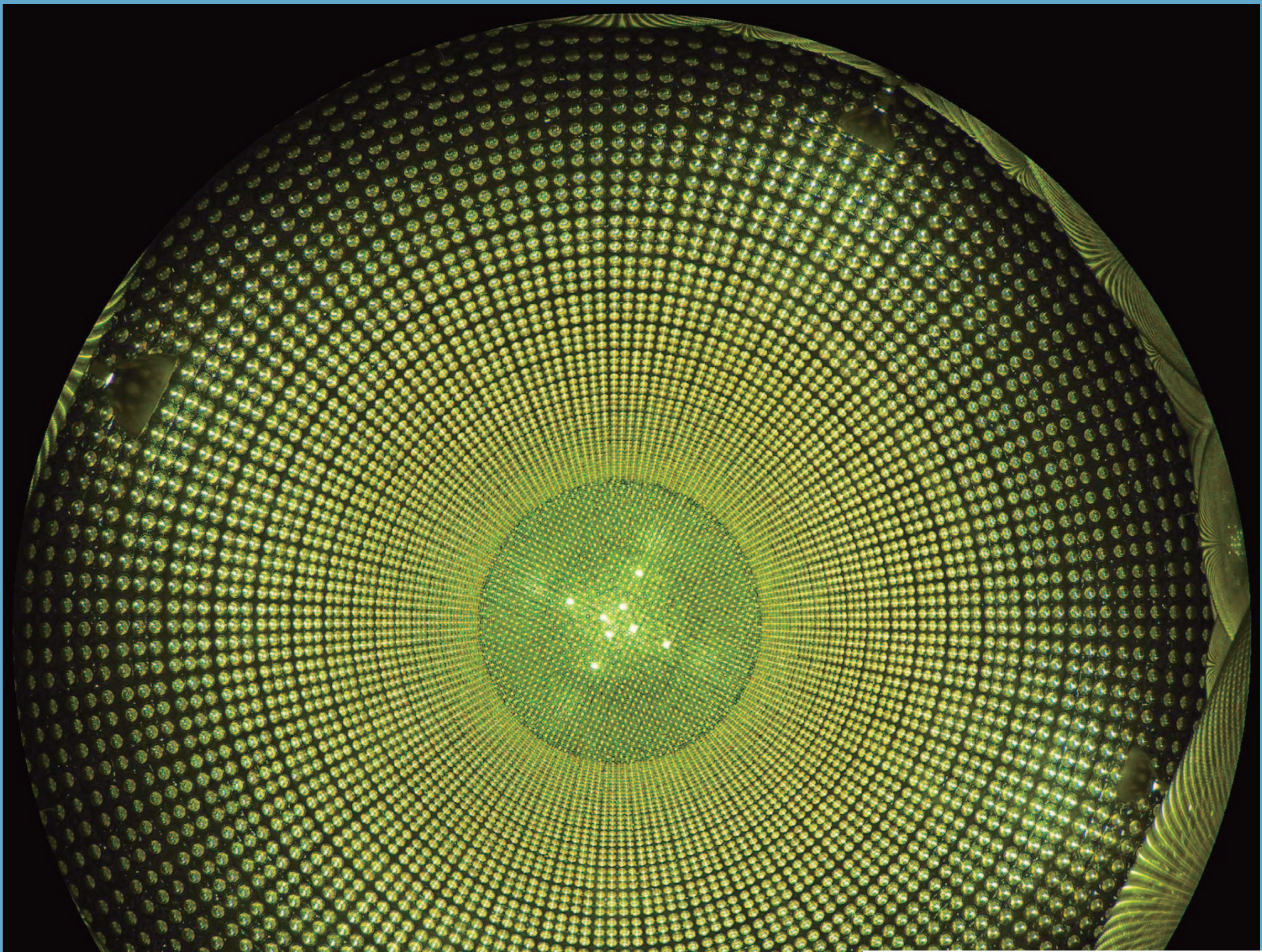

April 2020–March 2021

Kavli IPMU

ANNUAL REPORT 2020

THE UNIVERSITY OF TOKYO

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

UTIAS
東京大学国際高等研究所
THE UNIVERSITY OF TOKYO
INSTITUTES FOR ADVANCED STUDY

wpi World Premier International Research Center Initiative

KAVLI IPMU

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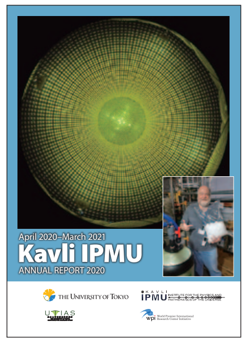


On the cover:
Looking directly down into the Super-Kamiokande detector after it was drained in preparation for loading with gadolinium. Inset: Kavli IPMU Professor and PI Mark Vagins holds a bag of gadolinium sulfate octahydrate in the EGADS laboratory of the Kamioka Observatory (Credits: Mark Vagins, Kai Martens).

FOREWORD

Hirosi Ooguri
Director

Though the COVID-19 pandemic continues to pose challenges to all of us, as I write this preface, we are beginning to see the light at the end of the tunnel thanks in part by the rapid rollout of the mRNA vaccine. As Anthony Fauci, the Chief Medical Advisor to the President of the United States, so eloquently wrote in his editorial article published in *Science* entitled "The story behind COVID-19 vaccines" [1], the success of the mRNA vaccine powerfully demonstrates the importance of long-term investments in basic science research. Here is what he wrote at the end of the article: "The speed and efficiency with which these highly efficacious vaccines were developed and their potential for saving millions of lives are due to an extraordinary multidisciplinary effort involving basic, preclinical, and clinical science that had been under way—out of the spotlight—for decades before the unfolding of the COVID-19 pandemic. When the stories and recounting of this pandemic are written, it is important that this history not be forgotten, as we are reminded once again of the societal value of a sustained and robust support of our scientific enterprise." Though we cannot foresee which basic research will benefit the humanity decades from now, the history tells us that supporting a broad range of research driven by the curiosity of researchers is the best investment strategy.

This Annual Report covers the period from April 2020 to March 2021. Our Long-Term Strategic Planning Report in 2019 identifies astrophysics surveys, cosmic microwave background (CMB) experiments, and Kamioka underground experiments as our three priority areas. I am pleased that our projects in these areas are making significant progress even during the pandemic, as you will see in Section 5 of this Annual Report. The Planning Report also recommended two new initiatives. One is the applications of X-ray and gamma-ray imaging techniques developed in astrophysics to medicine, in particular imaging of cancer stem cells in vivo. This project is in collaboration with the JAXA Institute of Space and Astronautical Science, the National Cancer Center, and the Institute for Advanced Medical Research at Keio University. Another is to develop new concepts in table-top experiments to explore the dark sector of the universe. Our scientists in this area collaborate with the optical lattice clock project led by Hidetoshi Katori in the Department of Applied Physics of the University of Tokyo. The 2019 Long-Term Strategic Planning Report will guide us in the coming years, when we make a transition from an institute with a fixed-term funding from the WPI program to a permanent institute with stable funding.

Talking about our transition to a permanent institute, we heard wonderful news in March 2021 that the University of Tokyo approved our proposal to place the university funding for the Kavli IPMU in the "core expenses" category, at about one billion yen per year. Being part of the core expenses category means that this funding is secure and permanent. Together with the income from the Kavli IPMU endowment established in 2012 and more than doubled in 2020, and with other fruits of our fundraising from both private and government sources, we will be able to operate at our current high level of research, perpetually. Section 5 of this Annual Report describes a variety of research projects conducted at the Kavli IPMU.

In my inaugural address as the Director of the Kavli IPMU in October 2018, I stated my commitment to provide an inclusive and supportive environment to the diverse group of people in our community. Following up on this promise, we are launching the Kavli IPMU Diversity Initiative in the 2021 – 2022 academic year. I plan to write about these in the next year's Annual Report.

I hope you will enjoy this report.

Hirosi Ooguri

Reference:

[1] A. S. Fauci, Science 372, 6538 (2021) 109

1

INTRODUCTION

FY2020 is the fourth year from the five-year extension period of the WPI funding. We have proposed the following nine challenges for the extension period addressing new objectives. Below are summaries of our effort to meet each challenge.

1. Creating new areas and tools of statistics, integrating mathematics with observation and experiments

A team led by N. Yoshida has developed machine-learning-based data analysis tools for Subaru Hyper Suprime-Cam Sky Survey (HSC Survey hereafter) and the Tomo-e Gozen project. They use the big astronomical data from HSC Survey to (1) detect and classify transient objects such as supernovae, and (2) reconstruct the large-scale matter distribution in the universe. For their objective (1), they have developed a multi-label classifier that automatically identifies and classifies astronomical transients into multiple types including the most important Type Ia supernovae. They have also tested several methods to detect transients from multi-petabyte movie data to be delivered by Tomo-e Gozen. For their objective (2), they have proposed a sparsity-based model to reconstruct a three-dimensional density field from HSC weak lensing data. Both the methods have been successfully applied to HSC data. In particular, their transient classifier achieved 95.3% accuracy for the three-class supernova classification.

2. Creating new synergies among fields not imagined at the launch

The team led by T. Takahashi has been organizing interdisciplinary activities to develop advanced detectors which could meet the needs in the field of nuclear medicine. They have established a network with researchers from the National Cancer Center, the Department of Medicine at Keio University, the Department of Medicine at Osaka University, RIKEN, and the Centre for Advanced Imaging at The University of Queensland. Under this network, they have started various bio-medical imaging experiments by using the imaging system developed at the Kavli IPMU. In 2020, they have performed various kinds of in vivo imaging experiments using a short-lived radionuclide, ^{211}At, with phantoms and tumor-bearing mice. The aim was to establish a detector that can use for the evaluation of in vivo biodistribution and dosimetry of therapeutics containing alpha particle emitting radionuclides. To study their pharmacokinetics of low concentrations, two systems, one is based on the multi-pinhole imaging system and the other is based on a parallel collimator, were used. Both detectors have a high energy resolution of ΔE=1-2 keV (FWHM), which is required to resolve multiple characteristic X-rays emitted from the decay of the radionuclide. They have succeeded to demonstrate the performance to isolate and identify all signals from multiple radionuclides, including the scattering component in the target.

3. Discovering new major frameworks for geometric thinking in mathematics and physics with the derived and noncommutative geometry, such as to unify various types of dualities

Noncommutative and derived geometry are powerful tools that allow us to enrich various familiar spaces in geometry to more sophisticated objects for which the functions may not commute, property motivated by quantum mechanics, or be equipped with a cohomological differential structure analogous to a supercharge in physics. Such enrichments can be defined in a purely mathematical fashion and turned out to be very useful in applications both to pure mathematics and to mathematical physics. Further, the study of derived categories of coherent sheaves combines both noncommutative and cohomological methods. In the derived geometry direction, Y. Toda introduced a new concept of d-critical (i.e., derived critical) loci. This allowed him to extend several fundamental results of birational geometry (such as wall-crossing equivalences) to a broad class of derived moduli spaces important in physics. One of the tools to study wall-crossing has been the cohomological Hall algebra (COHA) but its precise definition was restricted to quiver-like situations. M. Kapranov and E. Vasserot provided a definition and a study of COHA for algebraic surfaces, based on ideas of derived geometry. A little later, F. Sala and M. Porta gave a direct definition of the K-theoretical version, using derived moduli spaces. This work has a substantial following, including the work of Y. Toda on categorical refinement of Donaldson-Thomas invariants. Derived categories of coherent sheaves play a central role in mirror symmetry. A. Bondal, M. Kapranov and V. Schechtman interpreted the flop behavior of derived categories in terms of perverse schobers which are categorical analogs of perverse sheaves introduced by M. Kapranov and V. Schechtman earlier. Further, W. Donovan and T. Kuwagaki extended homological mirror symmetry to a certain class of perverse schobers. Working with Y. Soibelman and L. Soukhanov, M. Kapranov interpreted the Algebra of the Infrared of Gaiotto-Moore Witten in terms of Fourier transform of perverse schobers.

4. Executing projects successfully to produce world-competitive results on dark energy, dark matter, and inflation

LiteBIRD is in the concept design phase and the team successfully pushed the projects forward under the new standard. The international partners, including CNES from France and ASI from Italy, have started their Phase-A. The US team is supported by the NASA Technology development funding. Progress on various science and technological fronts has been shared over online meetings. Even with limited access to the lab, the LiteBIRD team presented 13 instrumental development-related presentations and proceedings (4 are from Kavli IPMU lead projects) at the online SPIE conference 2020. In relation to the demanding calibration requirement to the polarization angle, Y. Minami and E. Komatsu have developed the technique to extract both the cosmological birefringent rotational angle and the instrumental angle offset simultaneously.

The HSC papers published in PASJ received a lot of attention from the community, and contributed to the highest impact factor PASJ has ever achieved. The HSC cosmology paper from the cosmic weak lensing power spectra was awarded the 2020 PASJ excellent paper award. Our particle physicists and cosmologists proposed a scenario that primordial black holes (PBHs) were produced by nucleation of false vacuum bubbles during inflation. They showed that the multiverse PBH scenario can explain the total amount of dark matter and the possible event of PBH microlensing observed in HSC data. This work benefits from the synergy of a wide range of expertise available at the Kavli IPMU.

The instrumentation of PFS is in the phase to actively integrate and test the hardware and software of the subsystems. In Sep 2020, all 2394 "Cobra" robotic fiber positioners were fully installed over the focal plane of Prime Focus Instrument (PFI). The first fiber cable connecting PFI and Spectrograph System was delivered to Subaru and was successfully installed in Feb. 2021. The PFS team managed to install a dedicated little telescope system on the Subaru Telescope that feeds light from the sky to the PFS fiber cable and the spectrograph module. They plan to start on-sky engineering observations from fall 2021. In parallel to these instrumentation activities, the PFS science working group, led by the co-chairs M. Takada and R. Ellis (UCL), has been working on the PFS SSP survey design and feasibility studies in three scientific themes: cosmology, Galactic archaeology and galaxy evolution.

In April 2020, T2K published results on the measurement of the parameter that governs CP violation in neutrino oscillations in the journal Nature of which the corresponding author is M. Hartz. The measurement shows a preference for significant CP violation, although additional data will be necessary to exclude CP conservation and precisely measure the parameter. The paper was closely followed by the presentation of new T2K oscillation measurement results at the Neutrino 2020 with data collected through the beginning of 2020. This year also saw the addition of gadolinium (Gd) sulphate to the SK detector. After ten years of large-scale R&D studies on Gd in the 200-ton EGADS water Cherenkov detector located in the Kamioka mine, which is led by M. Vagins, the first batch of ultra-pure gadolinium sulfate octahydrate was dissolved in the 50 kilotons of water inside SK. The Gd ions now present in the detector allow us to easily observe and record approximately 50% of the previously invisible neutrons generated by various physics processes involving neutrinos, muons, and radioactive decays. While the J-PARC accelerator will soon go into a long shutdown for upgrades, T2K is collecting data in March and April of 2021 in order to have the first accelerator neutrino data with Gd in SK.

The Hyper-K project looks forward beyond T2K to make precision neutrino oscillation measurements, including CP violation, nucleon decay searches and supernova neutrino detection among a broad physics program. With the approval of the Hyper-K project in 2020, construction has begun, starting with the entrance yard to the mine where Hyper-K will be located. M. Hartz, is leading the Intermediate Water Cherenkov Detector (IWCD) effort within Hyper-K. The IWCD will be a kiloton scale water Cherenkov Detector located within 1km of the neutrino source at J-PARC in order to make precise measurements of neutrino-nucleus scattering necessary to reduce systematic uncertainties for Hyper-K. In 2020, the IWCD effort has focussed on internal documentation and review of the IWCD, with the preparation of a technical design report, and presentations at Hyper-K Project Advisory Committee meetings.

The XENON collaboration is currently in the process of commissioning the XENONnT detector, an upgrade of the XENON1T detector at the Laboratori Nazionali del Gran Sasso in Italy. They expect to start a first science data run shortly with the upgraded detector, which contains over 8 tons of liquid xenon, out of which about 4 tons constitute the target mass. The collaboration's ambition to directly detect dark matter particles has uncovered an intriguing excess of low-energy electron recoil events in its XENON1T data. Studying this excess under the significantly improved conditions that the upgraded detector offers has become another important goal for XENONnT's upcoming first science data run.

Upon the start of the Belle II data taking, the Kavli IPMU team converted its role to Belle II data analysis. They used 2019 and 2020 for analysis-tool development and detector-signal calibration for their use for all the future CP-asymmetry measurements and publications with the Belle II dataset. The results of the calibration were published. They will publish physics results with the tools and calibrated results from 2021, starting with the measurements of the B-meson lifetime, B^0-$\bar{B}^0$ mixing parameter followed by the CP-asymmetry measurement in the $B^0 \rightarrow J/\psi K^0$ decay. In parallel to the Belle II data analysis, they searched for new physics with the full Belle dataset, which is seven times larger in size than the current Belle II. The CP asymmetry was consistent with the Standard Model prediction, and they concluded no evidence for new physics there. They are finalizing the measurement of the CP-violating phase φ_2 and the search for an invisible gauge boson Z'.

5. Attracting and retaining the best and broadly minded scientists from around the world

From the developing stage, we had a firm belief that the key to gaining international recognition is to bring together top-level leaders and talented young researchers worldwide, and create an environment where researchers in different fields learn each other's way of thinking 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 "brain circulation". The total number of Principal Investigators (PIs) is 28, among which 11 are on-site PIs. All of our 28 PIs (7 non-Japanese: 25%) are world-leading scientists and ensure an international environment for research activities at the Kavli IPMU. T. Takahashi is performing a new interdisciplinary activity, applying hard X-ray and gamma ray detectors he developed to biomedical research. On-site PIs in mathematics, M. Kapranov, Y. Toda, and H. Nakajima, are distinguished mathematicians and research leaders in algebraic variety, derived category, and gauge theories. K. Martens was appointed the first non-Japanese Director of the Kamioka-branch, demonstrating the Kavli IPMU has established a truly international environment and support system. Other faculty members also play leading roles in each field including PIs of big international projects such as Belle II, T2K, EGADS, HSC, PFS, and LiteBIRD. Our former PI K. Nomoto was awarded the Order of the Sacred Treasure. Another former PI T. Yanagida was awarded the particle physics medal of Japan. Our former faculty member C. Schnell and an affiliate member A. Kusenko were selected as Simons Fellows in 2021.

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 to realize outstanding accomplishments during their three-year term at the Kavli IPMU. These post-doctoral researchers have 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. We have been able to recruit postdocs from many top-level research institutions in the world, such as Harvard, Princeton, MIT, etc. By the end of FY 2020, we employed 242 postdocs, and 193 had left the Kavli IPMU, some before the three-year term expiration. Some postdoc researchers who have left the Kavli IPMU have found faculty positions at many top-level institutions: Durham U., McGill U., Stony Brook U., ICRR, Osaka, and CNRS. Others have found another postdoc position at prestigious institutions: Oxford, Harvard, MPI, Caltech, CERN, YITP, and KEK, etc. The number of researchers currently in a faculty position became 115 in FY 2020. Also, 47 postdocs affiliated with us were supported by the JSPS Postdoctoral Fellowship.

6. Bringing successful system reforms to the rest of the University and other research institutions to help boost the overall competitiveness of Japan on a global scale

The Kavli IPMU has led system reform in not only the University of Tokyo (UTokyo) but also National Universities at large. We made split appointments possible with institutions inside and outside Japan. We offer merit-based salaries. The Kavli IPMU has employed the so-called "nenpo system", improving the mobility of the members. Kavli IPMU administrative staff members have been awarded the UTokyo's Special Prize for Business Transformation by the President six times and their development products have been requested by other organizations in the UTokyo.

We take the role of an evangelist to make these reforms permeate the system to boost the overall competitiveness of research in Japan. One of the examples we have achieved to spread these reforms can be seen in the Administrative Director T. Haruyama's contribution to Tokushima University on the program established by the Cabinet Office project "Promotion of Regional Industries and Universities". He gave a lecture to the President and board members of Tokushima University on the detailed successful experience of the WPI program at the Kavli IPMU. He has been assigned as a member of the External Evaluation Committee of the newly established laboratory at the university.

7. Making a serious attempt to create a new international graduate program with vigorous student exchanges

We have also made an impact on the globalization of the graduate programs at UTokyo. Our faculty has already contributed to the graduate programs at the Department of Physics and the Department of Mathematical Sciences through the supervision of graduate students and lectures voluntarily. 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 offers opportunities for interdisciplinary research to UTokyo graduate students in our international and interdisciplinary environment. In addition, our international faculty lectures on scientific writing in English in the Department of Physics, a very popular course among graduate students. So far, more than 110 students have taken the course.

Faculty members of the Kavli IPMU supervised doctoral students in astrophysics or particle physics at the University of Oxford to conduct joint research. To date, we have accepted nine students and five have defended their Ph.D. theses. For example, L. Cook, who was also a joint Oxford/Kavli IPMU graduate student, is developing atmospheric neutrino production modeling methods that build on techniques used by the T2K experiment. His work is set to play a key role in the future neutrino oscillation measurements that combine atmospheric and accelerator neutrino data. T. Ghigna, another joint Oxford/Kavli IPMU graduate student, received his Ph.D. in 2020 and became a Kavli IPMU postdoc now.

A new graduate program, which was coordinated by H. Murayama and involved departments of physics, mathematics, astronomy, etc., of UTokyo, was as one of the JSPS WISE Program (Doctoral Program for World-leading Innovative & Smart Education). This program trains graduate students in physics, mathematics, and astronomy for diverse career opportunities. Also, it gives us leverage so that more Kavli IPMU faculty members can directly supervise graduate students.

8. Enlarging the force for outreach to young students, by organizing workshops for scientists and high-school teachers

The Kavli IPMU has been extremely active in the outreach to the general public and high-school students. During the COVID-19 pandemic, we have continued outreach activities online.

We held an online talk series by four researchers featured in the Kavli IPMU Monoshiri Newspaper, which is a wall newspaper by the Kavli IPMU and aims to present easy-to-digest physics and mathematics talks that can be enjoyed by all, including people without a background in science. Each introduced research from their personal experience for around 30 minutes for junior and senior high school students and adults to enjoy the presentations remotely.

The Kavli IPMU and the Japan Association of Communication for Science and Technology (JACST) presented an online talk by Y. Toda, titled “Fundamental Talks, Vol.01: Mathematics – how to interact with objects in non-everyday manner”. Fundamental Talks is to be a 10-part series of seminars. Researchers from cutting-edge science, social sciences and contemporary art will be speakers for the events.

We hold a Kavli IPMUxICRR joint general lecture every year. The lecture in 2020 was “Explorations of the unknown and outer-most limits of the Universe and as New Physics” online for the audience of junior high school students and above. H. Takeo talked about the Belle II experiment and N. Koji (Associate Professor of ICRR) talked about gamma-ray bursts seen from the ground. We held another online Kavli IPMU x ICRR Joint Public Lecture: “New era of Space telescopes”, where H. Tagoshi (ICRR) and J. Silverman gave lectures for junior high school students and above. We held the 6th Kavli IPMU, ELSI, and IRCN Joint Public Lecture online: “A Question of Origins”. K. Fujishima (ELSI), H. Miyamoto, (IRCN) and T. Watari delivered public lectures for high-school students and above online. Moderated by a political science expert, the discussion also touched on cutting-edge scientific research and the theme, “What does it mean to ask a question of origins?”.

We held an online screening of the film “Secrets of the Surface: The Mathematical Vision of Maryam Mirzakhani” illustrating the life and mathematical work of Maryam Mirzakhani, the first woman and the first Iranian to be honored with the Fields medal. We invited the Film Director George Csicsery and other specialists on Mathematics including M. Yamazaki and had a panel discussion.

9. Attaining sufficient stability of the organization so that we can bring our research objectives beyond the WPI funding

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, employment after retirement, etc. UTokyo also committed to building the main research building specifically for the Kavli IPMU and a new international lodge near the Kashiwa campus, which became 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. Former UTokyo President J. Hamada decided to accept Kavli's donation despite some concerns and opposition within the University.

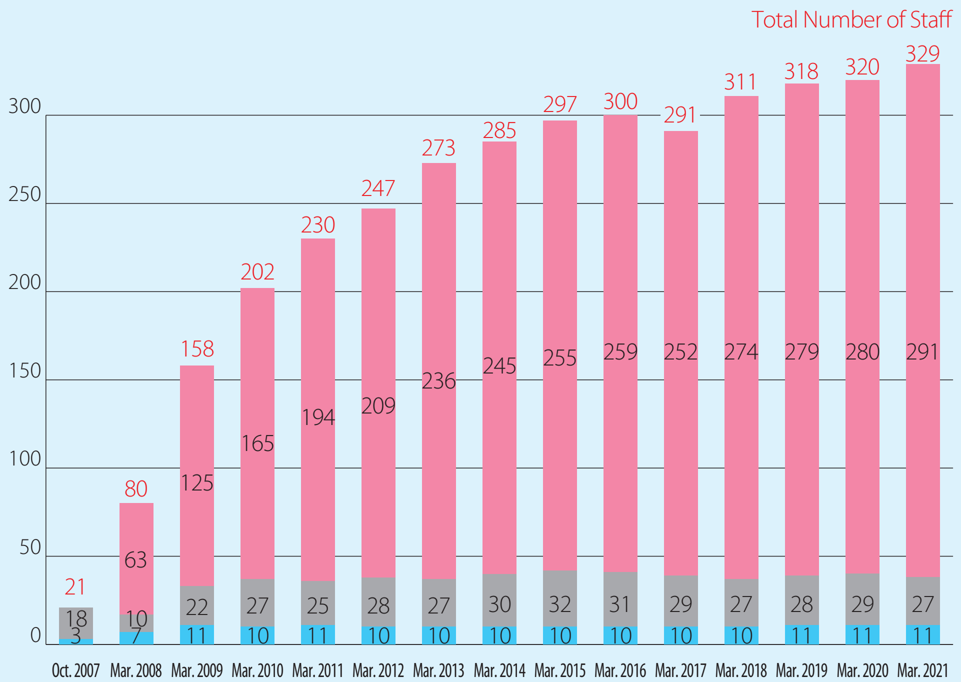
The creation of TODIAS (later UTIAS) in 2011 is an outstanding support, providing a permanent place for the Kavli IPMU within the University. Under this structure, UTIAS requested funding to MEXT to sustain the activity and won 13 permanent positions in UTIAS in 2017. Following the interim evaluation, UTokyo made several measures to make the Kavli IPMU sustainable. Finally, the University provided the Kavli IPMU with 10 tenure positions at the President's discretion. The University also secures nine people from the administrative bureau of the University. During the WPI program committee meeting in 2020, President M. Gonokami declared that “we will maintain IPMU as our permanent institute at its current high level of activities, after the WPI program support ends” by strengthening the Kavli Foundation fund, and securing budget request for permanent institute. The success of the Kavli IPMU has given credibility to UTokyo, a bond which is secured by the value of knowledge obtained by university research.

Others

Although our activity faces various challenges due to the COVID19, we have carried out various initiatives to encourage communication for mutual inspiration between different disciplines and to push our projects forward under the new standard. Instead of our daily teatime for informal interactions, we hold Kavli IPMU social hour in a virtual space. Precious lessons we have learned on how to utilize virtual spaces will help us work more efficiently and build stronger international connections, even after the pandemic ends. Almost all conferences and seminars were held online. In FY2020, we had 1465 participants for online conferences and 777 foreigners among them. We also had more than 100 seminars online, obtaining about 3000 participants. We started a new colloquium-style webinar series by Kavli IPMU postdocs to understand each field and each other. 7 astronomers, 10 theoretical physicists, and 4 mathematicians gave talks on their research at the postdoc colloquia. We recruited six short-term postdocs, “Postdocs en passant”, who could not move to their new appointments due to visa/travel restrictions but could come to Japan.

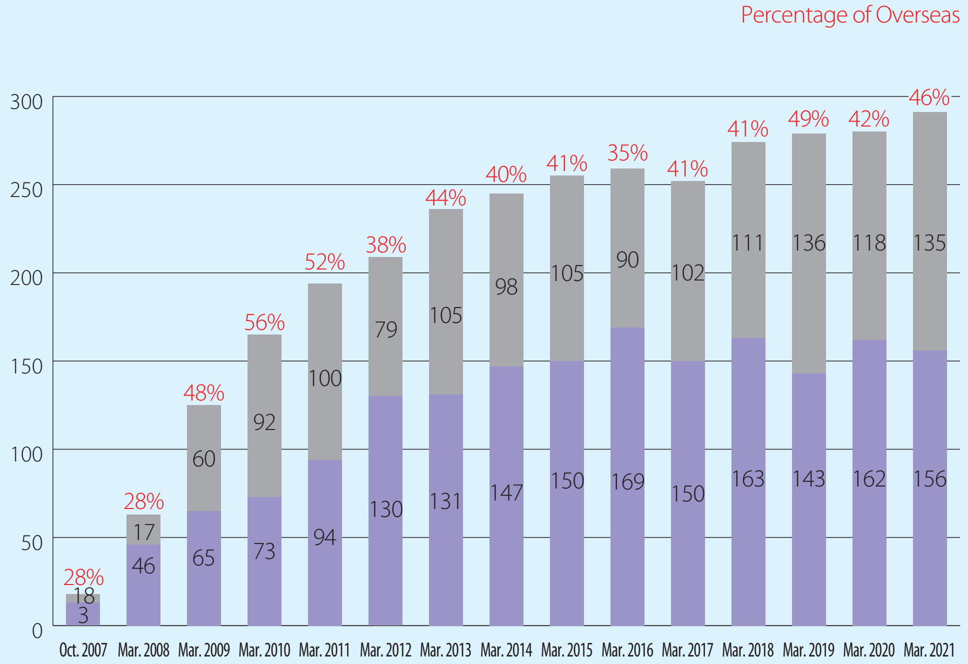
Director H. Ooguri has introduced several measures to improve our diversity, including bias training for the search committee, revision of harassment training, best practices for selections and recruitments, and diversity requirements on workshops. We have a weekly women’s lunch and provide leadership opportunities for female and international scientists. We also established our code of conduct. This has inspired UTokyo to establish its code of conduct.

STAFF



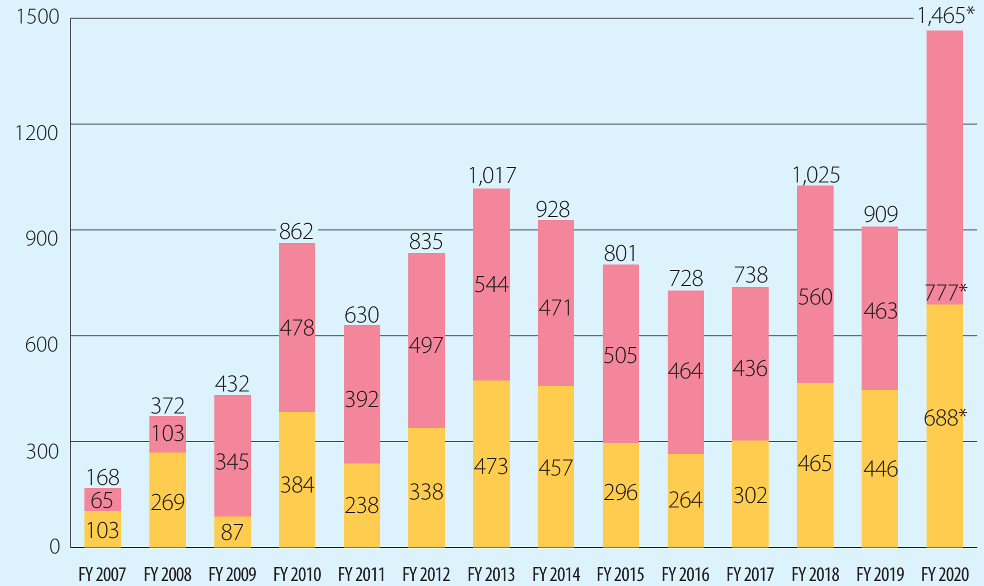
	Oct. 2007	Mar. 2008	Mar. 2009	Mar. 2010	Mar. 2011	Mar. 2012	Mar. 2013	Mar. 2014	Mar. 2015	Mar. 2016	Mar. 2017	Mar. 2018	Mar. 2019	Mar. 2020	Mar. 2021
🟥 Researchers	18	63	125	165	194	209	236	245	255	259	252	274	279	280	291
▨ Research Support Staffs	0	10	22	27	25	28	27	30	32	31	29	27	28	29	27
🟦 Administrative staffs	3	7	11	10	11	10	10	10	10	10	10	10	11	11	11
Total	21	80	158	202	230	247	273	285	297	300	291	311	318	320	329

RESEARCHERS



	Oct. 2007	Mar. 2008	Mar. 2009	Mar. 2010	Mar. 2011	Mar. 2012	Mar. 2013	Mar. 2014	Mar. 2015	Mar. 2016	Mar. 2017	Mar. 2018	Mar. 2019	Mar. 2020	Mar. 2021
▨ Overseas	5	17	60	92	100	79	105	98	105	90	102	111	136	118	135
🟪 Domestic	13	46	65	73	94	130	131	147	150	169	150	163	143	162	156
% of Overseas	28%	28%	48%	56%	52%	38%	44%	40%	41%	35%	41%	41%	49%	42%	46%
% of Female	0%	2%	5%	6%	5%	2%	5%	5%	6%	4%	6%	8%	9%	10%	9.3%

RESEARCH ACTIVITIES



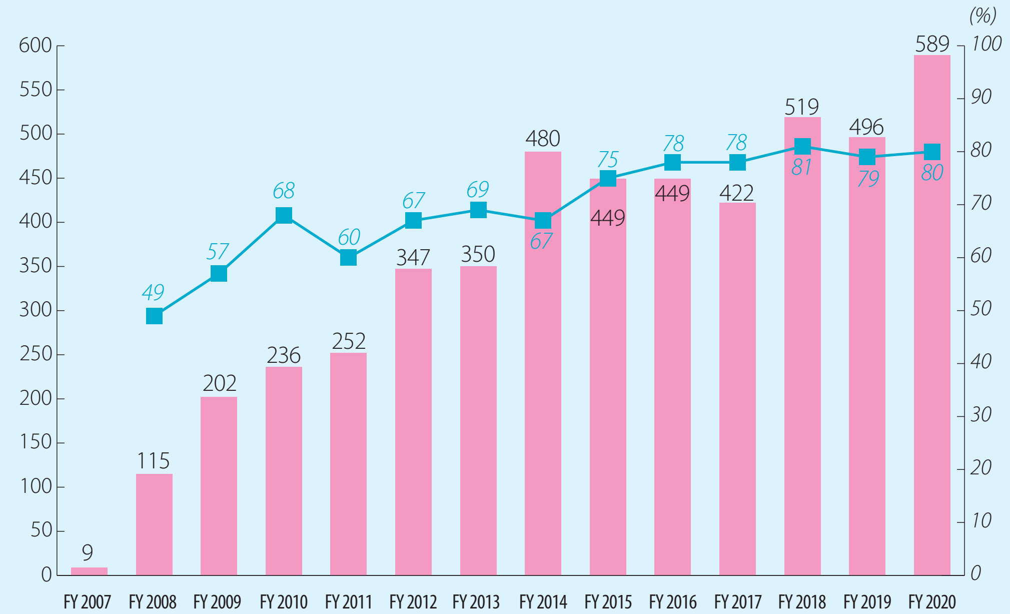
	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020
🟥 Visitors (Overseas)	65	103	345	478	392	497	544	471	505	464	436	560	463	777*
🟨 Visitors (Domestic)	103	269	87	384	238	338	473	457	296	264	302	465	446	688*
Visitors (Total)	168	372	432	862	630	835	1,017	928	1,801	728	738	1,025	909	1,465*

Multiple visits in a given year are counted as one.
* Number of participants for online conferences in 2020

SEMINARS & CONFERENCES

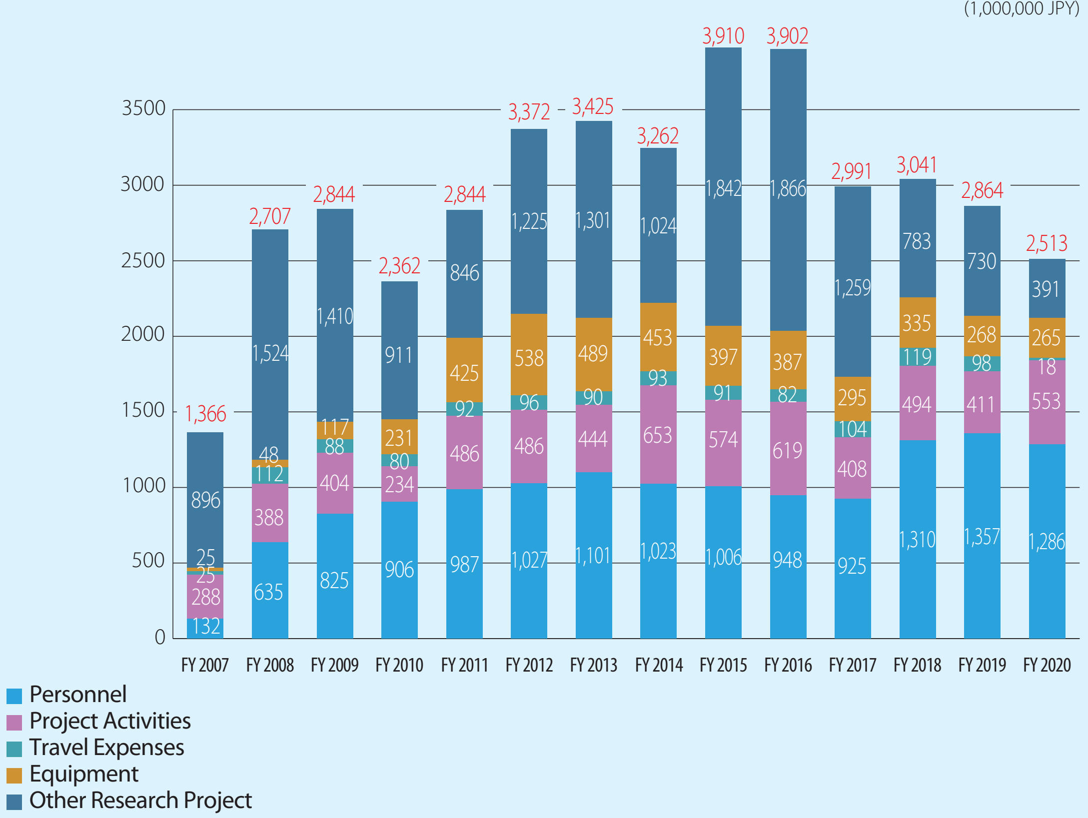
	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020
🟩 Seminars	24	156	140	186	196	232	249	246	222	184	192	216	207	116
🟦 Conferences	4	7	11	16	12	11	14	13	17	14	11	21	18	8

PUBLICATIONS

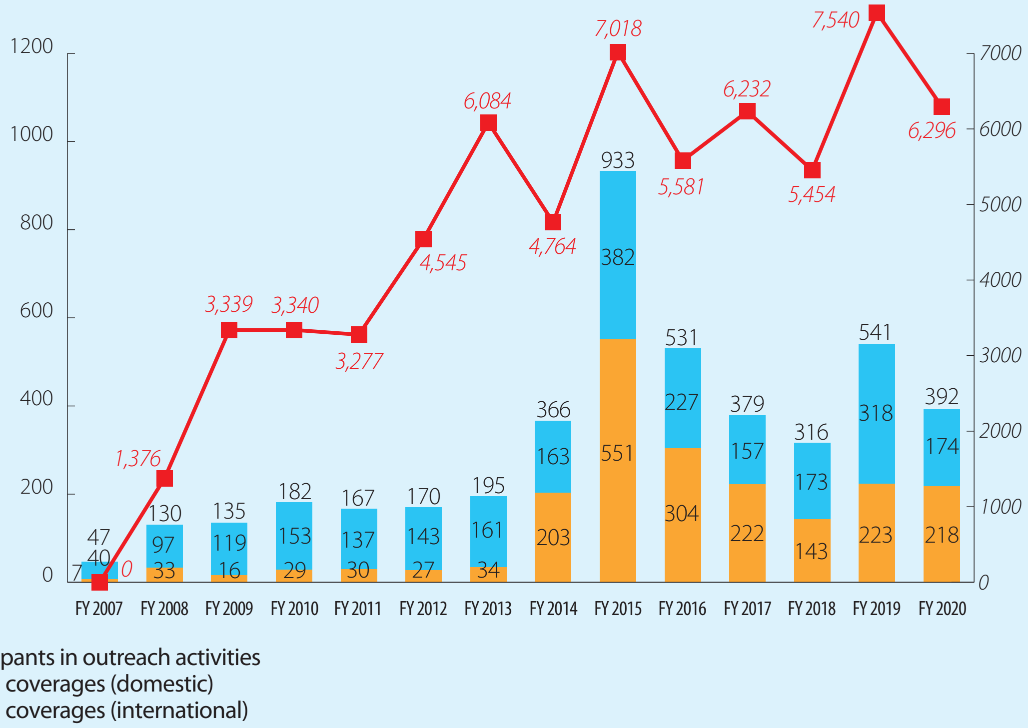


	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020
Publications	9	115	202	236	252	347	350	480	449	449	422	519	496	589
% of international collaboration		49%	57%	68%	60%	67%	69%	67%	75%	78%	78%	81%	79%	80%

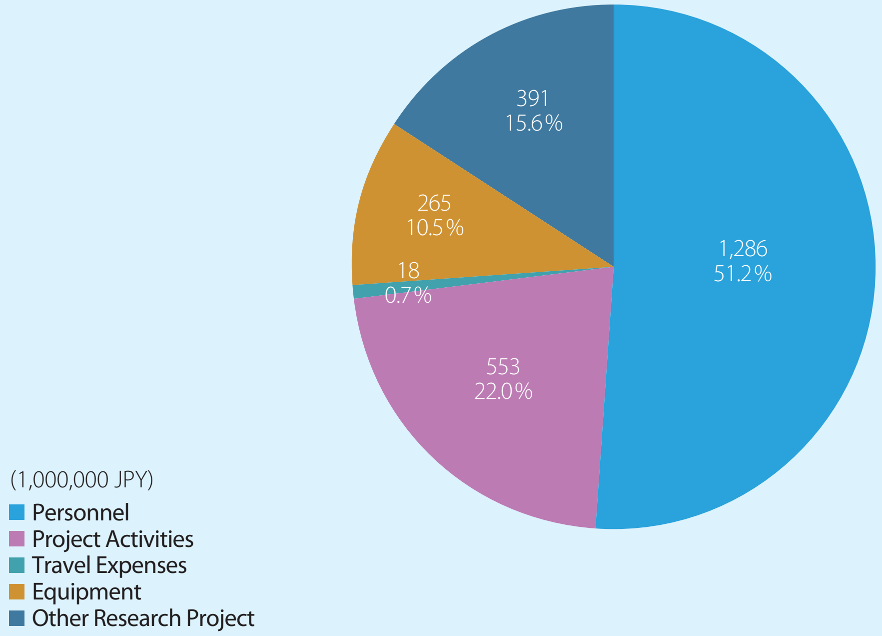
TOTAL EXPENDITURE



MEDIA COVERAGES AND OUTREACH ACTIVITIES



BREAKDOWN OF FY 2020 TOTAL EXPENDITURE



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NEWS & EVENTS

April 2020 - March 2021

APRIL

- Researchers pin down a quantum mechanical anomaly in electromagnetism
- Belle II explores new "portal" into dark matter - First results from the Belle II experiment
- T2K results restrict possible values of neutrino CP phase
- Kavli IPMU senior scientist Ken'ichi Nomoto awarded the order of the sacred treasure

MAY

- Hyper-K technical coordination meeting (Online)
- Kavli IPMU Monoshiri Journal online talk series (May 30-31)

JUNE

- The origin of Type Ia supernovae revealed by manganese abundances
- Observation of excess events in the XENON1T dark matter experiment
- Researchers find the origin and the maximum mass of massive black holes observed by gravitational wave detectors

JULY

- McKay correspondence, mutation and related topics (Online)

AUGUST

- Fundamental Talks (Online), Vol. 01: Mathematics—how to interact with objects in a non-everyday manner
- Fundamental Talks (Online), Vol. 02: What we talk about when we talk about color quality for science, art or philosophy
- Kavli IPMU x ICRR joint public lecture: "Explorations of the unknown and outer-most limits of the universe and a new physics"
- An international research team analysis rules out dark matter destruction as origin of extra radiation in galaxy center
- Rare encounters between cosmic heavyweights

SEPTEMBER

- WPI site visit
- Research suggests our galaxy's brightest gamma-ray binary system may be powered by a magnetar star
- Kavli IPMU's Tsutomu Yanagida awarded 20th particle physics medal of Japan
- Beauty 2020 (Online)
- Science cafe "Universe"

OCTOBER

- The Kavli Foundation in the United States receives the University of Tokyo's Shokumon Award
- History of temperature changes in the universe revealed—First measurement using the Sunyaev-Zeldovich effect
- Study of supergiant star Betelgeuse unveils the cause of its pulsations; Recalibrated its mass, radius, and distance
- Kashiwa campus open day, 2020
- Looking for dark matter near neutron stars with radio telescopes
- Galaxies in the infant universe were surprisingly mature -ALMA telescope conducts largest survey yet of distant galaxies in the early universe-
- Primordial black holes and the search for dark matter from the multiverse

NOVEMBER

- The world of mathematical physics (Online)
- 5th "Actually I really love physics!"–Career paths of female physics graduates (Online)
- Secrets of the surface online film screening + panel
- Kavli IPMU x ICRR joint public lecture: "New era of space telescopes"
- A hint of new physics in polarized radiation from the early universe
- Researchers validate theory that neutrinos shape the universe
- CMB systematics and calibration focus workshop (Online)

DECEMBER

- Science cafe "Universe"
- Kavli IPMU annual report 2019 released
- Principal Investigator David Spergel elected president of Simons Foundation
- World-class researchers are coming from WPI! (Online Event)
- American astronomers find secrets of Japanese universes

JANUARY

- The smallest galaxies in our universe bring more about dark matter to light
- Time-domain cosmology with strong gravitational lensing (Online)

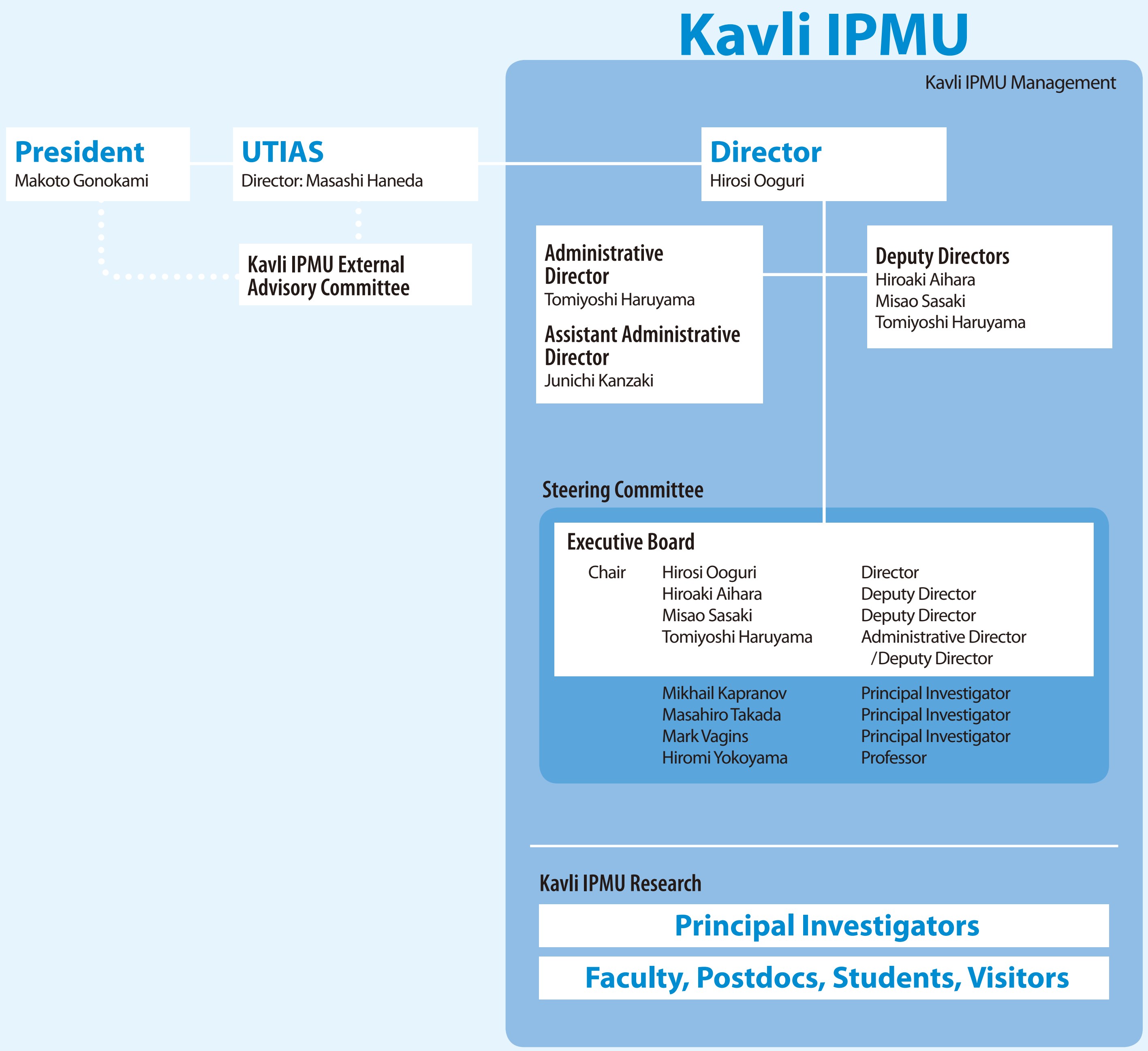
FEBRUARY

- Chiaki Hikage and others win the 2020 PASJ excellent paper award
- Kavli IPMU visiting senior scientist Alexander Kusenko and visiting scientist Christian Schnell selected as 2021 Simons Fellows
- What is dark matter? - Comprehensive study of the huge discovery space in dark matter (Online)
- WPI science symposium 2021 "Life" in the 21st century
- Establishing the origin of solar-mass black holes and the connection to dark matter
- The 6th Kavli IPMU, ELSI, and IRCN joint public lecture: "A Question of Origins"

MARCH

- 12th PFS collaboration meeting (Online)
- Social context affects gendered views of STEM subjects in England and Japan -New model of why physics and mathematics are seen as masculine subjects-
- String theory solves mystery about how particles behave outside a black hole photon sphere

3 ORGANIZATION



Kavli IPMU

Kavli IPMU Management

President
Makoto Gonokami

UTIAS
Director: Masashi Haneda

Kavli IPMU External Advisory Committee

Director
Hirosi Ooguri

Administrative Director
Tomiyoshi Haruyama

Assistant Administrative Director
Junichi Kanzaki

Deputy Directors
Hiroaki Aihara
Misao Sasaki
Tomiyoshi Haruyama

Steering Committee

Executive Board

Chair	Hirosi Ooguri	Director
	Hiroaki Aihara	Deputy Director
	Misao Sasaki	Deputy Director
	Tomiyoshi Haruyama	Administrative Director /Deputy Director
	Mikhail Kapranov	Principal Investigator
	Masahiro Takada	Principal Investigator
	Mark Vagins	Principal Investigator
	Hiromi Yokoyama	Professor

Kavli IPMU Research

Principal Investigators

Faculty, Postdocs, Students, Visitors

The Kavli IPMU has a rather unique organization. While research is conducted in a flat-structure manner with loosely defined grouping, the decision making is done in a top-down scheme under the Director's strong leadership. This scheme minimizes the administrative load for the researchers. It is also intended to maximally extract young researcher's creative and challenging minds as well as to encourage daily cross-disciplinary interactions.

The Director is appointed by the President of the University of Tokyo and reports directly to his office. The Director proposes to hire the Principal Investigators to the President. For other hiring of research staff and administrative staff, he has a complete authority. He is also solely responsible for making all other decisions. He is assisted by the three Deputy Directors and the Administrative Director. They constitute the Executive Board (EB) and regularly meet to ensure smooth operation of the Institute. The EB has direct access to the Office of the President for consultations on both scientific and administrative matters.

The Director is obliged to report the appointments of new Principal Investigators and faculty members to the Director of the University of Tokyo Institutes for Advanced Study (UTIAS). Also, to clear the university formality in faculty hiring, the decisions of the Institute have to be endorsed by the Steering Committee of the Kavli IPMU.

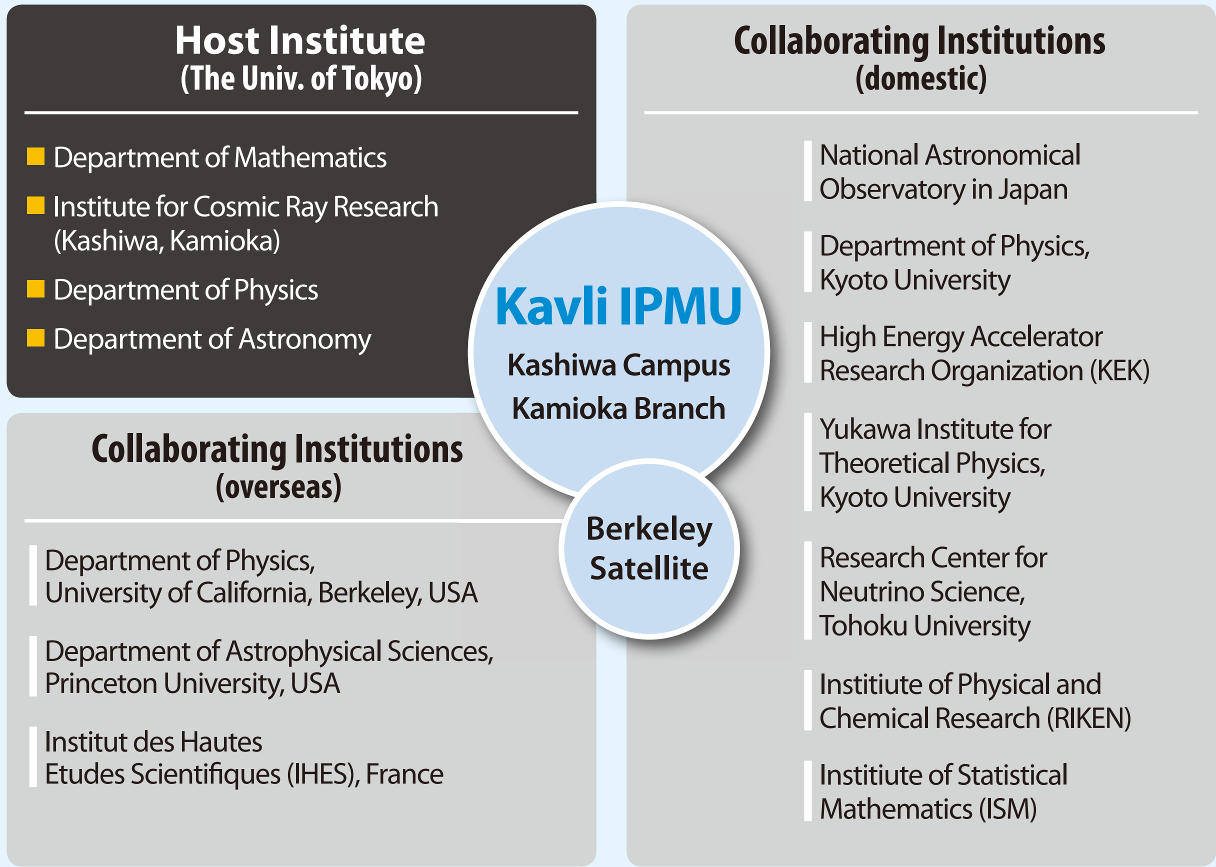
The Principal Investigators are world's leading scientists in their fields. They have a large autonomy in the research they conduct. They can make proposals to the Director to hire research staff at the Institute.

The External Advisory Committee (EAC), appointed by the President of the University of Tokyo, reviews annually the scientific achievement and activities of the Institute and advises the President on scientific priorities and the research activities to keep the Institute stay on the course of its objectives.

The External Advisory Committee Members (March 2021)

John Ellis	King's College London	Particle Theory
Giovanni Felder	ETH Zürich	Mathematics
Joshua Frieman	FNAL/U Chicago; Chair	Astrophysics
Masahiko Hayashi	JSPS Bonn Office	Astronomy
Tatsuya Nakada	EPFL	High Energy Experiment
Yongbin Ruan	Zhejiang University	Mathematics
Sakura Schafer-Nameki	U Oxford	Mathematical Physics
Nigel Smith	SNOLAB	Astroparticle Physics

The main laboratory building on the Kashiwa Campus provides a basis for our researchers. Even most of experimentalists who are involved in Kamioka experiments and astronomical observations spend a good fraction of their time in Kashiwa for analyzing data, sharing seminars and discussing with theorists. The Kamioka Branch is a basis for the Kavli IPMU staff members who are engaging in the underground experiments conducted at the Kamioka underground laboratory. The Berkeley Satellite, besides being a place for research, serves as a contact place to the US scientific community. We also have close collaborative relations with several institutions both in Japan and overseas as well as with other departments within the University of Tokyo.



Host Institute
(The Univ. of Tokyo)

- Department of Mathematics
- Institute for Cosmic Ray Research (Kashiwa, Kamioka)
- Department of Physics
- Department of Astronomy

Kavli IPMU
Kashiwa Campus
Kamioka Branch

Berkeley Satellite

Collaborating Institutions
(overseas)

- Department of Physics, University of California, Berkeley, USA
- Department of Astrophysical Sciences, Princeton University, USA
- Institut des Hautes Etudes Scientifiques (IHES), France

Collaborating Institutions
(domestic)

- National Astronomical Observatory in Japan
- Department of Physics, Kyoto University
- High Energy Accelerator Research Organization (KEK)
- Yukawa Institute for Theoretical Physics, Kyoto University
- Research Center for Neutrino Science, Tohoku University
- Instiitute of Physical and Chemical Research (RIKEN)
- Instiitute of Statistical Mathematics (ISM)

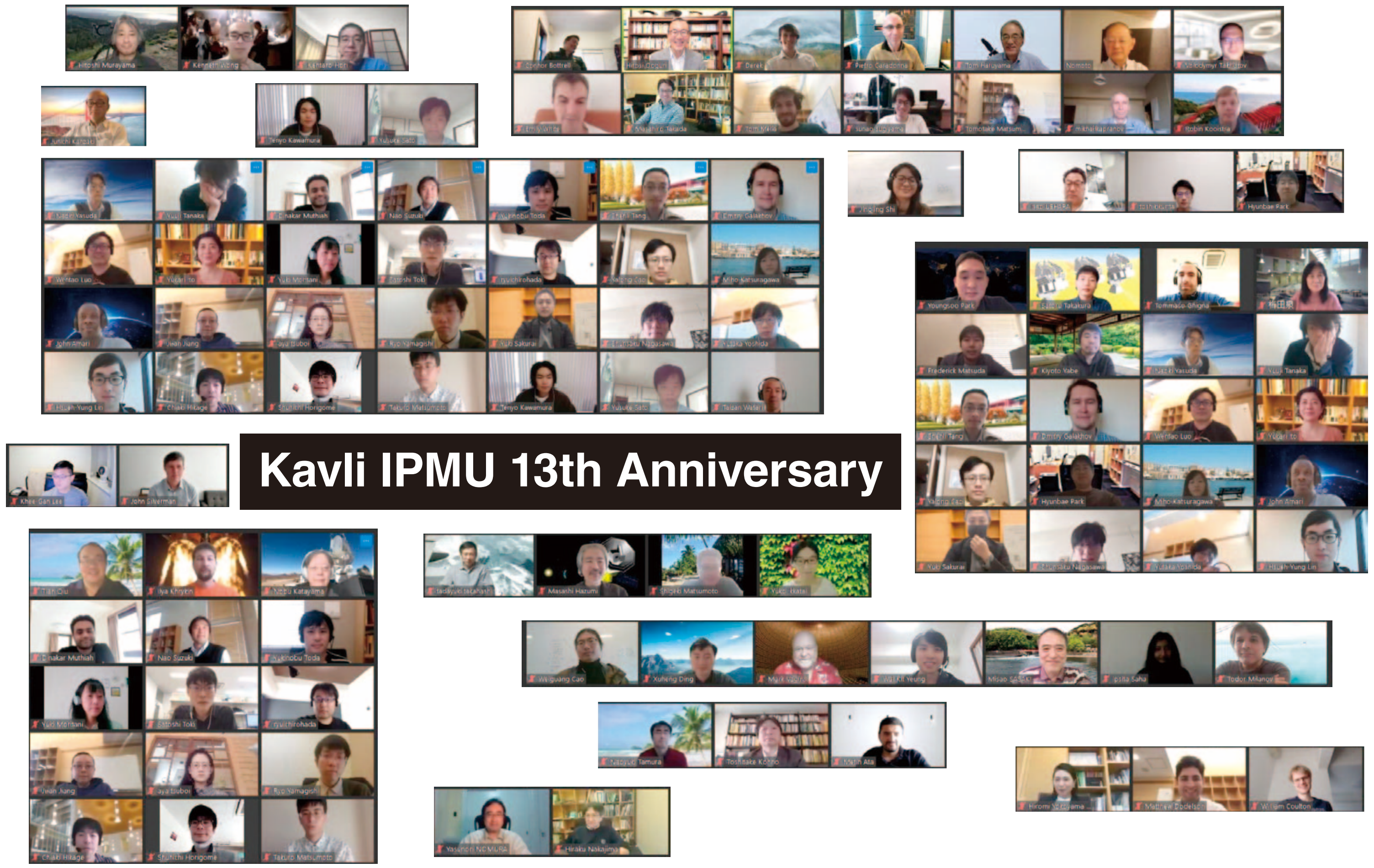
The Kavli IPMU holds close relations with similar research institutions in the world for encouraging exchanges in research and training of young research staff. We have signed either an agreement or a memorandum of understanding with those institutions.

Foreign institutions/consortia/programs having MOU with the Kavli IPMU

The University of California, Berkeley, Department of Physics
National Taiwan University, Leung Center for Cosmology and Particle Astrophysics (LeCosPA)
The Astrophysics Research Consortium [on the Sloan Digital Sky Survey III]
The Astrophysics Research Consortium [on the Sloan Digital Sky Survey AS3 ("After SDSS III")]
The Astrophysics Research Consortium [on the Sloan Digital Sky Survey IV]
Garching/Munich Cluster of Excellence on "The Origin and Structure of the Universe"
UNIFY (Unification of Fundamental Forces and Applications) [under the EU's Seventh Framework Program]
The Scuola Internationale Superiore di Studi Avanzati (SISSA)
The Academia Sinica Institute of Astronomy and Astrophysics of Taiwan (ASIAA) [on the SuMIRe Project]
The Intermediate Palomar Transient Factory (iPTF)
Steklov Mathematical Institute, Russian Academy of Sciences
Center for Mathematical Sciences, Tsinghua University
The Tata Institute of Fundamental Research
TRIUMF (Canada's National Laboratory for Particle and Nuclear Physics)
Deutsches Elektronen Synchrotron (DESY)
Princeton University
The University of Oxford, Department of Physics
The Kavli Institute for Astronomy and Astrophysics at Peking University (KIAA)
Le Centre National de la Recherche Scientifique (CNRS)
The Mainz Institute for Theoretical Physics (MITP)
Johns Hopkins University
The University of Bonn

4

STAFF



Director

Hirosi Ooguri, Mathematical Physics

Deputy Directors

Hiroaki Aihara, High Energy Physics
Tomiyoshi Haruyama, High Energy Physics
Misao Sasaki, Cosmology

Principal Investigators

Hiroaki Aihara (U Tokyo), High Energy Physics
Alexey Bondal (Steklov Math. Inst.), Mathematics
Kentaro Hori, String Theory
Kunio Inoue (Tohoku U), Neutrino Physics
Takaaki Kajita (U Tokyo, ICRR), Neutrino Physics
Mikhail Kapranov, Mathematics
Stavros Katsanevas (European Gravitational Observatory), Experimental Physics
Masahiro Kawasaki (U Tokyo, ICRR), Cosmology
Young-Kee Kim (U Chicago), High Energy Physics
Toshiyuki Kobayashi (U Tokyo, Math Sci), Mathematics
Toshitake Kohno (Meiji U), Mathematics
Eiichiro Komatsu (MPI for Astrophysics), Cosmology
Kai Uwe Martens, Experimental Physics
Shigeki Matsumoto, Cosmology
Shigetaka Moriyama (U Tokyo, ICRR), Neutrino Physics
Hitoshi Murayama (UC Berkeley), Particle Theory
Masayuki Nakahata (U Tokyo, ICRR), Astroparticle Physics
Hiraku Nakajima, Mathematics
Mihoko Nojiri (KEK), Particle Theory
Yasunori Nomura (UC Berkeley), Particle Theory
Hirosi Ooguri (CALTECH), Mathematical Physics
David Spergel (Princeton U), Cosmology
Naoshi Sugiyama (Nagoya U), Cosmology
Masahiro Takada, Cosmology
Tadayuki Takahashi, Experimental Physics
Yukinobu Toda, Mathematics
Mark Robert Vagins, Astroparticle Physics
Naoki Yoshida (U Tokyo), Astrophysics

Faculty Members

Tomoyuki Abe, Mathematics
Mark Patrick Hartz, Neutrino Physics
Tomiyoshi Haruyama, High Energy Physics
Simeon John Hellerman, String Theory
Takeo Higuchi, High Energy Physics
Chiaki Hikage, Cosmology
Kentaro Hori, String Theory
Yukari Ito, Mathematics
Mikhail Kapranov, Mathematics
Nobuhiko Katayama, High Energy Physics
Khee-Gan Lee, Astronomy
Kai Uwe Martens, Experimental Physics
Shigeki Matsumoto, Cosmology
Tomotake Matsumura, Experimental Physics
Thomas Edward Melia, Theoretical Physics
Todor Eliseev Milanov, Mathematics
Hitoshi Murayama (UC Berkeley), Particle Theory
Hiraku Nakajima, Mathematics
Hirosi Ooguri (CALTECH), Mathematical Physics
Tadashi Orita, Experimental Physics
Misao Sasaki, Cosmology
Satoshi Shirai, Particle Theory
John David Silverman, Astronomy
Yevgeny Stadnik, Theoretical Physics (from 2020/11/1)
Nao Suzuki, Astrophysics
Yuji Tachikawa, Particle Theory
Masahiro Takada, Cosmology
Tadayuki Takahashi, Experimental Physics
Shinichiro Takeda, Experimental Physics
Naoyuki Tamura, Astronomy
Yukinobu Toda, Mathematics
Mark Robert Vagins, Astroparticle Physics
Taizan Watari, Theoretical Physics
Atsushi Yagishita, Experimental Physics
Masahito Yamazaki, String Theory
Naoki Yasuda, Astronomy
Hiromi Yokoyama, Science and Society
Naoki Yoshida (U Tokyo), Astrophysics
Yutaka Yoshida, String Theory

Project Researchers

Shunsuke Adachi, Experimental Physics (from 2021/3/1)
Kazuyuki Akitsu, Cosmology
Ryosuke Akutsu, Neutrino Physics (2020/5/16-12/15)
Meer Ashwinkumar, String Theory (from 2020/11/1)
Metin Ata, Cosmology
Neil David Barrie, Particle Theory (till 2020/10/15)
Tobias Binder, Theoretical Physics
Connor Hugh Bottrell, Astrophysics (from 2020/10/16)
Yalong Cao, Mathematics
Pietro Caradonna, Experimental Physics
William Richard Coulton, Cosmology (from 2020/10/9)
Thomas Rafael Czank, Experimental Physics
Anton Reyes De la Fuente, String Theory
Zhiyuan Ding, Mathematics
Xuheng Ding, Astronomy (from 2020/9/1)
Matthew Dodelson, String Theory
Joshua Armstrong Eby, Cosmology (from 2020/11/13)
Fatemeh Elahi, High Energy Physics (from 2021/1/14)
Ryo Fujita, Mathematics (2020/8/16-10/6)
Dmitrii Galakhov, String Theory
Hua Gao, Astrophysics (from 2020/11/12)
Tommaso Ghigna, Experimental Physics (from 2020/11/26)
Ryuichiro Hada, Cosmology
Seyed Morteza Hosseini, String Theory
Chang-Tse Hsieh, Theoretical Physics (till 2020/8/31)
Yuko Ikkatai, Science and Society
Hiroaki Imada, Astronomy (2020/6/1-9/30)
Derek Beattie Inman, Cosmology (from 2020/9/16)
Jian Jiang, Astronomy
Ayuki Kamada, Cosmology (2020/11/1-2021/1/31)
Daisuke Kaneko, High Energy Physics (till 2020/7/31)
Miho Katsuragawa, Experimental Physics
Lalitwadee Kawinwanichakij, Astrophysics
Ilya Khrykin, Astrophysics
Robin Rinze Kooistra, Astronomy
Chiara La Licata, Experimental Physics
Yun-Tsung Lai, High Energy Physics (from 2020/6/1)
Chervin Laporte, Astrophysics (till 2021/2/28)
Hsueh-Yung Lin, Mathematics
Wentao Luo, Astrophysics
Oscar Macias , Astrophysics
Ryu Makiya, Astronomy (till 2020/8/31)
Abhiram Mamandur Kidambi, Mathematical Physics (from 2020/11/1)
Frederick Takayuki Matsuda, Experimental Physics
Yuki Moritani, Astronomy
Dinakar Muthiah, Mathematics (till 2021/1/4)
Keigo Nakamura, Neutrino Physics (till 2020/10/31)
Shusuke Otabe, Mathematics
Hyunbae Park, Cosmology
Youngsoo Park, Cosmology
Samuel Charles Passaglia, Cosmology (from 2020/12/14)
Shi Pi, Astrophysics (till 2020/10/24)
Alexis Roquefeuil, Mathematics
Ipsita Saha, Particle Theory
Yuki Sakurai, Experimental Physics
Yuya Sakurai, Astrophysics
Yota Shamoto, Mathematics
Jingjing Shi, Cosmology

Yevgeny Stadnik, Theoretical Physics (till 2020/10/31)
Satoru Takakura, Astronomy
Volodymyr Takhistov, Theoretical Physics (from 2020/10/1)
Tomohiko Tanabe, Particle Theory (from 2021/1/1)
Ryota Tomaru, Experimental Physics (till 2020/9/30)
Daisuke Toyouchi, Astronomy (from 2020/10/16)
Izumi Umeda, Medical Application of Gamma-ray Imaging
Valeri Vardanyan, Cosmology
John Welliaveetil, Mathematics
Graham Albert White, Particle Theory (from 2020/8/1)
Kenneth Christopher Wong, Astronomy
Kiyoto Yabe, Astronomy
Ryo Yamagishi, Mathematics
Hassen Yesuf, Astronomy (from 2021/3/1)
Wai Kit Yeung, Mathematics (from 2020/6/16)
Yunqin Zheng, Theoretical Physics (from 2020/11/5)
Zijun Zhou, Mathematics (from 2020/11/16)

Joint Appointments

Mark Patrick Hartz (TRIUMF), Neutrino Physics
Masashi Hazumi (KEK), High Energy Physics
Hitoshi Murayama (UC Berkeley), Particle Theory
Hirosi Ooguri (CALTECH), Mathematical Physics
Naoki Yoshida (U Tokyo), Astrophysics

Affiliate Members

Kou Abe (U Tokyo, ICRR), Astroparticle Physics
Mina Aganagic (UC Berkeley), String Theory
Shin'ichiro Ando (U Amsterdam), Astroparticle Physics
Bruce Berger (Lawrence Berkeley National Laboratory), Neutrino Physics
Melina Bersten (IALP CONICET-UNLP), Astronomy
Sergey Blinnikov (ITEP), Astronomy
Agnieszka Maria Bodzenta-Skibinska (U Warsaw), Mathematics (from 2021/2/1)
Raphael Bousso (UC Berkeley), Cosmology
Kevin Allen Bundy (UC Santa Cruz), Astronomy
Andrew Bunker (U Oxford), Astrophysics
Martin Gilles Bureau (U Oxford), Astronomy
Scott Huai-Lei Carnahan (U Tsukuba), Mathematics
Cheng-Wei Chiang (Natl Taiwan U), Particle Theory
Yuji Chinone (U Tokyo), Astronomy
Neal K Dalal (Perimeter Institute), Astrophysics
Patrick Decowski (U Amsterdam/GRAPPA), Neutrino Physics
Jason Detwiler (U Washington, Seattle), Neutrino Physics
Mamoru Doi (U Tokyo, IoA), Astronomy
Chris Done (Durham U), Astrophysics
William Ross Goodchild Donovan (Tsinghua U, Beijing), Mathematics (from 2020/9/1)
Yuri Efremenko (U Tennessee), Neutrino Physics
Motoi Endo (KEK), Particle Theory
Sanshiro Enomoto (U Washington, Seattle), Neutrino Physics
Andrea Ferrara (Scuola Normale Superiore di Pisa), Astronomy
Gaston Folatelli (IALP CONICET-UNLP), Astrophysics
Andreu Font-Ribera (IFAE-Barcelona), Cosmology
Brian Fujikawa (LBL, Berkeley), Neutrino Physics
Kenji Fukaya (SCGP), Mathematics
Masataka Fukugita (U Tokyo), Astrophysics
Shao-Feng Ge (Shanghai Jiao Tong U), Theoretical Physics
Lawrence J Hall (UC Berkeley), Particle Theory
Koichi Hamaguchi (U Tokyo), Particle Theory
Jiaxin Han (Shanghai Jiao Tong U), Astronomy
Tilman Hartwig (U Tokyo), Astrophysics
Tetsuo Hatsuda (RIKEN), Nuclear Physics
Yoshinari Hayato (U Tokyo, ICRR), Neutrino Physics
Karsten Heeger (Yale U), Neutrino Physics
Katsuki Hiraide (U Tokyo, ICRR), Astroparticle Physics
Raphael Hirschi (Keele U), Astronomy
Junji Hisano (Nagoya U), Particle Theory
Petr Horava (UC Berkeley), String Theory
Glenn Horton-Smith (Kansas State U), Neutrino Physics
Shinobu Hosono (Gakushuin U), Mathematical Physics
Kenta Hotokezaka (U Tokyo, School of Science), Astrophysics
Masahiro Ibe (U Tokyo, ICRR), Particle Theory
Koichi Ichimura (Tohoku U), Astroparticle Physics
Hirokazu Ikeda (JAXA), Experimental Physics
Motoyasu Ikeda (U Tokyo, ICRR), High Energy Physics
Shiro Ikeda (ISM), Mathematics
Yoshiyuki Inoue (Osaka U), Astrophysics
Ken'ichi Izawa (Tokushima U), Particle Theory
Nicholas Kaiser (École normale supérieure), Cosmology
Jun Kameda (U Tokyo, ICRR), Neutrino Physics
Yousuke Kanayama (RIKEN), Experimental Physics
Amanda Irene Karakas (Monash U), Astronomy
Masaki Kashiwara (Kyoto U), Mathematics
Akishi Kato (U Tokyo, Math Sci), Mathematical Physics
Yasuyuki Kawahigashi (U Tokyo, Math Sci), Mathematics
Edward T. Kearns (Boston U), Neutrino Physics
Sergey Ketov (Tokyo Metropolitan U), Theoretical Physics
Nobuhiro Kimura (U Tokyo, ICRR), High Energy Physics
Yasuhiro Kishimoto (Tohoku U), Neutrino Physics
Ryuichiro Kitano (KEK), Particle Theory
Chiaki Kobayashi (CAR, U of Hertfordshire), Astronomy
Kazuyoshi Kobayashi (Waseda U), Astroparticle Physics
Masayuki Koga (Tohoku U), Neutrino Physics
Kazunori Kohri (KEK), Cosmology
Satoshi Kondo (Middle East Technical University), Mathematics
Yusuke Koshio (Okayama U), Neutrino Physics
Akito Kusaka (U Tokyo), Experimental Physics
Alexander Kusenko (UCLA), Particle Theory
Tatsuki Kuwagaki (Osaka U), Mathematics
Alexie, Solange Leauthaud Harnett (UC Santa Cruz), Astrophysics
Shiu-Hang (Herman) Lee (Kyoto U), Astrophysics
Si Li (Tsinghua U, Beijing), Mathematical Physics
Marco Limongi (INAF), Astrophysics

Keiichi Maeda (Kyoto U), Astrophysics
Kazuo Makishima (U Tokyo), High Energy Physics
Ryu Makiya (ASIAA), Astronomy (from 2020/9/1)
Brice Menard (Johns Hopkins U), Astrophysics
Makoto Minowa (U Tokyo), Experimental Physics
Makoto Miura (U Tokyo, ICRR), High Energy Physics
Hironao Miyatake (Nagoya U), High Energy Physics
Hiroshi Mizuma (RIKEN), Experimental Physics
Anupreeta Sadashiv More (IUCAA), Astronomy
Surhud Shrikant More (IUCAA), Astronomy
Takeo Moroi (U Tokyo), Particle Theory
Tomoki Morokuma (U Tokyo, IoA), Astronomy
David Robert Morrison (UC Santa Barbara), Mathematics
Shinji Mukohyama (Kyoto U), Cosmology
Motohico Mulase (UC Davis), Mathematics
Dinakar Muthiah (U Glasgow), Mathematics (from 2021/1/5)
Kentaro Nagamine (Osaka U), Astrophysics
Yasuhiro Nakajima (U Tokyo, School of Science), Neutrino Physics
Kengo Nakamura (Butsuryo College of Osaka), Neutrino Physics
Kenzo Nakamura (KEK), Neutrino Physics
Tsuyoshi Nakaya (Kyoto U), High Energy Physics
Kazunori Nakayama (U Tokyo), Cosmology
Shoei Nakayama (U Tokyo, ICRR), Neutrino Physics
Yu Nakayama (Rikkyo U), Theoretical Physics
Takahiro Nishimichi (Kyoto U), Cosmology
Ken'ichi Nomoto (U Tokyo), Astronomy
Hirokazu Odaka (U Tokyo), High Energy Astrophysics
Hiroshi Ogawa (Nihon U), Astroparticle Physics
Masamune Oguri (U Tokyo), Cosmology
Shinnosuke Okawa (Osaka U), Mathematics
Kimihiro Okumura (U Tokyo, ICRR), Neutrino Physics
Teppei Okumura (Academia Sinica), Cosmology
Yoshiyuki Onuki (U Tokyo, ICEPP), High Energy Physics
Domenico Orlando (INFN), String Theory
Masaki Oshikawa (U Tokyo, ISSP), Theoretical Physics
Masami Ouchi (U Tokyo, ICRR), Astronomy
Andrei Pajitnov (U Nantes), Mathematics
Myeonghun Park (SEOULTECH), Particle Theory
Serguey Todorov Petcov (SISSA), Particle Theory
Shi Pi (Chinese Academy of Sciences), Astrophysics (from 2020/10/25)
Andreas Piepke (U Alabama), Neutrino Physics
J. Xavier Prochaska (UC Santa Cruz), Astronomy
Anna Puskas (U Queensland), Mathematics
Robert Michael Quimby (San Diego State U), Astronomy
Susanne Reffert (U Bern), String Theory
Jason Rhodes (NASA JPL/Caltech), Cosmology
Joshua Thomas Ruderman (New York U), Particle Theory
Wiphu Rujopakarn (Chulalongkorn U.), Astronomy
Kyoji Saito (Kyoto U), Mathematics
Ryo Saito (Yamaguchi U), Astrophysics
Shun Saito (Missouri U of Science and Technology), Cosmology
Yoshihisa Saito (Rikkyo U), Mathematics
Yoshio Saito (U Tokyo, ICRR), High Energy Physics
Hidetaka Sakai (U Tokyo, Math Sci), Mathematics
Francesco Sala (U Pisa), Mathematics
Katsuhiko Sato (JSPS), Astroparticle Physics
Vadim Schechtman (U Toulouse III-Paul Sabatier), Mathematics
Christian Schnell (SUNY, Stony Brook), Mathematics
Kate Scholberg (Duke U), Neutrino Physics
Hiroyuki Sekiya (U Tokyo, ICRR), Neutrino Physics
Masato Shiozawa (U Tokyo, ICRR), High Energy Physics
Gary Shiu (U Wisconsin, Madison), String Theory
Aurora Simionescu (SRON Netherlands Institute for Space Research), Astrophysics
Fedor Smirnov (LPTHE), Mathematics
Michael Smy (UC Irvine), Neutrino Physics
Charles Louis Steinhardt (U Copenhagen), Astronomy
Samantha Lynn Stever (Okayama U), Astrophysics
James L. Stone (Boston U), High Energy Physics
Shigeki Sugimoto (Kyoto U), Theoretical Physics
Toshikazu Suzuki (U Tokyo, ICRR), Gravity
Atsushi Takahashi (Osaka U), Mathematics
Fuminobu Takahashi (Tohoku U), Particle Theory
Tadashi Takayanagi (Kyoto U), String Theory
Atsushi Takeda (U Tokyo, ICRR), Astroparticle Physics
Yasuhiro Takemoto (U Tokyo, ICRR), Experimental Physics
Yasuo Takeuchi (Kobe U), Astroparticle Physics
Hidekazu Tanaka (U Tokyo, ICRR), Neutrino Physics
Masaomi Tanaka (Tohoku U), Astronomy
Atsushi Taruya (Kyoto U), Astrophysics
Takayuki Tomaru (NAOJ), Experimental Physics
Nozomu Tominaga (NAOJ), Astrophysics
Werner Tornow (Duke U), Neutrino Physics
Akihiro Tsuchiya (Nagoya U), Mathematics
Sachiko Tsuruta (Montana State U), Astrophysics
Edwin L Turner (Princeton U), Astrophysics
Kazushi Ueda (U Tokyo, Math Sci), Mathematics
Hokuto Uehara (Tokyo Metropolitan U), Mathematics
Alexander Voronov (U Minnesota), Mathematics
Christopher W. Walter (Duke U), Neutrino Physics
Shin Watanabe (JAXA), Experimental Physics
Bryan Webber (U Cambridge), Particle Theory
Roger Alexandre Wendell (Kyoto U), Neutrino Physics
Marcus Christian Werner (Duke Kunshan U), Mathematical Physics
Benda Xu (Tsinghua U, Beijing), Experimental Physics
Masaki Yamashita (Nagoya U), Astrophysics
Tsutomu Yanagida (Shanghai Jiao Tong U), Particle Theory
Jun'ichi Yokoyama (U Tokyo, School of Science), Cosmology
Masashi Yokoyama (U Tokyo), High Energy Physics
Shuichiro Yokoyama (Nagoya U), Cosmology

Graduate Students

Weiguang Cao, Theoretical Physics
Laurence Cook (U Oxford), Neutrino Physics
Henrique De Campos Affonso, Mathematics
Sho Egusa, String Theory
Yuichi Enoki, Particle Theory
Kento Furukawa, Experimental Physics
Tommaso Ghigna (U Oxford), Experimental Physics (till 2020/11/25)
Alexander Goldsack (U Oxford), Neutrino Physics (till 2020/8/31)
Shunichi Horigome, Astroparticle Physics
Yuxin Huang, Astronomy (from 2020/9/1)
Keita Kanno, Particle Theory
Taisuke Katayose, Theoretical Physics
Tenyo Kawamura, Experimental Physics
Tasuki Kinjo, Mathematics
Nozomu Kobayashi, Particle Theory
Yosuke Kobayashi, Cosmology
Asahi Kojima, Particle Theory
Toshiki Kurita, Theoretical Physics
Yasunori Lee, Particle Theory
Xiangchong Li, Cosmology
Peijang Liu , Mathematics
Tianle Mao, Mathematics
Takuro Matsumoto, Mathematics
Takahiro Minami, Experimental Physics
Kairi Mine, Experimental Physics
Yuto Moriwaki, Mathematics
Kai Murai, Particle Theory
Colm Murphy (U Oxford), High Energy Physics
Shunsaku Nagasawa, Experimental Physics
Masato Nakagiri, Mathematics
Shigenori Nakatsuka, Mathematics
Kanade Nishikawa, Particle Theory
Tian Qiu, Cosmology
Yotaro Sato, Theoretical Physics
Yusuke Sato, Mathematics
Yuta Sato, Particle Theory
Ryota Shimoda, Theoretical Physics
Yusuke Suetake, String Theory
Sunao Sugiyama, Theoretical Physics
Shenli Tang, Astronomy
Takanori Taniguchi, Cosmology
Shintaro Toita, Particle Theory
Satoshi Toki, Cosmology
Akira Tokiwa, Cosmology
Yutaka Tsuzuki, Experimental Physics
Yu Watanabe, Particle Theory
Xia Xiaokun, Mathematics
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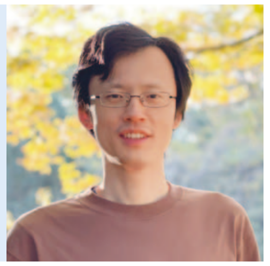
5 RESEARCH HIGHLIGHTS

5.1 Gopakumar-Vafa Type Invariants on Calabi-Yau 4-Folds

Cao Yalong



Gromov-Witten (GW) invariants are rational numbers (virtually) counting stable maps from curves to symplectic manifolds. They are not necessarily integers because of the possible multiple cover of a curve to itself. To figure out the underlying integer-valued curve counting invariants is a fundamental question in the world of enumerative geometry. On symplectic 4-manifolds, this question is explored by C. Taubes using hard analytic tools in a series of groundbreaking works [1, 2], where Seiberg- Witten invariants are deeply involved. Taubes' works are fundamentally important for our understanding of symplectic 4-manifolds.

On Calabi-Yau 3-folds, this question resists to be attacked until the great insight from string theory comes by the work of R. Gopakumar and C. Vafa [3]. Gopakumar and Vafa conjecture that there are integer-valued invariants (called GV invariants) which contain equivalent information of GW invariants and give an explicit formula for them. Mathematically one can read off GV invariants from GW invariants but the integrality of GV invariants is quite a nontrivial statement recently proved by E. Ionel and T. Parker [4].

On Calabi-Yau 4-folds, there seems no string theory insight into similar question. One major difference with CY 3-fold case is that only genus 0 and 1 GW invariants are nontrivial on CY 4-folds by a Riemann- Roch calculation. One instead considers an 'ideal' situation where curves behave in expected ways to be able to compute everything explicitly. In [5], A. Klemm and R. Pandharipande propose a definition of GV type invariants on CY 4-folds along this way. They conjecture the integrality of their invariants and do checks in lots of examples.

Looking back to Taubes' works, one may wonder whether there are analogous gauge theoretic in- variants appearing in the cases of CY 3-folds and 4-folds. In [6], S. Donaldson and R. Thomas give a proposal to extend theories of A. Floer and S. Donaldson on dimensions 3 and 4. However in com- plex dimensions 3 and 4, analytic tools are extremely difficult to work out, algebro-geometric method is necessary instead. In the setting of algebraic geometry, connections on bundles are replaced by general coherent sheaves and differential equations are replaced by deformation-obstruction theory. In [7], S. Hosono, M. Saito and A, Takahashi (see also S. Katz [8]) propose how to recover genus 0 GV invariants on CY 3-folds from counting invariants of stable sheaves which are supported on curves. Recently, such proposal is generalized to arbitrary genus by D. Maulik and Y. Toda [9].

Then it is natural to ask whether there are parallel sheaf theoretic approaches to GV type invariants on CY 4-folds. In a series of works [10, 11, 12], Yalong Cao, Yukinobu Toda at Kavli IPMU and Davesh Maulik at MIT give answers to this question. We consider moduli spaces of one dimensional stable sheaves (or stable pairs) on CY 4-folds and integrations of insertions on their virtual classes. Contrary to CY 3-fold case, our virtual dimension is positive, so invariants we define depend on the choice of insertions (i.e. observables in physicists' language). The most canonical insertion is given by the slant product of Chern characters of universal one dimensional sheaf by cohomology classes on the CY 4-fold. Insertions defined using the first nontrivial Chern character are called primary insertions and others are called descendent insertions. Our conjecture is that primary counting invariants give genus 0 GV type invariants of Klemm-Pandharipande while descendent counting invariants contain all genus 1 information. We prove our conjecture when CY 4-folds are 'ideal' and provide several computational evidences in examples. By a dimensional reduction, our genus 0 conjecture recovers the conjecture of Hosono-Saito-Takahashi and Katz on CY 3-folds. The formulation of our genus 1 conjecture involves nontrivial constrains on genus 0 GW/GV invariants of CY 4-folds which we prove to be equivalent to the Witten-Dijkgraaf-Verlinde-Verlinde (WDVV) equations. It is an interesting question to give a physical interpretation of our works.

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5.2 (Co-) Evolution of Supermassive Black Holes and Their Host Galaxies

John Silverman

Supermassive black holes (SMBHs) play an integral role in galaxy evolution. A coupling of their energy output to the surrounding gas internal to galaxies has been recognized as a vital ingredient for simulations to match the observed local mass distribution of galaxies [1]. Such feedback effects occur during phases of mass accretion onto SMBHs, typically observed as quasars and Active Galactic Nuclei.

Hence, much effort has been undertaken to establish a direct causal connection between the growth of galaxies and their SMBHs. In the local Universe, remarkable evidence exists for their coupled growth as seen by the tight relation between the mass of SMBHs and the properties of their host galaxy (i.e., mass, velocity dispersion) as established by the Hubble Space Telescope [2].

The central question is how the local mass relation got established, either black holes and their host galaxies grew together in lock step (i.e., co-evolved) or one preceded the other where a Universe first seeded by black holes would open many new questions. To determine how SMBHs and their host galaxies migrate onto the local mass relation, observations at earlier cosmic times are needed to view the progenitors of such local systems.

John Silverman, Xuheng Ding and their collaborators have completed an effort to establish the link between the mass of SMBHs and the stellar mass of their host galaxies in the distant universe. To do so, the team has carried out a Hubble Space Telescope (HST; PI Silverman) program based on near-infrared imaging with WFC3 of the host galaxies of 32 actively-growing SMBHs at epochs when the Universe was only 4 billion years old ($z \sim 1.5$). Using sophisticated 2D image analysis routines, they decompose the host galaxy emission from the bright quasar to measure their stellar mass (Figure 1 top). Using black hole mass estimates from near-infrared spectroscopy with Subaru/FMOS [3], they find a ratio between the mass of SMBHs and the stellar mass of their host galaxy consistent with the local relation thus indicating a co-evolutionary scenario (Figure 1 bottom; [4]) after proper selection biases are accounted for.

Furthermore, the level of intrinsic scatter in the mass ratio (M_{BH}/M_*) at high redshift is low and matches the local value. This is surprising since one would expect the dispersion to increase with lookback time if the growth of galaxies and their black holes is driven by primarily by galaxy mergers in a scenario of hierarchical assembly of structure. The current explanation is that there is a physical coupling between SMBHs and their hosts through quasar feedback. This is supported by a comparison of the HST data to hydrodynamic simulations which include such feedback effects [5]. To add further intrigue, these processes appear to be linked to galaxies undergoing structural changes from being disk- to bulge-dominated [6] as required to have SMBHs and their hosts migrate onto the local mass relation.

Currently, the wide-field optical imaging from the Hyper Suprime-Cam (HSC) Subaru Strategic Program is being used to significantly expand upon studies of the connection between SMBHs and their host galaxies up to $z \sim 1$ by using 5000 quasars from the Sloan Digital Sky Survey (SDSS) thus improving upon the statistical significance of the results.

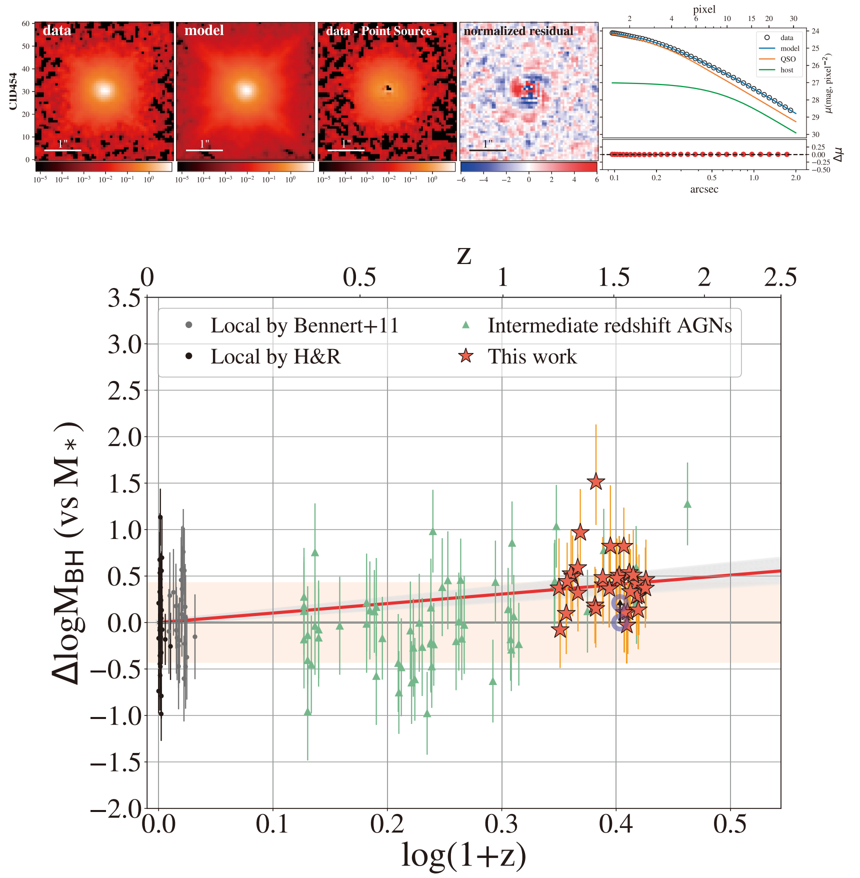

Figure 1: (Top) Example of 2D decomposition of an HST infrared image of an accreting SMBH with the host galaxy shown as "data - point source". (Bottom) Mass ratio (M_{BH}/M_*) between SMBHs and their host galaxies relative to the local ($z = 0$) relation. The 32 accreting SMBHs at $1.2 < z < 1.7$, observed by HST to determine the mass in stars of their host galaxy, are shown in orange. Most of the increase in the mass ratio relative to the local relation (horizontal line at $y = 0$) is due to a bias in the selection of the sample as indicated by the small purple circle. Therefore, *the observations at high redshift are nearly consistent with the local ratio thus illustrative of a co-evolutionary scenario between SMBHs and their host galaxies.*

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5.3 XENONnT – Finding Dark Matter Particles with Liquid Xenon

Kai Martens

Dark Matter (DM) is out there. That much we know from our ever growing knowledge and understanding of the Universe we live in. As we integrated our knowledge of the particles that make up ordinary matter with careful observations of the luminous wonders dotting a clear, dark night-sky, we arrived at a consistent story of how our Universe evolved. And DM is an indispensable ingredient to and actor in this story.

But this was also a bit of a humbling experience: Our trusty "standard model" (SM) of particle physics has no candidate for a DM particle with the properties astronomical observations require of it: we really do not know what DM is. Astronomical observations tell us that our planet and its Sun are plowing through our Milky Way's halo of DM particles. If there is any kind of interaction with these DM particles other than the gravitational one, we should be able to see collisions mediated by that interaction between the DM halo particles and ordinary matter particles in a suitably designed detector here on Earth. That is the idea of a direct detection experiment. Liquid xenon (LXe) experiments are currently the most sensitive such experiments for DM particles with masses on GeV to TeV scales. The XENON collaboration LXe experiments look for signs of DM particles' collisions with ordinary matter as the Earth moves through the Milky Way's DM halo.

Watching DM all throughout the Universe allows us to constrain what a collision between individual DM particles and particles of ordinary matter should look like. First and foremost it informs us that such a collision must be very, very weak. It also tells us that DM particles themselves should be moving slow enough that indeed the motion of our Earth through this DM particle halo is relevant for such collisions. To detect DM particles – and thus get a handle to study their true nature – we therefore need to build detectors that are:

- very massive, so that our detector's target material contains as many electrons and nuclei as possible for the DM particles to collide with
- very clean in terms of the detector's own radioactivity, so that radioactive decays in and around the detector cannot overwhelm recoils from collisions with DM particles
- hidden as far underground as is practical, so that penetrating remnants of cosmic rays cannot produce new radioactive isotopes in the detector material itself

The most important choice in designing a DM particle detector is that of the detector's target material: the material in which either electron (ER) or nuclear (NR) recoils from collisions with DM particles *or* radioactive decays will be recorded. Most of the time it is impossible to know if the detector saw a radioactive decay or a collision with a DM particle; that means we need to find target and detector materials that contain as few radioactive isotopes as possible.

Liquid xenon (LXe) is the target material of choice in today's highest sensitivity DM particle detectors. It has dominated direct detection DM searches since in 2008 XENON10 for the first time produced limits that reached beyond those obtained with other materials. Noble gases in general are attractive target materials because their chemical inertness allows for efficient cleaning from contaminants that are not themselves noble gases, while distillation allows to also separate out traces of other noble gases. And simply filling liquid in a bigger bucket allows for easy scaling of target mass. Xenon is the heaviest of the noble gases, and unlike argon it has no radioactive isotope with a half-life that would make it a source of background intrinsic to the detector's target mass. The half-life of the neutrinoless double beta (0νββ) decay candidate ^{136}Xe on the other hand is long enough that its background contribution remains acceptable while its presence adds new physics potential to the detector – the search for 0νββ-decay is still on-going. Another advantage of LXe targets is their high density, which provides effective shielding against external gamma radiation.

Right now three very similar LXe detectors are competing or getting ready to compete to be the first to find DM particles: XENONnT, LZ, and PandaX-4T. All use dual-phase LXe detectors drifting electrons to independently measure both, the direct scintillation light yield and the ionization yield from a charged particle recoiling in the detector. The relative strength of these two signals allows efficient discrimination between nuclear and electron recoils and thus provide a powerful means to isolate nuclear recoil signals in the presence of the ubiquitous electron recoil background from residual radioactive contamination. Since 2008 this detector design has consistently lead the field – and is still doing so.

After the successful conclusion of the XMASS experiment at the Kamioka Observatory here in Japan three of the XMASS groups joined the XENON collaboration at the end of 2017 to help upgrade the XENON1T detector to XENONnT. Figure 1 shows the infrastructure supporting the detector in Hall B underground at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Apart from the 3-fold increase in LXe target mass the upgrade also introduced three new detector sub-systems, each targeting a specific background contribution or signal loss mechanism to maximize the cumulative sensitivity of the experiment:

1. purification in the liquid phase of xenon to remove electronegative contaminants
2. a water Cherenkov based neutron veto surrounding the LXe target's cryostat
3. radon distillation to reduce the equilibrium ^{222}Rn concentration in the LXe target

The point here is that with the larger overall exposure each new generation of LXe experiments is collecting, previously acceptable background now has to be suppressed. Kavli IPMU played a particularly important role in designing the neutron veto for XENONnT. Figure 2 shows the new, white neutron veto volume inside the existing gray muon veto water shield. Inside the octagonal neutron veto is the cylindrical LXe target, also clad in white for optimal efficiency of the neutron veto. Both, the outer muon veto and the inner neutron veto, will use the same gadolinium loaded water, allowing for high efficiency tagging of neutrons as soon as they emerge from the detector's LXe target and get captured on Gd. The new Gd-water system that maintains water transparency in the veto counters uses technology originally proposed for use at Super-Kamiokande (SK) by KIPMU's Prof. Mark Vagins. The XENONnT Gd-water system also incorporates some newer developments made for SK at the Kamioka Observatory, which now allow SK to tag inverse beta decays throughout its whole inner detector volume. This is a great example for synergy between the different experimental programs at Kavli IPMU's Kamioka Branch. Another important Japanese contribution was to the liquid phase purification of the detector's LXe target material.

At the time of writing this article XENONnT is taking first science data. The most immediate goal for XENONnT is to follow up on XENON1T's much discussed excess of low energy electron recoil events: With our new, enlarged, and cleaner LXe target and the new, larger structures providing the drift field and holding more photomultipliers, the background situation is very different from XENON1T. If the excess is reproduced in XENONnT, the higher statistic and changed environment will ultimately allow us to determine its true origin.

After ~5 years of data taking with XENONnT we hope to have observed first DM particle interactions in the detector – if not, we will push the exclusion limit for a 50 GeV weakly interacting massive particle down to 1.4×10^{-48} cm^2. What else will we either discover or learn? Our data will show, and our analysis methods are designed to prevent errors.

The next, 3rd generation of LXe drift chambers after the current ~10 ton 2nd generation will require ~50 tons of xenon, too much for the world to afford more than one detector. The PIs and senior members of DARWIN/XENON – among them myself – and LUX-ZEPLIN (LZ) have recently signed a Memorandum of Understanding and pledged to work together to build that 3rd generation detector, combining our respective strengths to deliver to the world the optimal detector in this next, presumably final, round of LXe DM hunting, which will push our detection capability to where neutrinos become the major background.

Figure 1: XENONnT support building and structures in Hall B at LNGS

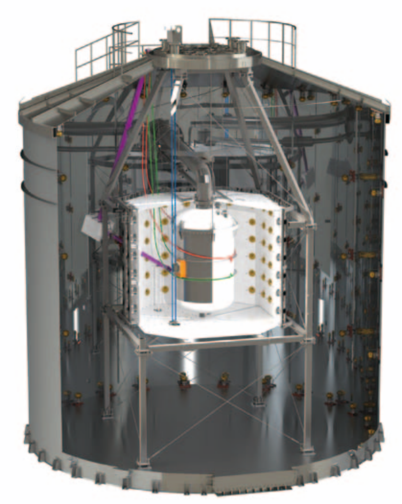

Figure 2: White neutron veto surrounding the LXe target

5.4 Guided by EGADS, Loading Super-Kamiokande with Gadolinium for the First Time

Mark Vagins

Nearly two decades ago, Ohio State University theorist John Beacom and Kavli IPMU Professor and PI Mark Vagins first proposed introducing tons of a water-soluble gadolinium [Gd] compound, gadolinium chloride, $GdCl_3$, or the less reactive though also less soluble gadolinium sulfate, $Gd_2(SO_4)_3$, into the Super–Kamiokande (Super-K, SK) detector. Originally called GADZOOKS! (Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!), this load-SK-with-Gd idea was then detailed in a *Physical Review Letters* article [1]. Dissolving Gd in SK means that neutrons, nearly invisible in pure water Cherenkov detectors, would be rapidly captured on the aqueous Gd ions, leaving their nuclei in a highly-excited state which would then decay, emitting bursts of easily detectable gamma rays. Making neutrons visible and thereby gaining hitherto unattainable end-state information from particle interactions would allow a very large reduction, about a factor of 10^4, in Super-K's physics background rates and greatly enhance the detector's response to both supernova neutrinos (galactic and diffuse) and reactor antineutrinos. Many other physics topics would also benefit, from proton decay searches to studies of atmospheric, solar, and long-baseline neutrino oscillations.

In order to conclusively demonstrate that the GADZOOKS! concept was viable, in 2009 a new experimental chamber was excavated in the Kamioka mine, close to Super–K. There, a dedicated, large-scale gadolinium test facility and water Cherenkov detector (a 200-ton scale model of Super–K), was built as depicted in Figure 1. Known as EGADS (Evaluating Gadolinium's Action on Detector Systems), this joint ICRR/IPMU project was designed to make absolutely sure that the introduction of Gd would allow neutrons to be seen without impairing the water quality or adversely affecting the detector materials. After years of work, the EGADS studies ultimately showed that putting gadolinium in Super-K should work exactly as predicted [2]. As a result, the SK tank was drained and refurbished in 2018/9 in preparation for the loading of gadolinium.

Figure 1: EGADS, the large-scale gadolinium test facility in the Kamioka mine

Finally, on July 14th, 2020, the first gadolinium sulfate was dissolved and injected into the SK tank. As shown in Figure 2, the procedure involved laboriously transporting the gadolinium sulfate in small buckets which were then emptied into the dissolving system's hopper. Working round-the-clock in this manner, Gd-loaded water was continuously injected until, on August 17th, 2020, a total of 13.2 tons of $Gd_2(SO_4)_3$ had been transferred into the SK water. This brought the concentration by mass of dissolved Gd^{3+} ions to 0.01%, meaning that - as shown in Figure 3 - about 50% of the neutrons in SK were being captured on gadolinium (the remainder mostly wind up invisibly on hydrogen just as before) and could now be seen. A tagged neutron-emitting calibration source was deployed at various positions in the SK tank and confirmed both the fraction of visible neutron captures as well as the uniformity of gadolinium loading within the detector.

Everything has been working as expected in SK at 0.01% Gd^{3+}, but even higher neutron capture efficiency is desired. So, in November of 2020 the Gd loading of EGADS was increased to 0.03% Gd^{3+} ions bring its visible neutron fraction to about 75%. Again, all went well with this demonstration, and so the plan to similarly increase Super-K's loading to 0.03% in 2022 was officially approved. As this is a flagship Kavli IPMU experimental initiative, the Institute has agreed to help purchase SK's additional 27 tons of $Gd_2(SO_4)_3$.

It has certainly been a long journey, but exciting new SK data are already being collected!

Figure 2: Carrying pure gadolinium sulfate to be dissolved and injected into Super-K.

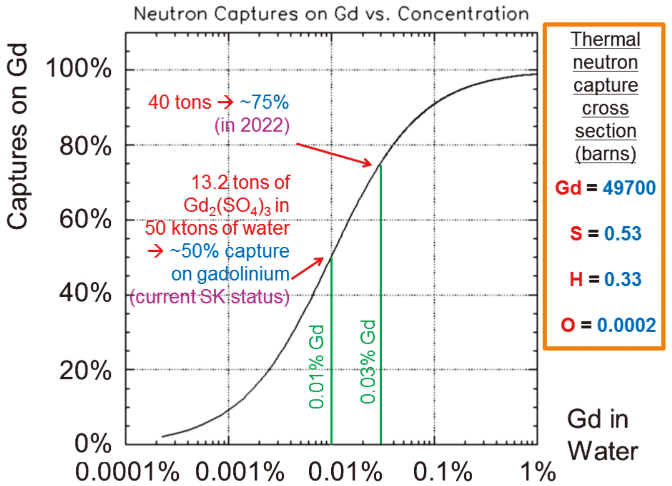

Figure 3: The relationship between Gd concentration in the water and visible neutron capture.

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5.5 Subaru Prime Focus Spectrograph (PFS): Towards Science Operation

Masahiro Takada

We at Kavli IPMU are working on a major astronomical instrument project, called PFS (Prime Focus Spectrograph), which has been promoted by the international collaboration that involves various institutes: Kavli IPMU, National Astronomical Observatory of Japan (NAOJ), Academic Sinica Institute of Astronomy and Astrophysics (ASIAA) in Taiwan, California Institute of Technology (Caltech)/NASA Jet Propulsion Laboratory, Princeton University, Johns Hopkins University, Brazilian Consortium, Group of Max Planck Society in Germany, Chinese PFS Participation Consortium (CPPC), and North-East Participation Group (NEPG) in the US. PFS is a next generation facility instrument on the 8.2 m Subaru Telescope at the 4,200 m summit of Mt. Maunakea in Hawaii. It is a very wide-field, massively-multiplexed, and optical & near-infrared spectrograph, and Kavli IPMU is the leading institute in both aspects of the instrument development and the planning of a 360-night observation campaign for three major science areas of cosmology, galaxy evolution, and Galactic archaeology. Exploiting the Subaru's prime focus, 2394 reconfigurable fibers will be distributed in the 1.3 degree-diameter field of view. The spectrograph system has been designed with 3 arms of blue, red, and near-infrared cameras to simultaneously deliver spectra from 380 nm to 1260 nm in one exposure. From the Subaru's prime focus, the Hyper Suprime-Cam (HSC) has been continuously delivering superb imaging data over a large area of the sky. Conducting spectroscopic follow-up of HSC objects (stars and galaxies) with PFS is crucial to complete a comprehensive census of the universe. This is unique not only because it exploits the unique capabilities of the Subaru Telescope such as the light-gathering power of the 8.2 m primary mirror, and the wide field of view on the prime focus, but also because HSC and PFS enable deep imaging and spectroscopic surveys of the same patches of the sky using the same telescope and from the same site, so one can well understand various systematics in the data which is essential for robust understandings of statistical properties of the universe.

The instrumentation has been carried out by the above international collaboration, being managed by the PFS Project Office: Project Manager is a Kavli IPMU member, Naoyuki Tamura. During this difficult period of 2020 and 2021 under the COVID-19 pandemic, the Project Office has made best efforts to minimize the impact on the instrumentation. The team is actively integrating and testing the hardware and software of the subsystems, and some of them have been delivered to the Subaru Telescope observatory. In September 2020 the team successfully installed all about 2400 "Cobra" positioners on the focal plane of the Prime Focus Instrument (PFI) at ASIAA in Taiwan (Fig. 1). The Cobra positioner, which was mainly developed at Caltech/JPL, is a slender, two-stage motor assembly system that is capable of positioning a fiber to a desired target to within of 5 micrometer. The PFI was successfully shipped to and arrived at the Subaru Telescope in Hawaii in June 2021, and is now being tested at the telescope site (Fig. 1). One of major challenges for an observation with PFS is a precise calibration of the night sky emission. To tackle this problem, the team had a big milestone during 2021. The team installed a pair of small-aperture (36 mm) telescopes, named the Subaru Night Sky Spectrograph (SuNSS), on the top ring of the Subaru Telescope in February 2021. Both SuNSS telescopes have the same focal ratio and the same field of view as PFS, and can receive the same sky signal through the fiber as that of the PFI and can deliver the sky light to PFS fiber cable unit and then to PFS spectrograph modules. As shown in Fig. 2, the team successfully obtained the sky spectra as well as spectra of stars with the SuNSS and the PFS spectrograph. The spectra were used to test and refine the PFS data analysis pipeline.

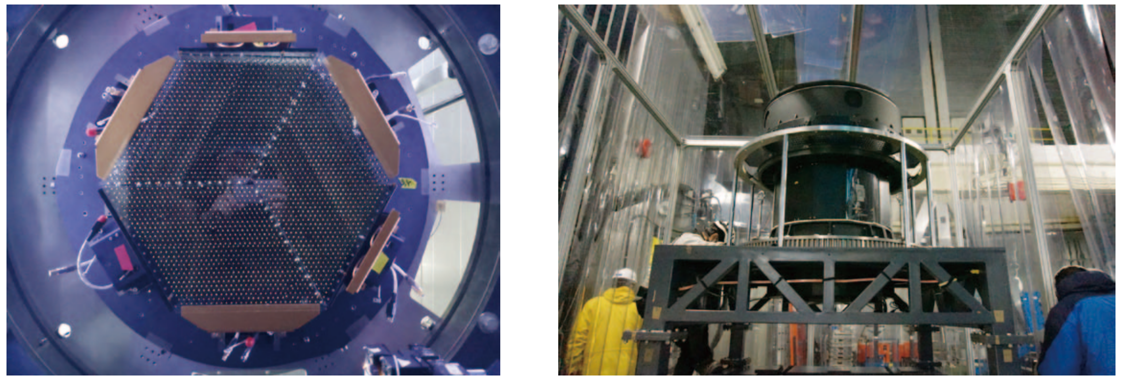


Figure 1 (Left panel): A photo of the PFS Prime Focus Instrument (PFI), taken at the Academic Sinica Institute of Astronomy and Astrophysics (ASIAA) in Taiwan. All about 2400 "cobra" positioners were installed in PFI in September 2020. (Right panel): A photo of PFI taken at the Subaru Telescope. PFI was successfully shipped to the Subaru Telescope in Hawaii in June 2021.

Thus the PFS instrumentation is relatively well underway even during this COVID-19 period. The PFS team is planning to have the first "real" on-sky observation with the PFS PFI, fiber cable and spectrograph module in the commissioning runs of October and November 2021. This will be a big milestone for the PFS project, and we look forward to these commissioning data.

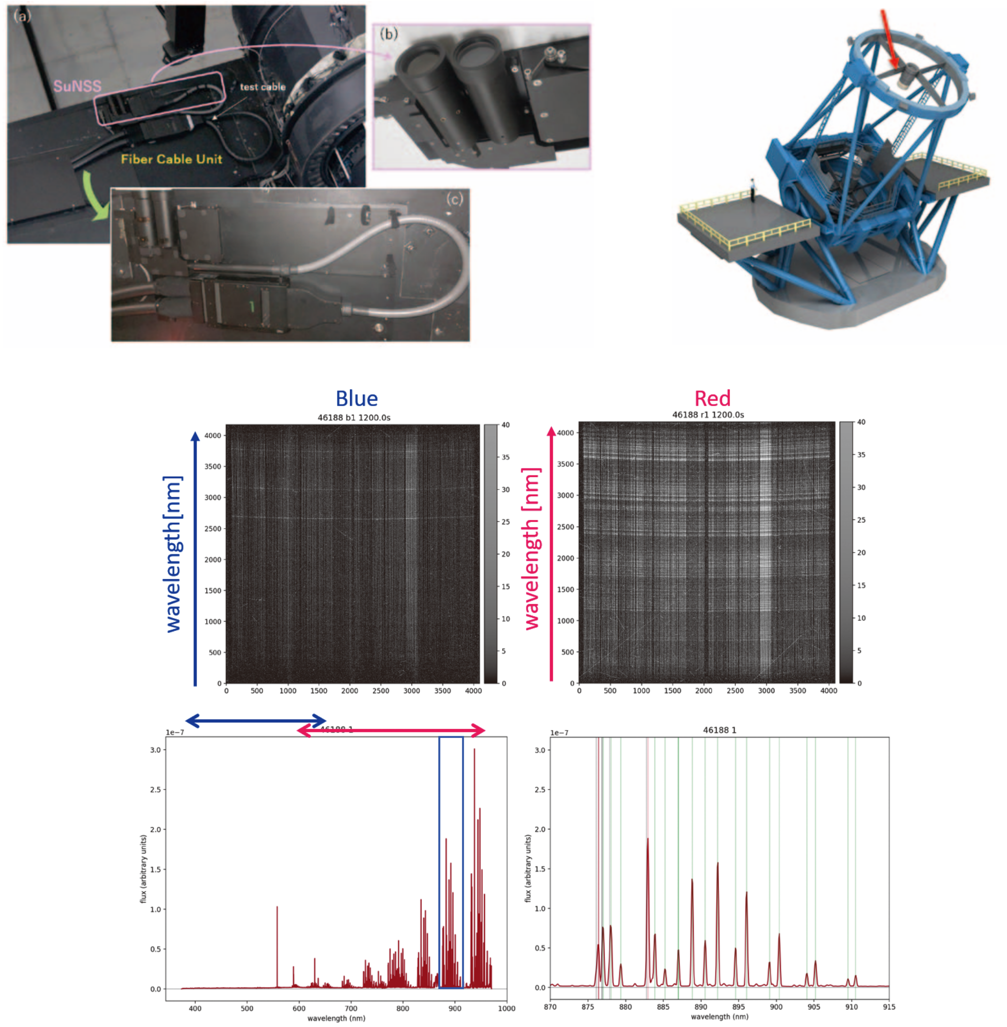
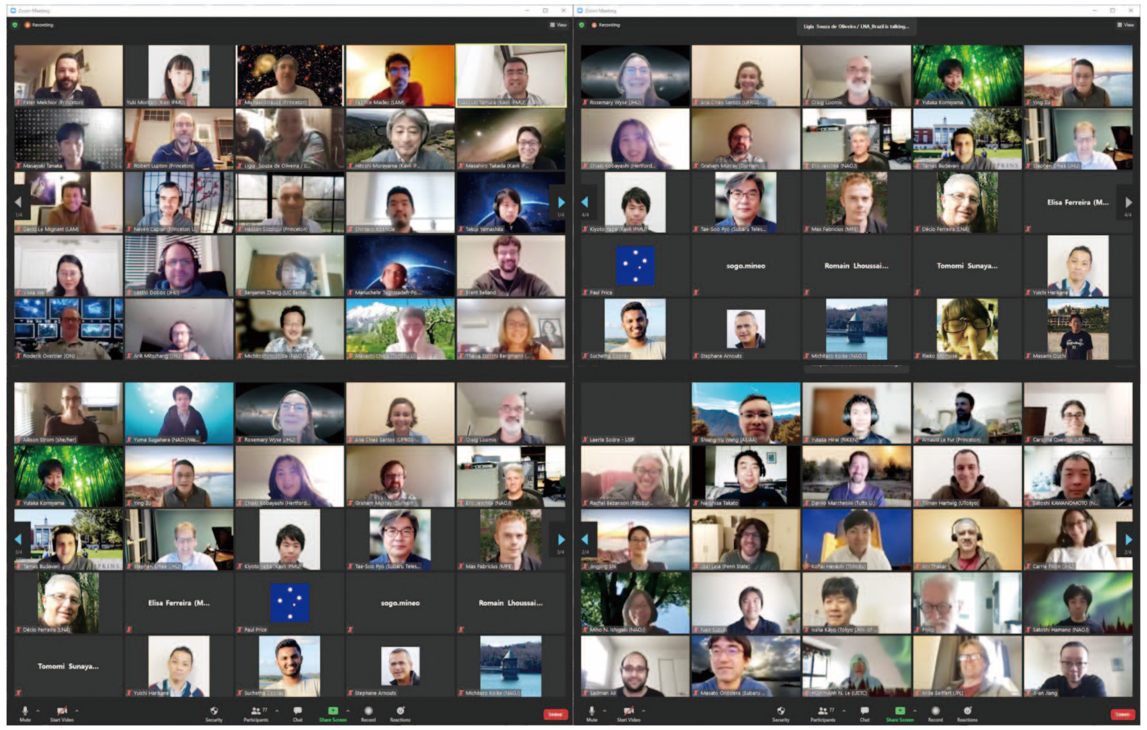
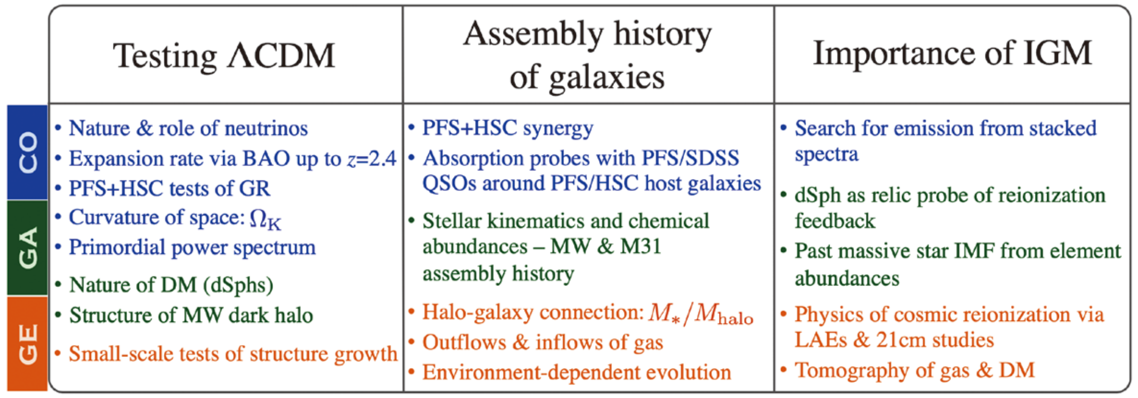


Figure 2 (Upper-left panel): A photo of the Subaru Night Sky Spectrograph (SuNSS) system. The image (a) is a photo of the SuNSS system, the image (b) is the two SuNSS telescopes (each of which has 36 mm aperture), and (c) is the fiber cable unit. The SuNSS was installed on the top ring of the Subaru Telescope, as indicated by the upper-right image, in February 2021. (Lower four panels): The night sky spectra taken with SuNSS that delivers the sky light to the PFS fiber cable unit and PFS spectrograph module. The bottom two panels show the sky spectra that are obtained by the PFS data analysis pipeline. The vertical lines in the bottom right panel denotes the expected wavelengths of OH sky lines, in the wavelength range from 870 to 915 nanometers.

In parallel to the PFS instrumentation, the PFS Science Working Group is developing a timely, concrete plan of large-sky survey observation to be proposed and conducted in the framework of Subaru Strategic Program (SSP). Having the three main survey components in areas of cosmology, galaxy evolution, and Galactic archaeology, the team is aiming at addressing key questions in the modern cosmology and astrophysics by multiple approaches over multiple scales of dark matter density structure, leading to comprehensive challenges to the ΛCDM structure formation paradigm (see the lower panel of Fig. 3). During the COVID-19 period, the team has been continuously updating and refining the plan in detail through discussions regularly by remote meetings and e-mails (Fig. 3). The team, being led by the Science WG co-chairs Masahiro Takada (Kavli IPMU) and Richard Ellis (UCL), completed the writing of the draft of the PFS SSP proposal that will be submitted to the Subaru community in 2022. The proposal is now being reviewed by the external review committee members, assigned by the FPS team, that consist of world-leading experts in cosmology and survey astronomy. We envision that we will start our science operation in 2023. As we are approaching the period of on-sky engineering observations and start of the PFS SSP survey, the interplays between the science team and technical team are more and more crucial, to share not only the basic performances but also the other detailed characteristics of the instrument, and mutually optimize the software components, data flow, and survey management. The members in Kavli IPMU will be playing key roles not only in the integration and commissioning of the PFS instrument, but also in the coagulation of the entire collaboration during the coming key phases of the project in the following fiscal years for ultimate scientific and technical success of PFS.

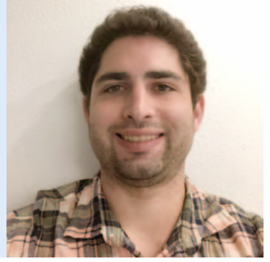




	Testing ΛCDM	Assembly history of galaxies	Importance of IGM
CO	• Nature & role of neutrinos • Expansion rate via BAO up to z=2.4 • PFS+HSC tests of GR • Curvature of space: Ω_K • Primordial power spectrum	• PFS+HSC synergy • Absorption probes with PFS/SDSS QSOs around PFS/HSC host galaxies	• Search for emission from stacked spectra
GA	• Nature of DM (dSphs) • Structure of MW dark halo	• Stellar kinematics and chemical abundances – MW & M31 assembly history	• dSph as relic probe of reionization feedback • Past massive star IMF from element abundances
GE	• Small-scale tests of structure growth	• Halo-galaxy connection: $M_*/M_{\rm halo}$ • Outflows & inflows of gas • Environment-dependent evolution	• Physics of cosmic reionization via LAEs & 21cm studies • Tomography of gas & DM

Figure 3 (Upper panel): A photo of the online 12th PFS collaboration meeting. (Lower panel): Top-level scientific goals we aim at achieving with the planned PFS program spending 360 Subaru nights over 5 years from 2023.

5.6 Resolution of Singularities of Thermal Correlators in String Theory

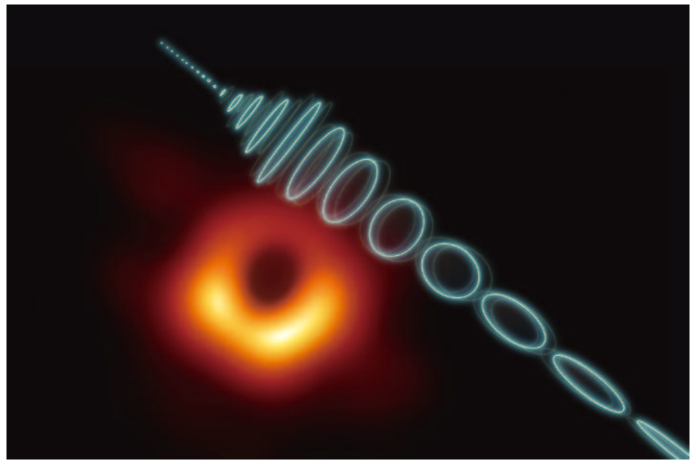


Matthew Dodelson

The fundamental objects in conformal field theory are correlation functions, which measure the correlations between operators at different points in spacetime. One interesting property of these correlation functions is the location of their singularities. At zero temperature the correlation function is singular when two points are lightlike separated, corresponding to a massless particle propagating between the two points. In recent work with Oogur[1], we studied the analogous question at finite temperature. In particular, we addressed possible singularities in the thermal two point function in the Lorentzian regime.

To study this question, we made use of the AdS/CFT duality, which relates conformal field theory in d dimensions to a gravitational theory in d+1 dimensions. In this duality, a thermal state on the boundary is mapped to a black hole in Anti de Sitter space. Singularities of the two-point function in the conformal field theory then correspond to null geodesics connecting two boundary points. Therefore the problem can be reduced to classifying all possible null geodesics in the black hole background that extend to infinity. We showed that in addition to the standard light cone, there are new exotic singularities corresponding to null geodesics that extend into the bulk. These additional null geodesics may wrap the photon sphere many times, and give new singularities in the thermal two point function in the holographic limit.

Although the aforementioned analysis shows that the singularity arises in the strict holographic limit, it may be the case that it is actually resolved at finite coupling constant, corresponding to a finite but small string length. We showed that this resolution indeed occurs by studying string theory in the black hole background. This string theory can be solved exactly by going to the Penrose limit, which describes the geometry very close to the null geodesic. Carrying out the analysis of stringy excitations, one finds that tidal effects stretch out the string more and more as one goes closer and closer to the geodesic. These tidal effects lead to production of massive particles on the worldsheet, which resolves the singularity on the light cone. The behavior of the correlation function near the light cone therefore probes string theory in the bulk, leading to a novel interesting connection between string theory and conformal field theory.



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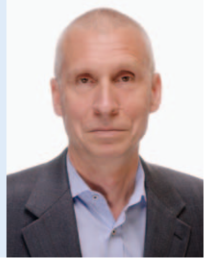
5.7 Perverse Sheaves and Their Categorification



Mikhail Kapranov

Perverse sheaves are local topological data, analogous to those expressed by the mathematical concept of a sheaf. They were introduced in the 1980s in the study of singular algebraic varieties, to provide far-reaching generalizations of various dualities in topology such as Poincaré duality between homology and cohomology. The name "perverse sheaves" simply signifies that they are analogous to sheaves but are not sheaves. In fact, they appear naturally in many areas such as linear PDE.

In many cases perverse sheaves can be classified by quiver diagrams such as

$$\begin{tikzcd} \Phi \arrow[r, bend left, "a"] & \Psi. \arrow[l, bend left, "b"] \end{tikzcd} \tag{1}$$

In this particular case (corresponding to perverse sheaves on the complex line with one singularity) Φ is known as the *space of vanishing cycles* and Ψ as the *space of nearby cycles*. Such diagrams tend to be of balanced nature (arrows going back and forth) which matches the self-dual nature of perverse sheaves themselves. Another example of such balanced structure is provided by the concept of a Hopf algebra so important both in algebra and in mathematical physics (quantum groups). A Hopf algebra A, although not a quiver diagram, has both a multiplication and a comultiplication going in opposite directions

$$A \otimes A \xrightarrow{\text{mult.}} A, \qquad A \xrightarrow{\text{comult.}} A \otimes A.$$

In fact, one can relate Hopf algebras with perverse sheaves on the *configuration spaces*, which are the space of polynomials in one variable

$$f(x) = x^n + a_1 x^{n-1} + \cdots + a_n,$$

stratified by the multiplicity of roots. See [1, 2].

An important organizing principle in mathematics is that of *categorification*, i.e., lifting numerical data to data consisting of vector spaces and the latter to data consisting of categories. In this way, for example, the scalar product (a number) (a, b) of vectors in a Hilbert space can be sometimes upgraded to the vector space of morphisms Hom (A, B) in a category. It was proposed sometime ago by M. Kapranov and V. Schechtman that the concept of a perverse sheaf itself should allow such a categorfied lifting; these conjectural structures were called *perverse schobers*.

One can give a precise meaning to perverse schobers in one dimension, and the resulting theory is already very interesting. For example, the study of Fourier transform of perverse schobers, very natural from the point of view of analogy with PDE, leads to a natural conceptual explanation of the Algebra of the Infrared of Gaiotto-Moore-Witten, a certain "calculus of convex polygons" [3]. See [4] This suggests that a natural encoding of the infrared behavior of a certain class of supersymmetric 2d quantum field theories can be provided by a perverse schober on the complex plane of central charges. The singularities are the central charges of various vacua of the theory. The "vanishing cycles categories", i.e., the categorical analogs of the spaces Φ in (1), are the categories of D-branes corresponding to the vacua, and the tunnelling between the vacua is encoded by the perverse schober structure.

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5.8 Milky Way Dark Matter Severely Constrained by Two New Papers

Oscar Macias

The Universe is filled with an invisible substance (called "Dark Matter") that holds galaxies and clusters of galaxies together. While we are certain of its existence, it is still unclear what are its ingredients. Many particle physics models predict new particles with just the right properties to explain away the astrophysical observations of Dark Matter. Two of the most popular Dark Matter particle candidates are: WIMPs (Weakly Interacting Massive Particles) and Axions. The former is implicated in solving the so-called "hierarchy problem" —*which is associated with explaining the large hierarchy between the electroweak and the Plank scale*— and the latter is involved in preventing the model from assigning a particle in the nucleus of every atom (the neutron); properties that are inconsistent with laboratory observations.

A strong glow of either WIMPs or Axion emission is expected to be originated in the center of the Milky Way. This is both because of its proximity to Earth, and the very large concentration of Dark Matter particles in that sky region. However, the characteristics of the emission from either candidate are predicted to be very different. In the case of WIMPs, since such particles have masses that are a few hundred times heavier than that of a proton, the glow of their self-destruction (or decay) could be observable with highly energetic light detectors (gamma-ray telescopes). While in the case of Axions, which have masses smaller than a billionth times the mass of an electron, their emission could be measured with telescopes scanning the sky for less energetic light signals (radio telescopes).

In two separate articles [1, 2], we have searched for emission of WIMP and Axion Dark Matter in data collected by the *Fermi Gamma-Rays Space Telescope*, and the Effelsberg Radio Telescope, respectively. We have meticulously modeled the astrophysical background (regular emission from objects such as stellar objects, interstellar gas, etc.) in the Galactic Center and concluded that up to the sensitivity level of these instruments, the observations are consistent with the background-only hypothesis. This is the same to say that if either WIMPs or Axions turned out be correct descriptions of Dark Matter, they should be emitting signals that are below the limits displayed in Fig.1.

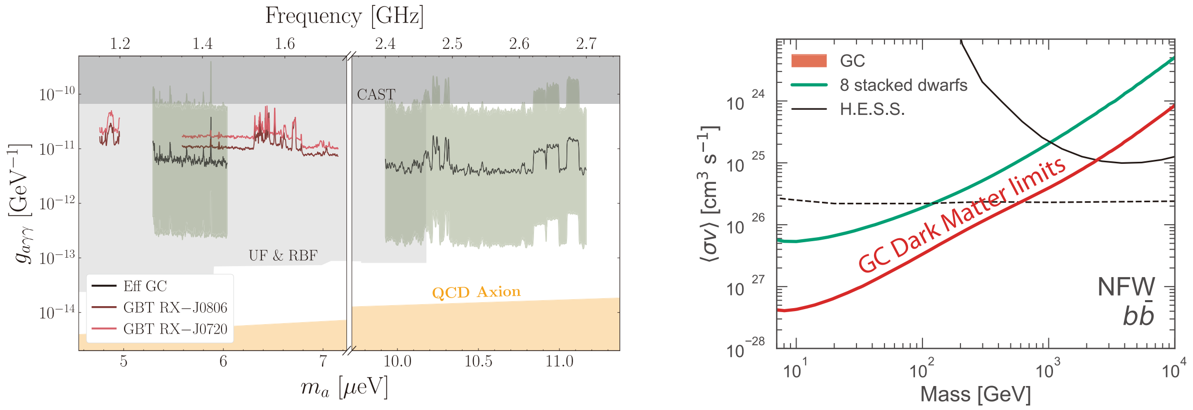

Fig.1. Left: The limits on Axion coupling with photons as a function of the axion mass (black lines). Previous limits from the CAST helioscope and the UF and RBF haloscopes are shown in shaded grey. The range of couplings expected for the QCD axion is shaded in orange. The green band depicts theoretical uncertainties on the Axion coupling limit associated with the GC analysis for the Effelsberg data. Right: The limits on the average dark matter cross section times relative velocity for WIMP particles self-destructing in bottom quarks. The parameter space above the red line is ruled out by null observations of WIMPs from the Galactic Center. Previous limits from dwarf spheroidal galaxies are shown by a green curve. Current limits by the H.E.S.S. observatory are represented by the black solid line. The dashed line is the thermal Dark Matter cross section.

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5.9 Foreground Effect on the J-Factor Estimation of Dwarf Spheroidal Galaxies

Shunichi Horigome

The Standard Model (SM) of particle physics is a well-established framework describing our world with high accuracy, but it is not complete yet. Various cosmological and astrophysical observations show the presence of dark matter (DM), an unknown source of the gravitational force in the universe. Since observations show that it is mainly difficult for macroscopic objects such as primordial black holes to account for all of the DM mass except for a small mass region, most physicists believe that DM is a kind of unknown particle not listed in the SM [1]. The study of DM could therefore lead to a deeper understanding of particle physics.

Once we assume particle DM, from the viewpoint of quantum physics, DM can be categorized by its quantum numbers (charges) such as particle statistics (boson, fermion), the color charge of the strong interaction, the weak isospin, and the U(1) hypercharge. Different compositions of these quantum numbers describe different candidates of DM, hence we have various phenomenology of DM candidates. In particular, *electroweakly interacting massive particle* (EWIMP) is a well-motivated candidate because some theoretically-motivated extensions of the SM predict the presence of such new particles, and also it can naturally explain the relic density of DM in the present universe by the so-called freeze-out mechanism.

Dark matter candidates can be detected by using several detection methods: pair creation detection, direct detection, and indirect detection. Each method has its own advantages and disadvantages and should be used appropriately in different cases. In the case of EWIMP, the indirect detection method is useful because of the enhancement of the annihilation cross-section thanks to the non-relativistic quantum effect, Sommerfeld enhancement [2]. Actually, the gamma-ray observation by Fermi Large Area Telescope (Fermi-LAT) excludes EWIMP DM whose cross-section is less than $O(10^{26})$ $\mathrm{cm}^3\mathrm{s}^{-1}$ when assuming the DM mass is $O(10-100)$ GeV.

The indirect detection method utilizes the annihilation of DM particles in astronomical objects in the universe. When DM annihilates into known particles such as gamma-ray, we can detect these signals by telescopes. In order to increase the efficiency of the detection, target objects must contain as a large amount of DM as possible and their signal-noise ratio must be small. With this taken into consideration, it is known that dwarf spheroidal galaxies (dSphs) are hopeful targets satisfying both conditions.

However, the indirect detection utilizing dSphs suffers from two kinds of biases: i) Biases from dSph modeling and ii) those from data contamination. The former one stems from the fact that we have not determined yet a proper model describing actual dSph systems, hence there is ambiguity in the choice of empirical models. On the other hand, the latter one is due to the contamination of non-dSph member stars when observing dSphs (see fig. 1). These biases could generate large (about $O(10)$) systematical uncertainty of the DM constraint, which is problematic in the current and future DM detection.

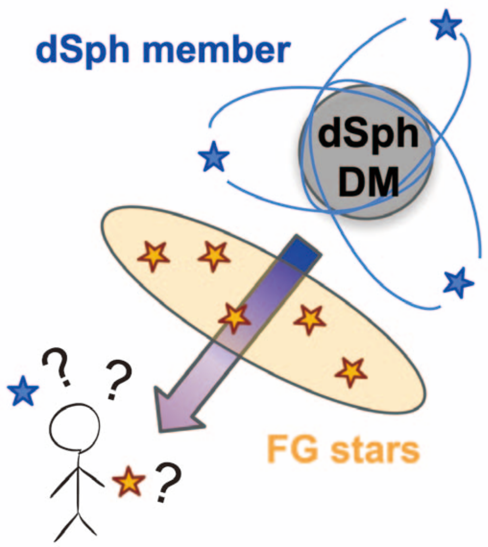

Figure 1: Illustration of the foreground contamination. Blue and yellow stars denote member stars of a dSph and non-member stars (mainly from the Milky Way), respectively. It is difficult for us to distinguish these stars only by using spectroscopic data set, because .

In our study [3, 4], we focused on the latter one, the foreground contamination effect, and developed a new method that can estimate the amount of DM in dSphs even under the influence of the contamination effect. Generally, the amount of DM is estimated by solving dSph kinematics with a spectroscopic stellar data set. In the conventional method, the stellar data set is sorted by using the expectation-maximization (EM) algorithm. Non-member-like stars are eliminated before the kinematical analysis, and only the member-like stars are used in the estimation of the amount of DM. However, there are some issues in this procedure; what we can observe by spectroscopic telescopes is just the velocity projected along the line-of-sight, hence it is difficult in principle to distinguish whether some stars are members or non-members. The conventional method forces these ambiguous stars to be distinguished, which is a source of systematical bias. Moreover, the EM algorithm requires a too simplified approximation of the dSph distribution model (flat velocity dispersion profile), which is also problematic. In order to solve these problems, our method models not only member stars but also non-member stars based on a well-motivated stellar distribution model. All of the stars including ambiguous ones are then analyzed simultaneously, and the amount of DM is directly obtained. This method allows us to estimate the amount of DM in a statistically proper way, in contrast with the conventional method, whose systematical bias cannot be estimated without additional analysis. Using our method, in Ref. [5], we estimated the amount of DM of some hopeful dSphs: Draco, Sculptor, and Ursa Minor, reported as very DM-rich dSphs.

Figure 2 shows that the amount of DM estimated by using different methods. The DM amounts obtained by our method are almost consistent with those reported in the conventional method but slightly deviated from each other due to the contamination effect. We also emphasized that this difference must be larger in the case of ultrafaint dSphs, dSphs recently discovered thanks to improved detection capabilities of telescopes, because of the smaller number of member stars. Our method is a powerful tool even for such a case and works better by using larger stellar data set collected by future spectroscopic telescopes such as Prime Focus Spectrograph (PFS) mounted on the Subaru telescope.

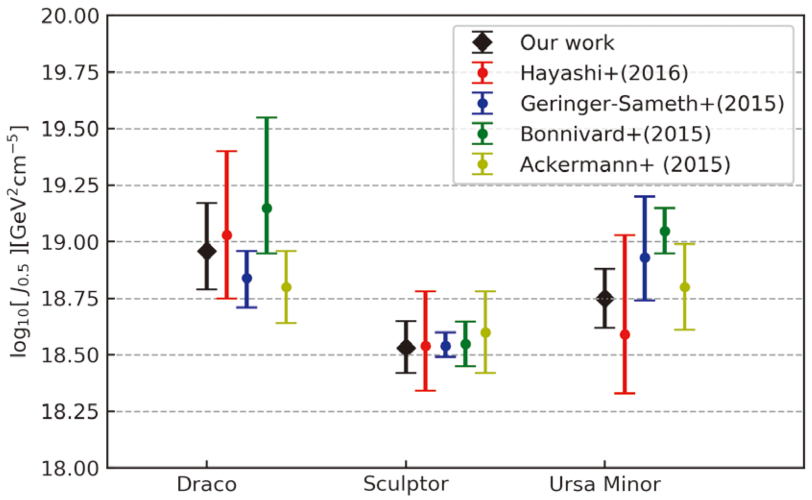

Figure 2: *J*-factor values (squared DM density averaged over the certain region in the celestial sphere) estimated by using our method (black bars) and other conventional methods (colored bars).

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5.10 Sign of Hard X-Ray Pulsation from the Gamma-Ray Binary System LS 5039

Tadayuki Takahashi

A team including former graduate student Hiroki Yoneda, Senior Scientist Kazuo Makishima and Principal Investigator Tadayuki Takahashi has analyzed previously collected data to infer the true nature of a compact object—found to be a rotating magnetar, a type of neutron star with an extremely strong magnetic field—orbiting within LS 5039, the brightest gamma-ray binary system in the Galaxy. They also suggest that the particle acceleration process known to occur within LS 5039 is caused by interactions between the dense stellar winds of its massive primary star, and ultra-strong magnetic fields of the rotating magnetar.

Gamma-ray binaries are a subclass of binary systems consisting of massive stars and compact stars. They were discovered only recently, in 2004, when observations of very-high-energy gamma-rays in the teraelectronvolt (TeV) band from large enough regions of the sky became possible. When viewed with visible light, gamma-ray binaries appear as bright bluish-white stars, and are indistinguishable from any other binary system hosting a massive star. However, when observed with X-rays and gamma-rays, their properties are dramatically different from those of other binaries. In these energy bands, ordinary binary systems are completely invisible, but gamma-ray binaries produce intense non-thermal emission, and their intensity appears to increase and decrease according to their orbital periods of several days to several years.

Once the gamma-ray binaries were established as a new astrophysical class, it was quickly recognized that an extremely efficient acceleration mechanism should operate in them. While the acceleration of TeV particles requires tens of years in supernova remnants, which are renowned cosmic accelerators, gamma-ray binaries boost electron energy beyond 1 TeV in just tens of seconds. Gamma-ray binaries can thus be considered one of the most efficient particle accelerators in the Universe.

In addition, some gamma-ray binaries are known to emit strong gamma-rays with energies of several megaelectron volts (MeV). Gamma-rays in this band are currently difficult to observe; they were detected from only around 30 celestial bodies in the whole sky. But the fact that such binaries emit strong radiation even in this energy band greatly adds to the mystery surrounding them, and indicates an extremely effective particle acceleration process going on within them.

Around 10 gamma-ray binaries have been found in the Galaxy thus far—compared to more than 300 X-ray binaries that are known to exist. Why gamma-ray binaries are so rare is unknown, and, indeed, what the true nature of their acceleration mechanism is, has been a mystery—until now.

Through previous studies, it was already clear that a gamma-ray binary is generally made of a massive primary star that weighs 20-30 times the mass of the Sun, and a companion star that must be a compact star, but it was not clear, in many cases, whether the compact star is a black hole or a neutron star. The research team started their attempt by figuring out which is generally the case.

One of the most direct pieces of evidence for the presence of a neutron star is the detection of periodic fast pulsations, which are related to the neutron star rotation. Detection of such pulsation from a gamma-ray binary almost undoubtedly discards the black hole scenario.

In this project, the team focused on LS 5039, which was discovered in 2005, and still keeps its position as the brightest gamma-ray binary in the X-rays and gamma-ray range. Indeed, this gamma-ray binary was thought to contain a neutron star because of its stable X-ray and TeV gamma-ray radiation. However, until now, attempts to detect such pulses had been conducted with radio waves and soft X-rays—and because radio waves and soft X-rays are affected by the primary star's stellar winds, detection of such periodical pulses had not been successful.

This time, for the first time, the team focused on the hard X-ray band (>10 keV) and observation data from LS 5039 gathered by the hard X-ray detector (HXD) on board the space-based telescopes Suzaku (between September 9 and 15, 2007) and NuSTAR (between September 1 and 5, 2016)—indeed, the six-day Suzaku observation period was the longest yet using hard X-rays.

Both observations, while separated by nine years, provided evidence of a neutron star at the core of LS 5039: the periodic signal from Suzaku with a period of about 9 seconds. The probability that this signal arises from statistical fluctuations is only 0.1 percent. NuSTAR also showed a very similar pulse signal, though the pulse significance was lower—the NuSTAR data, for instance, was only tentative. By combining these results, it was also inferred that the spin period is increasing by 0.001 s every year.

Based on the derived spin period and the rate of its increase, the team ruled out the rotation-powered and accretion-powered scenarios, and found that the magnetic energy of the neutron star is the sole energy source that can power LS 5039. The required magnetic field reaches 10^{11} T, which is 3 orders of magnitude higher than those of typical neutron stars. This value is found among so-called magnetars, a subclass of neutron stars which have such an extremely strong magnetic field. The pulse period of 9 seconds is typical of magnetars, and this strong magnetic field prevents the stellar wind of the primary star from being captured by a neutron star, which can explain why LS 5039 does not exhibit properties similar to X-ray pulsars (X-ray pulsars usually occur in X-ray binary systems, where the stellar winds are captured by its companion star).

Interestingly, the 30 magnetars that have been found so far have all been found as isolated stars, so their existence in gamma-ray binaries was not considered a mainstream idea. Besides this new hypothesis, the team suggests a source that powers the non-thermal emission inside LS 5039—they propose that the emission is caused by an interaction between the magnetar's magnetic fields and dense stellar winds. Indeed, their calculations suggest that gamma-rays with energies of several MeVs, which has been unclear, can be strongly emitted if they are produced in a region of an extremely strong magnetic field, close to a magnetar.

These results potentially settle the mystery as to the nature of the compact object within LS 5039, and the underlying mechanism powering the binary system. However, further observations and refining of their research is needed to shed new light on their findings.

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5.11 Identifying the Origin of Black Holes

Volodymyr Takhistov

Black holes (BHs), peculiar gravitational objects from which even light cannot escape, have been a central theme for both science as well as popular science media for decades. Definitively established to exist, BHs continue to harbor numerous fascinating mysteries. As demonstrated in pioneering work by Deputy Director Misao Sasaki [1, 2], primordial black holes (PBHs) from the early Universe could be directly connected with the recent breakthrough gravitational wave (GW) observations by LIGO as well as the elusive dark matter (DM). Frontiers of PBH research are being advanced across variety of directions by leading scientists affiliated with IPMU including Masahiro Kawasaki, Kazunori Kohri, Alexander Kusenko, Masahiro Takada and Tsutomu Yanagida.

Solar-mass BHs pose particular interest, as they are not expected from textbook astronomy and their detection could thus promise discovery of new physics. Aside solar-mass PBHs, such BHs could also appear as "transmuted" [3] remnants of neutron stars that were eventually swallowed by captured DM (either accumulation of particle DM or tiny PBHs). Intriguingly, solar-mass BH candidates have already been detected by LIGO. *Where do they come from?* As demonstrated in my *Physical Review Letters* study [4], done in collaboration with George M. Fuller (UCSD) as well as Alexander Kusenko (UCLA/Kavli IPMU), a simple but with powerful consequences idea is to analyze the detected BH mass distribution. As displayed in Fig. 1 (left panel), transmuted BHs will follow the known neutron star mass distribution. This immediately leads to a striking result with significant implications for the DM, that BHs with mass $\gtrsim 1.5\ M_\odot$ are unlikely to be from DM consuming neutron stars. Statistical analyses exploiting this approach will further improve our understanding of DM with upcoming data.

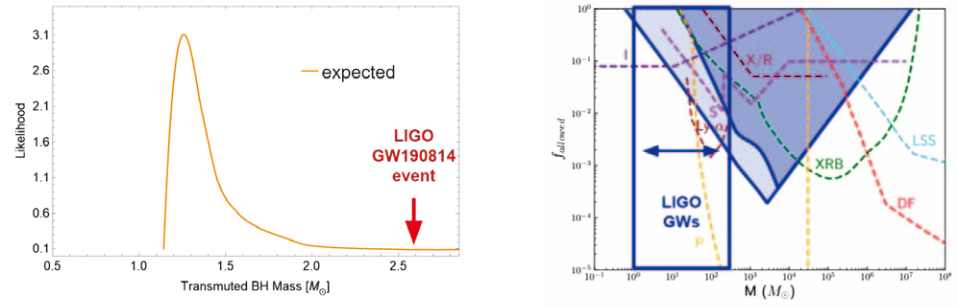

FIG. 1

Significant attention has been devoted to PBH DM in the stellar and intermediate-mass ranges, prime for GW observations [1, 2]. As demonstrated in a series of works [5, 6] that I have led, which were carried out in collaboration with experts from multiple areas of astronomy and high energy physics (including Alexander Kusenko, Yoshiyuki Inoue and Kohei Hayashi affiliated with IPMU) and with results initially appearing in *Astrophysical Journal Letters*, such PBHs can leave significant imprints on host astrophysical systems due to their interaction with interstellar medium gas. Through variety of mechanisms PBHs will deposit energy and heat onto the surrounding gas, which allows for a sensitive probe of PBH DM (especially in well understood systems, such as dwarf galaxy Leo T) over many orders of magnitude in mass, as shown in Fig. 1 (right panel). Curiously, as demonstrated in a different study of mine [7], interactions and heating of surrounding gas also allow to broadly explore emission from minute PBHs efficiently undergoing Hawking evaporation. Thus, gas heating constitutes a novel powerful observable for probing PBHs independently of assumptions about cosmology.

The results of these studies help advance fundamental mission questions of Kavli IPMU, such as *What is the Universe Made of?*, and allow us to understand the Nature from distinct perspectives at a deeper level.

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5.12 Diversities of Supernovae and Their Origin

Ken'ichi Nomoto

Recent very extensive searches of supernovae (SNe) have led to discoveries of new types of supernovae. We (Ken Nomoto and Shing-Chi Leung, a former Kavli IPMU Project Researcher until 2019 September, now a postdoc at Caltech) have studied the following diverse topics of supernovae with international collaborators.

1. Type Ia Supernovae and Supernova Remnants

For Type Ia SNe, whether the progenitor is the Chandrasekhar mass (Chandra-mass) (~$1.4M_\odot$) white dwarf (WD) or a sub-Chandrasekhar (sub-Chandra) mass WD (~1.0–$1.1M_\odot$) have long been controversial. Furthermore, the existence of a new type of fainter Type Ia SNe has been established, which is now called Type Iax SNe. This has provided more controversial materials. To identify the progenitors of SNe Ia (and Iax), is critically important for understanding the nature of dark energy in cosmology and the origin of elements in the Universe.

We have taken the approach to examine the elemental abundances in the remnants of SNe Ia and compare them with the theoretical models of SNe Ia. One of the keys to identify the progenitors is the abundance pattern of the ejecta observed in the supernova remnants. There is one supernova remnant near the galactic center, Sgr A East, whose type has been unknown and controversial. We have made a collaboration with a group in Amsterdam who analyzed the X-ray spectroscopic data taken by the Chandra X-ray observatory and obtained detailed elemental abundance pattern, especially iron-peak elements.

The results in Figure 1 shows that the Mn/Fe and Ni/Fe ratios are much higher than the solar abundance ratios. By comparing our theoretical models of various types of supernovae (types II, Ia, Iax), we found the observed abundance pattern is uniquely explained by the abundance pattern of the pure deflagration model for SN Iax (Figure 1). The high Mn/Fe and Ni/Fe ratios are realized in nucleosynthesis at central densities as high as 5×10^9 g cm^{-3}. Such a high central density implies that the exploding star is the Chandra-mass WD. This is not the sub-Chandra WD where nuclear burning occurs at densities as low as 10^6 g cm^{-3}. In addition, the small S/Fe and Ca/Fe ratios indicate the Type Iax origin, which is the first evidence of the remnant of SNe Iax.

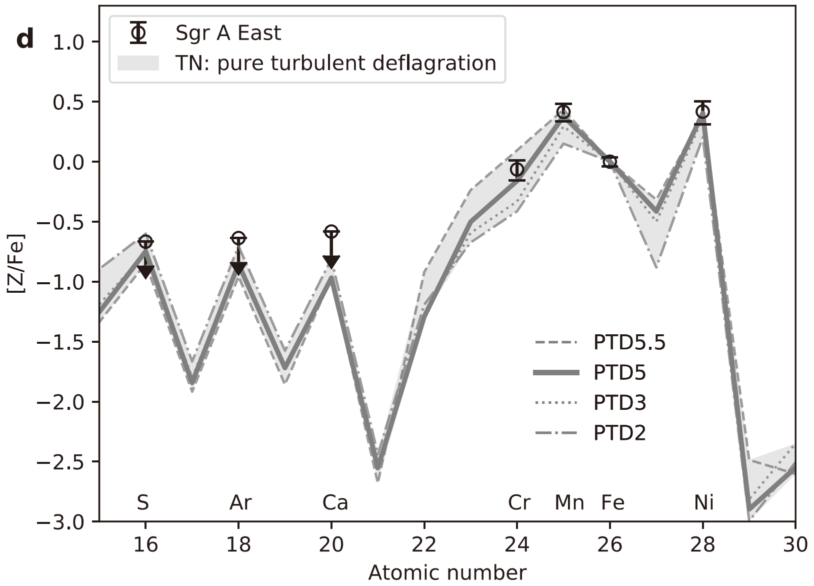

Figure 1. The chemical abundance pattern of the supernova remnant Sagittarius A, EAST for the data points. Here [Z/Fe]=$\log_{10}$ (X(Z)/X(Fe)) – $\log_{10}$ (X(Z)/X(Fe))$_\odot$ with X(Z) is the mass fraction of the element Z and $\odot$ indicates the solar value. The abundance ratios of Cr, Mn, and Ni relative to Fe are well-reproduced by the pure deflagration (PTD) model that occurs in the Chandra mass white dwarf with the central density of ~5×10^9 g cm^{-3} (PTD5: solid line). Other lines PTD2-PTD5.5 show the abundance patterns for the WDs with central densities of 2-5.5×10^9 g cm^{-3}.

The other supernova remnant is 3C397. We have collaborated with the X-ray astronomy group at ISAS/JAXA who observed 3C397. They obtained the abundance pattern and found that the Ti/Fe and Cr/Fe ratios are much higher than the solar ratios. This implies that the supernova ejecta is highly-neutronized by electron capture at such a high central density as 5×10^9 g cm^{-3}, which also implies that the progenitor WD is the Chandra-mass WD, not sub-Chandra WD. Other element ratios indicate that the explosion is of ordinary Type Ia rather than Iax. These results imply that the X-ray observations of supernova remnants to determine the abundance pattern is a very efficient approach to identify the progenitor WDs.

2. Light Variations of Betelgeuse and Its Implications

Betelgeuse is a red-supergiant which is an evolved massive star. It is normally one of the brightest, most recognizable stars of the winter sky, marking the left shoulder of the constellation Orion. But lately, it has been behaving strangely: an unprecedentedly large drop in its brightness has been observed in early 2020 (Figure 2), which has prompted speculation that Betelgeuse may be about to explode.

We analyzed the brightness variation of Betelgeuse with the international team by using evolutionary, hydrodynamic and seismic modelling. We obtained that its radius is ~750$R_\odot$ (solar radius), which is smaller than the expected radius of ~1000$R_\odot$ at the pre-supernova stage. We then concluded that Betelgeuse is in the core helium-burning phase, which is more than 100,000 years before a supernova explosion happens. It has smaller mass (16.5–19$M_\odot$) and radius and is 25 percent closer to Earth (530 light years) than previously thought.

We showed that smaller brightness variations of Betelgeuse (Figure 2) have been driven by the so-called kappa-mechanism of stellar pulsations, and suggested that the large dip in brightness in early 2020 (Figure 2) is unprecedented, and is likely due to a dust cloud in front of Betelgeuse.

3. Electron Capture Supernovae of Super AGB Stars

Electron-capture supernovae have been predicted by K. Nomoto and collaborators in the early 1980s to arise from the explosions of massive "super-asymptotic giant branch (SAGB)" stars whose main-sequence masses are ~8-10$M_\odot$ (Figure 3). However, there has been scant clear evidence.

The observational team led by the group of Las Cumbres Observatory in Santa Barbara found that the supernova SN 2018zd had many unusual characteristics, some of which were seen for the first time in a supernova. We have collaborated with the observer group. We noticed that SN 2018zd had all six indicators predicted for electron capture supernovae, namely, (1) an apparent SAGB progenitor, (2) strong pre-supernova mass loss, (3) an unusual stellar chemical composition, (4) a weak explosion, (5) little radioactivity, and (6) a neutron-rich core. This indicates that an electron capture supernova was finally discovered after 40 years since its existence was predicted by K. Nomoto and collaborators.

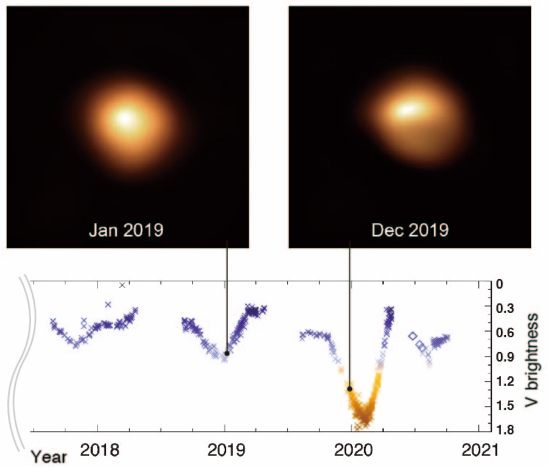

Figure 2. Recent brightness variations of Betelgeuse. A comparison of direct images of the surface of Betelgeuse between Jan 2019 and Dec 2019 show that large portions of the star faded in Dec 2019, which could indicate a dust cloud appearing in front of it.

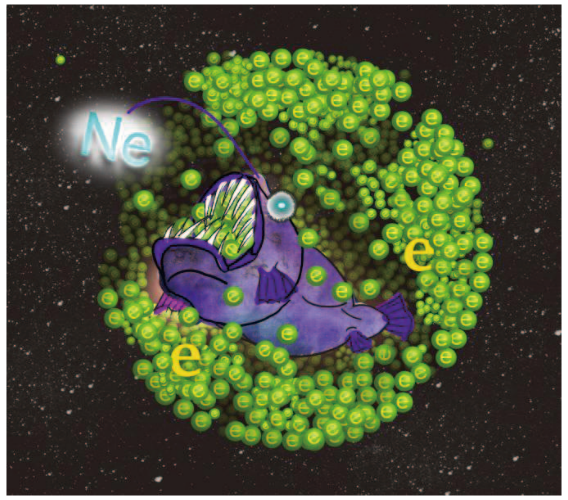

Figure 3. An artist's impression of the "electron capture" supernova. It shows how an imaginary deep-sea fish "football-fish" (having Neon-Sign) eats away at the electrons, which induces the collapse of the electron-degenerate O+Ne+Mg core of the 8–10 $M_\odot$ super-AGB star.

4. Fast Blue Optical Transient (FBOT): COW and GEP

Compared with normal core-collapse SNe (Types II, IIb, Ib), appearing ten to a hundred times brighter at its peak, and with a much faster rise toward the peak (~1–3 days), optical transients AT 2018cow (nicknamed COW) and SN 2018gep (GEP) represent a new type of supernova called Fast Blue Optical Transient (FBOT) (Figure 4).

We have succeeded to explain such an extreme property of COW and GEP as a collision between the supernova and circumstellar materials with no-hydrogen which were ejected before the explosion (Figure 4). In particular, we suggested that such He and C-rich circumstellar materials were ejected from very massive stars which have the initial masses of 80–140$M_\odot$ and undergo big pulsations caused by electron-positron pair production just before the core-collapse.

These circumstellar materials are dense and opaque, making the radius of the star effectively large. When the supernova explosion occurred due to core-collapse, a strong shock wave propagated through the circumstellar materials. When it reached the surface, its kinetic energy was converted into radiation energy, causing a sudden and a very bright event to occur thanks to the large radius. This mechanism can explain the very fast rise of the observed brightness. For the smaller mass of circumstellar materials, the decline of the light curve is also faster.

We are proposing that the variation of the circumstellar mass formed from the pulsational pair-instability of very massive stars would cause variation among FBOTs. If the circumstellar mass is large enough, the resulting supernova would be observed as a so-called Superluminous Supernova which is bright, but shows much slower rising. Such a massive star is related to the formation of massive Black Holes observed by the gravitational wave and also related to the First Stars in the universe.

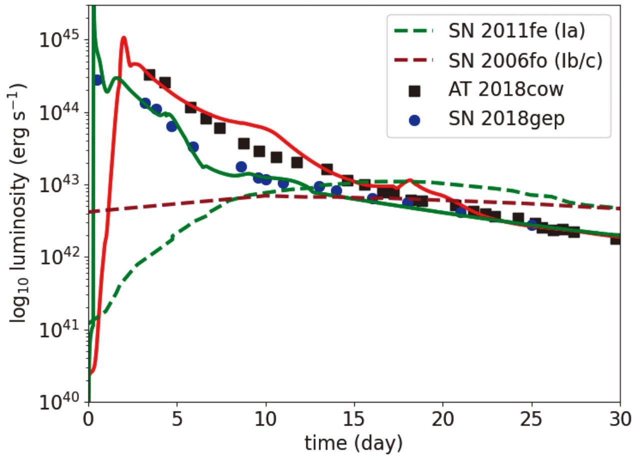

Figure 4. The observed light curves of AT 2018cow (COW) and SN 2018gep (GEP) are shown by the filled circles and squares, respectively. The solid lines show the light curve models for COW (green) and GEP (red). For comparison, the dashed lines show the observed light curves of Type Ia supernova SN 2011fe (green) and Type Ibc supernova SN 2006fo (red). The COW and GEP are much brighter than Type Ia and Ibc supernova at early phase.

6 AWARDS

Kavli IPMU Senior Scientist Ken'ichi Nomoto awarded the Order of the Sacred Treasure

Ken'ichi Nomoto, University of Tokyo Emeritus Professor and Kavli Institute for the Physics and Mathematics of the Universe Senior Scientist, has been selected as one of the recipients of the Order of the Sacred Treasure, it was announced by the Japan government on April 29 as part of the 2020 Spring Conferment.

Nomoto has been a worldwide leader in astronomy, developing theoretical work that has helped researchers study the last stages of stellar evolution, supernovae, nucleosynthesis, gamma ray bursts, neutron star evolution, and the chemical evolution of galaxies amongst many things. A keen educator, Nomoto has also spent a significant amount of time teaching young students and spreading interest in the subject.

Kavli IPMU's Tsutomu Yanagida Awarded 20th Particle Physics Medal of Japan

In September 2020, Kavli IPMU Visiting Senior Scientist Tsutomu Yanagida was awarded the 20th Particle Physics Medal of Japan. The award is conferred by the Particle and Nuclear Theory Forum of the Physical Society of Japan to persons who have given long-term and important contributions to the development of particle physics theory.

Yanagida's award-winning achievement was in recognition of his work in a paper titled "Formulation of a Hidden Local Symmetry and its Application to Hadron Physics." In a prior publication—titled "Is the ρ Meson a Dynamical Gauge Boson of Hidden Local Symmetry?"—Yanagida and his collaborators succeeded in formulating a hidden local symmetry in QCD (quantum chromodynamics), and proposed the ρ meson as a composite gauge field.

Principal Investigator David Spergel Elected President of Simons Foundation

On December 17, 2020 (local time in the US), the Simons Foundation in the United States announced that Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) Principal Investigator (PI) David Spergel will become the next president of the foundation from July 1, 2021. The Simons Foundation was established in 1994 by James Simons and Marilyn Simons to support science and science education.

PI Spergel's research interests range from exoplanet exploration to mapping the early Universe and the formation of galaxies, including as a leading research member of the Wilkinson Microwave Anisotropy Probe (WMAP), a pioneering satellite initiative that has made precise observations of the cosmic microwave background. The WMAP has had a significant impact on science, such as greatly improving our knowledge about the density fluctuations that seeded the formation of galaxies. In recognition of his research, PI Spergel has received numerous awards, including the 2018 Breakthrough Prize in Fundamental Physics.

Kavli IPMU Visiting Senior Scientist Alexander Kusenko and Visiting Scientist Christian Schnell Selected as 2021 Simons Fellows

On February 4, 2021 (local time in the US), the Simons Foundation of the United States announced the 2021 Simons Fellows. The selected researchers included Professor Alexander Kusenko of the University of California, Los Angeles, and Professor Christian Schnell of the State University of New York at Stony Brook.

Established by James and Marilyn Simons in 1994, the Simons Foundation is an organization that supports science and science education, including supporting researchers via the Simons Fellowship. The fellowship is awarded to tenured professors at a university in the United States or Canada with outstanding achievements in mathematics or theoretical physics. Simons Fellows can extend their sabbatical period from a semester to a year, allowing them time to focus solely on long-term research. Professor Kusenko and Professor Schnell were awarded Simons Fellowships for theoretical physics and mathematics, respectively.

CERTIFICATE

The PASJ Excellent Paper Award 2020

Publications of the Astronomical Society of Japan
The Astronomical Society of Japan

Dr. Chiaki Hikage

"Cosmology from cosmic shear power spectra with Subaru Hyper Suprime-Cam first-year data"

The above paper, published in PASJ, 71, 43 (2019), has been selected as the most outstanding paper in the recent publications of PASJ. You, as a coauthor, are awarded the 25th PASJ Excellent paper award.

March 18, 2021
The Astronomical Society of Japan
President ***Masayuki Umemura***

(Credit: Chiaki Hikage)

Chiaki Hikage and Others Win the 2020 PASJ Excellent Paper Award

An international research team led by the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) Project Associate Professor Chiaki Hikage has received the 2020 PASJ Excellent Paper Award, an honour given by the Astronomical Society of Japan (ASJ).

The PASJ Excellent Paper Award recognizes particularly outstanding papers published within the previous five years in ASJ's journal, the Publications of the Astronomical Society of Japan (PASJ). The award-winning papers not only have to be original; they must also have made significant contributions to astronomy.

The award honors all the authors and their institutions, including the University of Tokyo; Nagoya University; Princeton University; Carnegie Mellon University; and the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), Taiwan. The award-wining paper, "Cosmology from cosmic shear power spectra with Subaru Hyper Suprime-Cam first-year data," was published in 2019.

Other prestigious awards

Recipient's name	Name of Award
Shunsaku Nagasawa	School of Science Encouragement Award (Master program)

7 CONFERENCES

Conference title Date, Place	Attendees (from abroad)
Hyper-K Technical Coordination Meeting 18-21 May 2020, [Online]	73 (32)
McKay Correspondence, Mutation and Related Topics 6 July - 14 August 2020, [Online]	54 (40)
19th International Conference on B-Physics at Frontier Machines (Beauty 2020) 21-24 September 2020, [Online]	346 (332)
The World of Mathematical Physics 6-7 November 2020, [Online]	223 (2)
CMB Systematics and Calibration Focus Workshop 30 November-3 December 2020, [Online]	228 (190)
Time-domain Cosmology with Strong Gravitational Lensing 25 January - 2 February 2021, [Online]	114 (95)
What is Dark Matter? - Comprehensive Study of the Huge Discovery Space in Dark Matter 6 February 2021, [Online]	293 (14)
12th PFS Collaboration Meeting 9-11 March 2021, [Online]	134 (72)

8 CONFERENCE PRESENTATIONS AND SEMINAR TALKS

Invited talks given by the Kavli IPMU researchers (Selected 10 of 132)

Date	Presenter	Presentation title	Conference name
Jul. 2, 2020	Hiraku Nakajima	Euler numbers of Hilbert schemes of points on simple surface singularities and quantum dimensions of standard modules of quantum affine algebras	Leicester Algebra and Geometry Open Online Seminar (LAGOON)
Aug. 14, 2020	Yukinobu Toda	On d-critical birational geometry and categorical DT theories	AGEA seminar
Aug. 31, 2020	Yevgeny Stadnik	Search for very low mass feebly-interacting particles (atomic physics, quantum technology)	CERN online workshop on "Feebly-Interacting Particles"
Oct. 23, 2020	Yukari Ito	The McKay correspondence	Kinosaki Algebraic Geometry Symposium 2020
Oct. 26, 2020	Hitoshi Murayama	The Higgs boson and the understanding of the Universe	Higgs 2020
Nov. 19, 2020	Hsueh-Yung Lin	Algebraic approximations of compact Kähler threefolds	Workshop on birational geometry
Dec. 9, 2020	Tom Melia	New analytic probes of effective field theory	NCTS Annual Theory Meeting 2020
Dec. 14, 2020	Mark Vagins	DSNB Detection with a Gadolinium-loaded Super-Kamiokande	SNEUNW20 - Supernova and Early Universe Neutrinos Workshop (SNOWMASS NF04)
Jan. 15, 2021	Naoyuki Tamura	Subaru Prime Focus Spectrograph: A next generation facility instrument of the Subaru telescope is coming to First Light	237th American Astronomical Society meeting
Feb. 24, 2021	Volodymyr Takhistov	A New Window into Neutrino Astronomy with Dark Matter Experiments: Supernova Forecast and the Origin of Supermassive Black Holes	XIX International Workshop on Neutrino Telescopes

9

OUTREACH AND PUBLIC RELATIONS

EVENT TITLE	DATE	VENUE	number of participants
Kavli IPMU Monoshiri Newspaper Online Talk Series "Seeing the World with Mathematics"	May 30, 2020	Online	643
"A Prism to Unveil the Universe"	May 30, 2020	Online	423
"A Way to Look at the Universe"	May 31, 2020	Online	414
"In Search of the Theory of Everything"	May 31, 2020	Online	415
Fundamental Talks (online), Vol. 01: Mathematics—how to interact with objects in a non-everyday manner	Aug. 2, 2020	Online	93
Kavli IPMU x ICRR Joint General Lecture: “Explorations of the unknown and outer-most limits of the Universe and a New Physics”	Aug. 8, 2020	Online	700
Collaborative Knowledge Creation Practical Learning Course with the University of Tokyo CoREF "Learning and Creating Physics - From High School to the Forefront Research of the Universe"	Aug. 4,6,8-9, 2020	Online	108
Science Cafe "Universe"	Sep. 22, 2020	Online	20
Kashiwa Campus Open Day, 2020	Oct. 18 & 25, 2020	Online	1,302
5th “Actually I Really Love Physics!”–Career Paths of Female Physics Graduates	Nov. 7, 2020	Online	18
SECRETS OF THE SURFACE online film screening + panel	Nov. 8, 2020	Online	204
Kavli IPMU x ICRR Joint Public Lecture: “New era of Space telescopes”	Nov. 22, 2020	Online	563
Science Cafe "Universe"	Dec. 5, 2020	Online	51
World-class Researchers are Coming from WPI!	Dec. 26, 2020	Online	70
WPI Science Symposium 2021 "Life" in the 21st Century	Feb. 7, 2021	Online	686
The 6th Kavli IPMU, ELSI, and IRCN Joint Public Lecture: “A Question of Origins”	Feb. 28, 2021	Online	586

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