution, similar to the Niels Bohr Institute in Copenhagen or the Institute for Advanced Study in Princeton.

Yukawa Hall was inaugurated in 1952 and in the following year (1953) it became the Research Institute for Fun-

damental Physics (RIFP). Yukawa was appointed as the first director of the institute and led the institute until his retirement in 1970.

RIFP was a new type of national research center for theoretical physics, with its facilities available for open use for research collaborations by the entire community of theoretical physicists in Japan. The institute adopted a new system for its operation: although it formally belongs to Kyoto University, its basic policy was - and still is - discussed and decided by the representatives of physicists elected from all over the country together with the institute's own academic staff members.

The institute started with four academic staff members, including Yukawa himself. The size of the institute has

gradually grown. A major expansion of the institute took place in 1990 when it was joined by all academic staff members of the Research Institute for Theoretical Physics (RITP) of Hiroshima University, which was founded in 1944 by Yoshitaka Mimura for the research of the mathematical foundations of theoretical physics. The current English name, the Yukawa Institute for Theoretical Physics (YITP), was adopted at the time of the unification of the two institutes.

The institute was located in two campuses in Kitashirakawa and Uji for a while after the unification. In 1995, a new building was completed next to Yukawa Hall and since then the institute has been centralized in one place. Thanks to donations from Panasonic Corporation, Panasonic Auditorium was constructed inside Yukawa Hall in April 2008. Panasonic Auditorium serves as a main venue for workshops, seminars, and conferences hosted by the institute.

In 2008, Toshihide Maskawa, a professor emeritus and former director of the institute, was awarded the Nobel Prize in physics, being the second Nobel laureate from YITP.

SCIENTIFIC ACTIVITIES

High Energy Physics

The goal of high energy physics is to elucidate the basic constituents of matters and the laws that govern their dynamics. The High Energy Physics Group aims to understand the fundamental laws of nature realized in mi-

croscopic scales. The members of the group are working on the following themes:

Superstring Theory

The most fundamental building blocks of the world might be spatially extended objects, such as strings. Superstring theory emerged from this simple idea. It is now known that superstring theory can describe all the particles and their interactions (electromagnetic, weak, strong and gravitational) in a unified manner. We study ten-dimensional superstring theory and its eleven-dimensional extension called M-theory through various approaches, such as low energy effective supergravity and string field theory. Recent studies of string theory and quantum field theory revealed surprising correspondences, called duality, between two seemingly different physical systems. AdS/CFT correspondence is one of the most important examples of duality. It has wide applications not only to elementary particle physics but also to nuclear theory, condensed matter and black holes.

Quantum Gravity

While general relativity was a great success as a classical theory of gravity, it has not yet been formulated in a manner compatible with quantum mechanics. There are various approaches to quantum gravity; e.g. string theory and other approaches in which space-time itself is regarded as a dynamical object. Consistent quantum gravity is necessary for understanding strongly gravitating systems such as the creation of the universe or black holes, and it may lead us to a new picture of the universe.

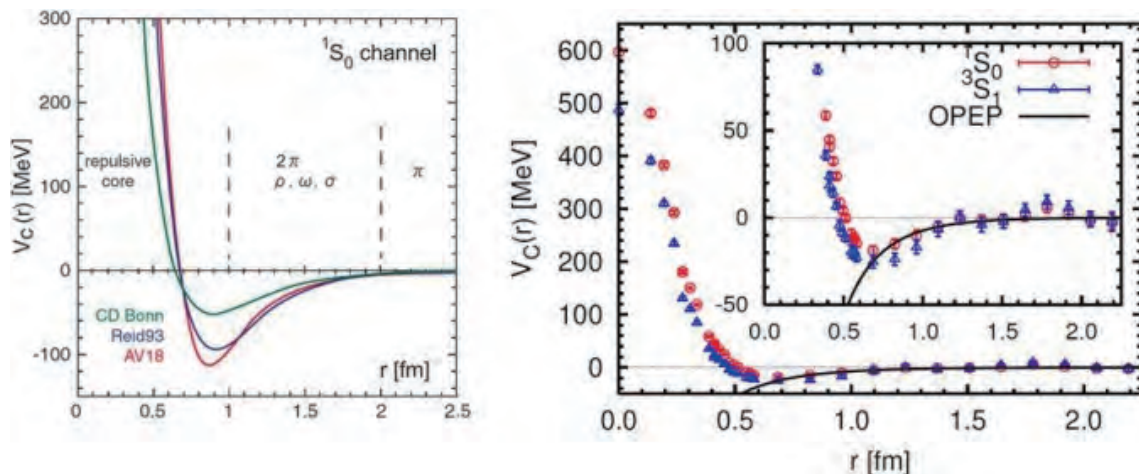


Fig. 2: Examples of phenomenological nuclear potential (left) and the lattice QCD result of nuclear potential (right). (Ishii, Aoki, Hatsuda 2007).

Non-perturbative Quantum Field Theory

Quantum field theory, a framework for representing the behavior of elementary particles, is formulated as quantum mechanics with an infinite number of degrees of freedom. In a weak coupling regime, perturbative treatment works well, but numerical analysis based on lattice gauge theory defined on the discretized lattice proves especially effective in situations that investigate strong coupling quantum field theory, like QCD describing the dynamics of quarks and gluons. Lattice QCD with Monte Carlo simulations enable us to compute, for example, masses of hadrons. In addition, it has recently become possible to compute hadron-hadron interactions like the nuclear force acting between a proton and a neutron, which Hideki Yukawa succeeded in explaining by introducing the pion. Such numerical methods are beginning to be used to analyze non-perturbative properties of superstrings, while many attempts are also being made to examine various non-perturbative aspects of quantum field theory by investigating supersymmetric gauge theory.

Particle Phenomenology

Particle phenomenology is a bottom-up approach to investigate new physics beyond the standard model based on experimental and/or observational results. In high-energy experimental physics, the latest major breakthrough is the discovery of Higgs boson by the Large Hadron Collider (LHC) at CERN. We also expect to discover new particles in the next generation collider, and we expect to be able to verify more precise properties of the Higgs boson. In addition, a wide variety of experiments and observations, including high energy cosmic ray observations, the searches for dark matter and the precise measurements of the cosmic microwave background, are now in progress. We are attempting to check the consistency between existing models and new results and also to construct new consistent models.

Nuclear Theory Group

The Nuclear Theory Group studies various aspects of quark-hadron-nuclear systems interacting via “strong interactions”, widely extending from quarks and gluons, and hadrons such as mesons and nucleons, to nuclei made of nucleons and hyperons. In order to study these systems belonging to different hierarchies, we utilize various theoretical techniques in physics — quantum mechanics, relativity, field theories, and many-body theories. The main subjects discussed in the nuclear theory group at present include the structure and dynamics of nuclei

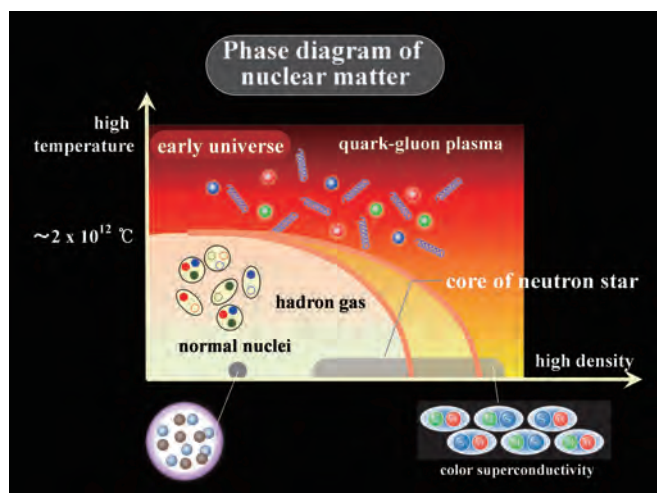


Fig. 3: A schematic view of the phase structure of nuclear matter.

and hadrons, and hadronic and quark matter under extreme conditions. These are closely related to particle physics, astrophysical phenomena, condensed matter theories as well as to recent accelerator experiments in the world.

Nuclear Many-Body Physics

Nuclei have various complicated structures and excitation modes as quantum mechanical many-body systems. The primary goal of this area is to elucidate and predict the evolution of nuclear properties as functions of proton and neutron numbers; i.e., nuclear shape, density and mass of the ground and excited states, and the structure of excited level spectrum. Novel properties and formation mechanisms of super heavy elements, which do not exist in nature, are also themes of great interest.

Quark-Hadron Many-Body Physics

Quarks and gluons, strongly interacting fundamental particles, are confined inside hadrons at low temperatures and densities, while hadronic matter undergoes phase transitions to deconfined quark-gluon matter under extreme conditions such as the early universe, neutron star cores and relativistic heavy-ion collisions. We are studying in-medium properties of quark and hadrons to reveal the phase structure of quark, hadronic and nuclear matter. Hadronic resonance states are also important research targets to understand hadronic dynamics.

Condensed Matter Physics Group

All matter is an aggregate of numerous particles interacting with each other in various manners. The Condensed

Matter Physics Group aims at elucidating the complex dynamics and the states that are uniquely observed in many-body systems. Furthermore, it aims to elucidate the mode of material movement and the dynamic changes in phase structure in non-equilibrium open systems, including biological systems.

Solid State Physics

The subject of condensed-matter physics is how matter behaves at low temperatures where the quantum nature of particles becomes manifest. Electrons are correlated with each other through electromagnetic interaction and at the same time each electron obeys the so-called Fermi statistics, which is purely quantum in its origin. As a consequence of the interplay among these two and other factors, matter shows a variety of phases, e.g. metallic, insulating, magnetic, and superconducting ones. With the help of field theories and large-scale numerical simulations, we study low-energy dynamics of internal degrees of freedom carried by electrons in various phases of strongly correlated electron systems, quantum phenomena found in low-dimensional magnets and frustrated spin systems, mechanisms of high-temperature superconductivity, and super-fluidity in ultracold atoms.

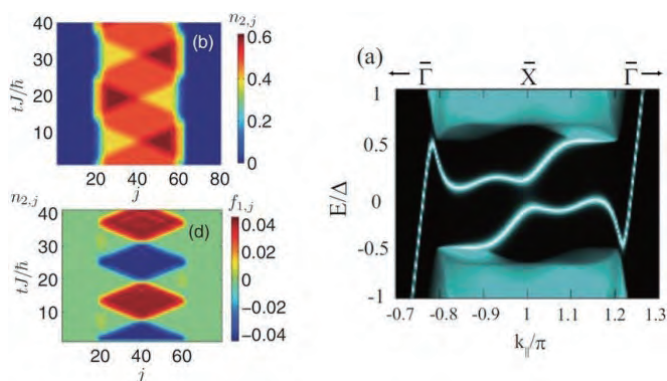


Fig. 4: Examples of counterflow superfluidity in ultracold atom systems (left) and the surface spectral function of a topological crystalline insulator (right). (Hu, Mathey, Tiesinga, Danshita, Williams, Clark 2011 and Hashimoto, Yada, Sato, Tanaka 2015, respectively)

Advanced Statistical Dynamics

Various structures having dynamical orders and functions appear in systems far from equilibrium. We study a fundamental principle to characterize such dynamical processes. In particular, we are interested in rheology and transport processes, and dynamical phase transitions of non-equilibrium systems. In addition, we also study uncertainty relations and quantum feedback controls in

terms of information gain by quantum measurements, biomechanics to describe the motion of biological elements, and various aspects of living systems including evolution and the emergent processes.

Astrophysics and Cosmology

The Astrophysics and Cosmology Group studies cosmological and astrophysical systems under extreme conditions.

Cosmology and the Theory of Gravity

Recent cosmological observations have established the standard model of the history of the Universe. However, the model contains several ingredients that need further explanation, e.g., dark energy, dark matter, cosmic inflation, etc. We aim to narrow down the possible models of inflation by constructing a model based on particle physics and extracting its observational signatures such as non-Gaussianity or primordial gravitational waves. We are also developing methods for cosmological perturbations and structure formation in order to extract information on the early universe from observational data of the large-scale galaxy distribution and the cosmic microwave background. We are also studying modified gravity to solve the cosmological constant problem and to understand gravity in a consistent manner with quantum mechanics.

Gravitational Wave Physics

On September 14, 2015, Advanced LIGO succeeded in the first direct detection of gravitational waves emitted from the merger of binary black holes. For reliable and efficient detection of gravitational waves, accurate theoretical prediction of the waveform is necessary. In order to predict the waveform, we need to solve Einstein's equations accurately. We are investigating the motions of gravitational wave sources and the emitted gravitational waves by means of various methods including numerical relativity techniques. The electro-magnetic counterparts of the gravitational wave sources are also in the scope of our study.

High Energy Astrophysics

The Universe provides extreme conditions such as high energy, strong gravity, high density and strong magnetic fields, which are not reachable by any terrestrial experiments, and it is very interesting to observe high-energy astrophysical phenomena as such. The 21st century is a multi-messenger era as we use gravitational waves,

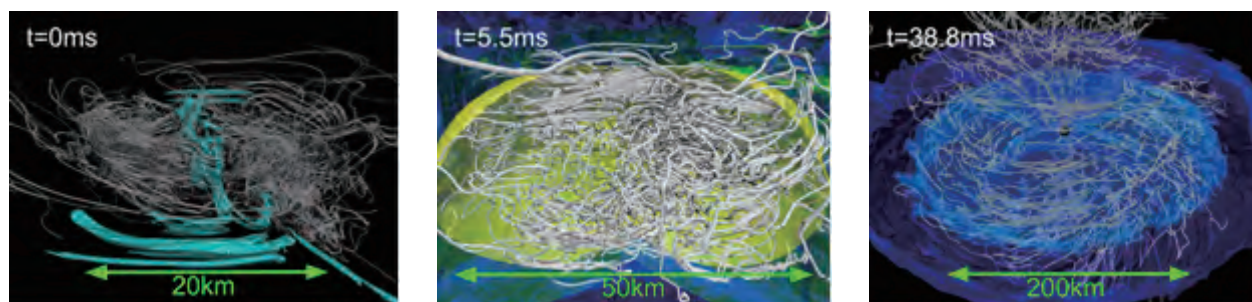


Fig. 5: Results of a numerical simulation of a neutron star merger, which show the birth of a black hole, an accretion disk, and the magnetosphere of the black hole (Kiuchi, Kyutoku, Sekiguchi, Shibata and Wada 2014).

neutrinos and cosmic rays, in addition to photons to observe the Universe. We are studying various theoretical topics of high-energy astrophysics, such as the most violent transients, particularly supernova explosions and gamma-ray bursts, accretion disk-magnetosphere-jet systems of compact objects like black holes and pulsars, and multi-messenger emissions from these objects.

Numerical Simulations

Most astrophysical and astronomical phenomena are nonlinear systems, in which gravity, hydrodynamics, and radiative transport play important roles. Numerical simulations are necessary to make quantitative predictions on such phenomena. We perform research using such numerical simulations. Using numerical relativity, we study neutron star binary mergers and black holes and accretion disks formation processes from gravitational collapses of massive stars. We also study super novae explosion processes using radiative transfer simulations.

YITP PROGRAMS

Since its foundation in 1953, YITP has played a role not only domestically but also internationally as a hub for the research community. The following sections show some examples of the projects/programs that we have been running.

Workshops selected from a nationwide contest

We host about 30 workshops every year which are selected from applications by researchers in Japan who wish to hold and organize workshops. These workshops have played a role of the center for research communication. The number and the size of the workshops held in recent five years are summarized in Table I.

Fiscal Year	Workshops	Participants
2015	28	2,819
2014	23	2,481
2013	31	3,332
2012	28	3,182
2011	33	2,789

Table 1: The number of workshops and total participants for five fiscal years (2011-2015).

Yukawa International Program for Quark-hadron Sciences (YIPQS)

In 2007, we started a new project, the “Yukawa International Program of Quark-Hadron Sciences (YIPQS)”, which is funded by the Japan Ministry of Education, Culture, Sports, Science and Technology. In this project we select research topics each year for long-term workshops and invite leading experts from abroad to stimulate discussion and to foster collaborations among workshop participants. At present, the topics covered include not only quark-hadron sciences but also related subjects such as string theory, condensed matter physics, cosmology, etc. A number of internationally renowned scientists have participated in the workshops, and have actively interacted with each other during the workshops, which has led to scientific achievements with high impact. The following list shows the titles and the number of participants in three long-term workshops held recently:

“Nuclear Physics, Compact Stars, and Compact Star Mergers 2016”, October 17-November 18, 2016: 140 participants (61 from abroad).



Fig. 6: A group photo from “Quantum Information in String Theory and Many-body Systems”.

“Quantum Information in String Theory and Many-body Systems”, May 23-June 24, 2016:
277 participants (128 from abroad).

“Computational Advances in Nuclear and Hadron Physics”, September 21-Oct 30, 2015:
124 participants (55 from abroad).

In addition to the long-term workshops, many “molecule-type” workshops are held every year under the YIPQS program, which are meant to encourage deep and intensive discussions for a specific theme among selected experts.

Yukawa International Seminars (YKIS)

In 1978, the institute started to host the Kyoto Summer Institute as a series of international research seminars. This series was renamed and became the Yukawa International Seminars (YKIS). Table II shows a list of five recent YKIS conferences.

Other Programs

In addition to the above programs, we have financially supported regional schools and summer schools, which play an important role in training young researchers. We have also accepted many visitors for long (i.e., several months) and short (i.e., several weeks) terms. In 2015, for example, we had 19 short-term and five long-term visitors.

International Research Unit of Advanced Future Studies (IRU-AFS)

The International Research Unit of Advanced Future Studies was established on July 28, 2015, in collaboration with 12 (now 13) Kyoto University research organizations. Its vision is to use multi-disciplinary integration to realize paradigm shifts in the exploration of universal laws and emerging principles governing living organisms, materials, the mind, human societies, education and economics.

Year	Title
YKIS2016	Quantum Matter, Spacetime and Information
YKIS2015	New Frontiers in Non-equilibrium Statistical Physics 2015
YKIS2014	Nonequilibrium Phenomena in Novel Quantum States
YKIS2013	Gravitational Waves -Revolution in Astronomy and Astrophysics
YKIS2012	From Gravity to Strong Coupling Physics

Table 2: Titles of five recent YKIS international conferences.

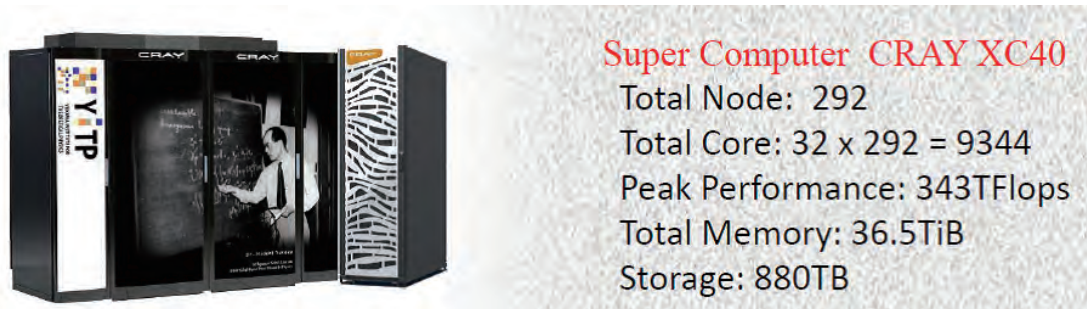


Fig. 7: CRAY XC40.

The Center for Gravitational Physics

The Center for Gravitational Physics was established on April 1, 2016 at YITP. With the first detection of gravitational waves by Advanced LIGO on September 14, 2015, we are now at the dawn of gravitational-wave astronomy. The purpose of this center is to stimulate various fields in theoretical physics with new perspectives, with “gravity” as the keyword, and to establish an international center for gravitational physics in a wider sense through collaborations with researchers and institutions from all over the world.

COMPUTING FACILITIES

Our large-scale computer system, which was replaced in January 2016, is used not only by institute members and

visitors but also by other theoretical physicists in Japan remotely. At present, more than 600 users have accounts. Our computer systems consist of a super computer (Cray XC40), a numerical calculation server, a visualization server, a fileserver, a web server and a mail server. We are participating in the Japan Lattice Data Grid (JLDG). JLDG is the network of the lattice QCD collaboration in Japan, using supercomputers installed at distant sites, and managing and sharing daily research data. JLDG contributes to the secure management of important research data and also its effective utilization.

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Masatoshi Murase is the editor-in-chief of the *Journal of Integrated Creative Studies* (ISSN: 2424-0370), and is an associate professor at the Yukawa Institute for Theoretical Physics at Kyoto University. He is also director of the Research Promotion Strategy Office at the International Research Unit of Advanced Future Studies of Kyoto University. He received a PhD from the University of Tokyo in 1987. Positions held overseas include work as a postdoctoral fellow in the Department of Physiology at Duke University Medical Center (1987-1988), and as a visiting associate professor in the Department of Mathematics at the University of California, Davis (1990-1991). His research topics are meta-biology, theoretical biology and the theory of aging.