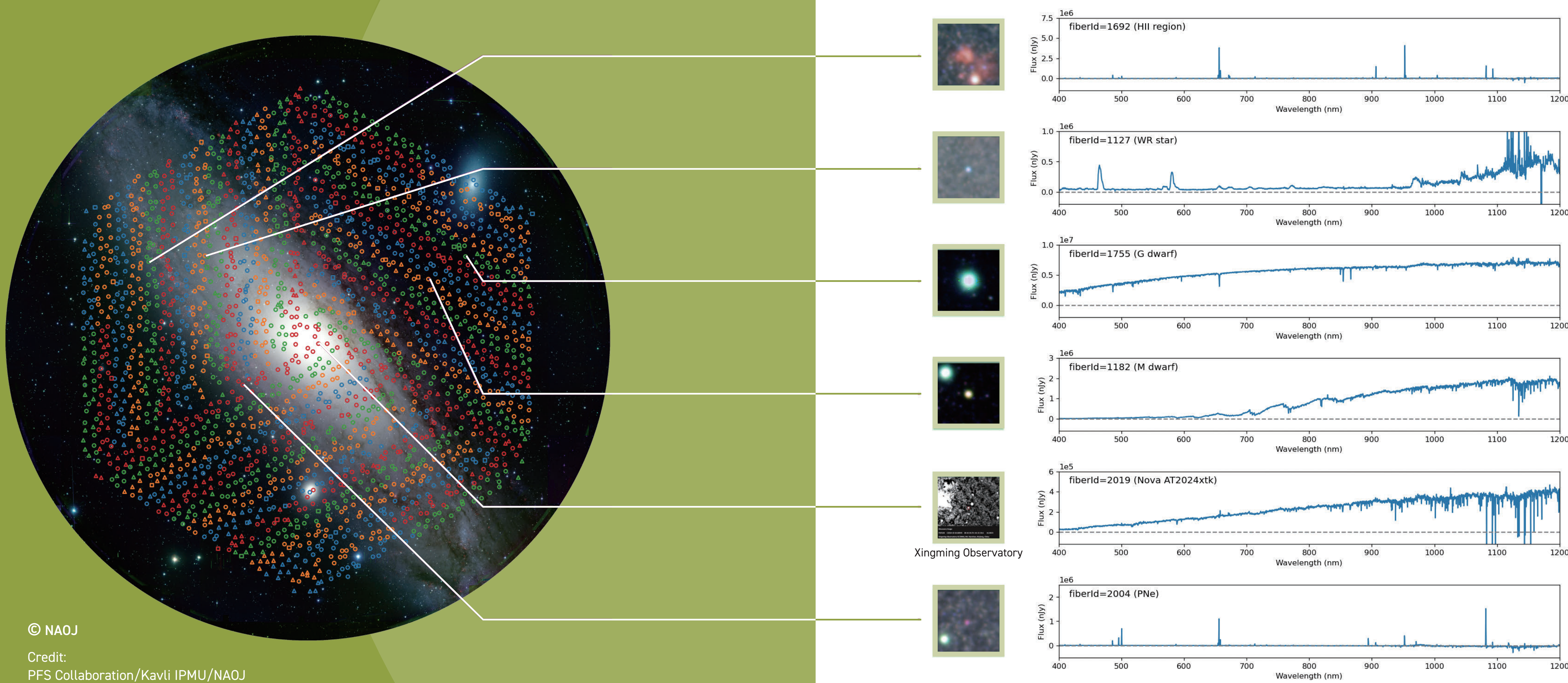
Kavli IPMU
Annual Report 2024 April 2024 - March 2025



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Credit:
PFS Collaboration/Kavli IPMU/NAOJ

Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI)
The University of Tokyo Institutes for Advanced Study
The University of Tokyo

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April 2024–March 2025

Kavli IPMU

ANNUAL REPORT 2024

KAVLI IPMU

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Editing Staff: Shoko Ichikawa
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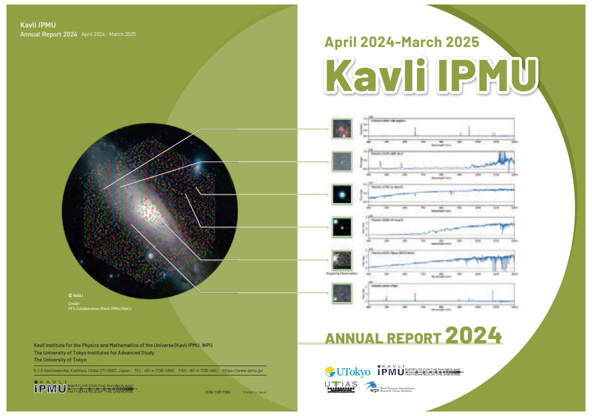


On the cover:
Spectra of Andromeda Galaxy (M31) taken by the Prime Focus Spectrograph mounted on the Subaru Telescope.
For details, please read the Research Highlight article 5.2.

Foreword

Jun'ichi Yokoyama
Director

After 17 years since its founding, Kavli IPMU has matured from its early "childhood" into a vibrant "youth," poised to take on new challenges while building on its solid foundations. Our mission—to seek fundamental truths about the Universe through the unifying power of mathematics, physics, and astronomy—remains as vital as ever.

This year was particularly meaningful in several respects. After more than 15 years of development, the **Prime Focus Spectrograph (PFS)**—an ambitious project led by Kavli IPMU for the Subaru Telescope—was finally completed and is ready for scientific observations. PFS will open a new window onto the Universe, enabling large-scale surveys that will transform our understanding of cosmic structure, dark matter, and dark energy. Its successful realization is a testament to the perseverance and collaboration of many scientists, engineers, and partner institutions around the world.

In addition, this year we signed a new agreement with the Fukushima Institute for Research, Education and Innovation (F-REI). The research group at Kavli IPMU that has been developing medical imaging applications based on X-ray astronomy observation technologies will relocate to F-REI under this agreement. This transition will further strengthen the connection between fundamental research and its practical applications, while fostering new opportunities for collaboration.

In parallel, we engaged in extensive discussions on the **future of theoretical research** at Kavli IPMU. One important outcome was the direction to pursue **the mathematical foundations of quantum information** as a new and emerging area of focus. This field represents a fresh interface between mathematics and physics, with the potential to deepen our understanding of quantum theory while stimulating novel interdisciplinary connections.

Our researchers also continued to make important advances across a wide range of topics—from exploring the origin and composition of the Universe to revealing the elegant mathematical structures underlying physical laws. These achievements exemplify the collaborative and open spirit that defines Kavli IPMU, where ideas move freely across disciplines and borders.

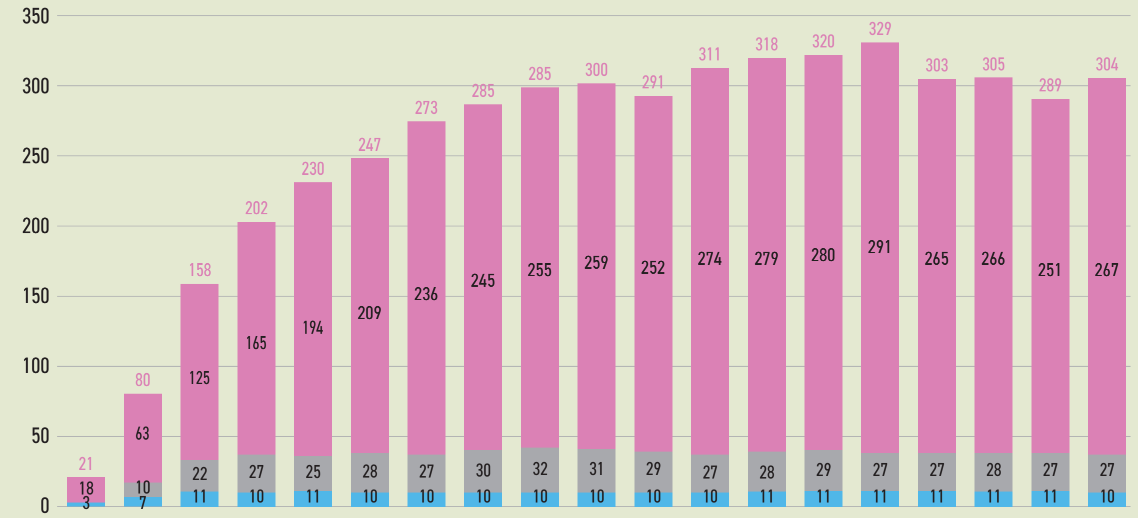
We are deeply grateful for the continued support from the University of Tokyo Headquarters, the Kavli Foundation, our partners, funding agencies, and the broader scientific community. In a time when the research landscape is rapidly evolving, this support enables us to sustain the openness, creativity, and excellence that are central to our mission. With flexibility and collaboration, we will continue to build on our strong foundations and push forward into new frontiers of science.

As we look ahead, we remain committed to nurturing the next generation of scientists—fostering an environment that encourages independent thinking, diverse perspectives, and cross-disciplinary exploration. Together, we will continue to expand the horizons of knowledge and deepen our understanding of the Universe.

Jun'ichi Yokoyama

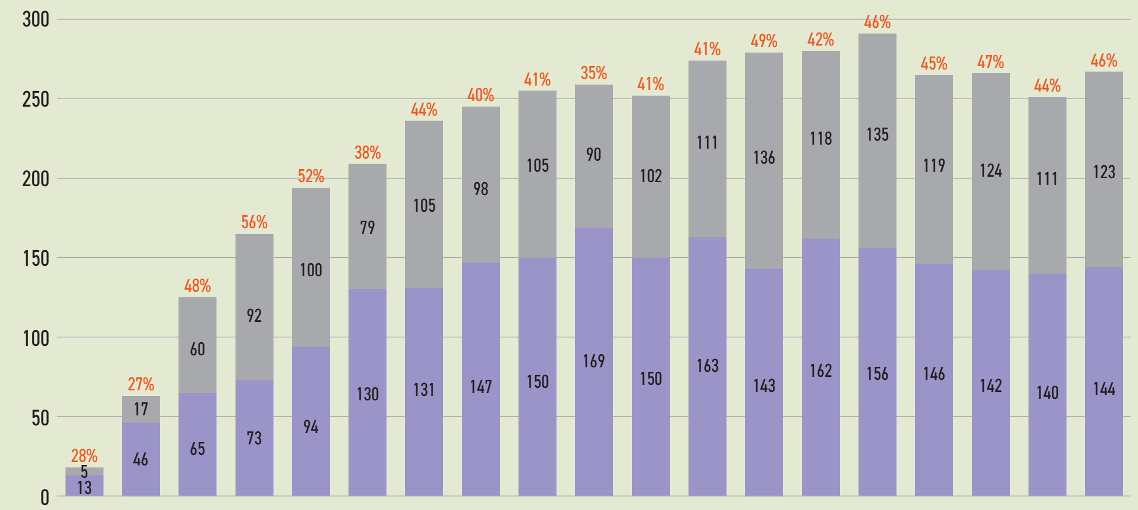
1 Statistics

Staff



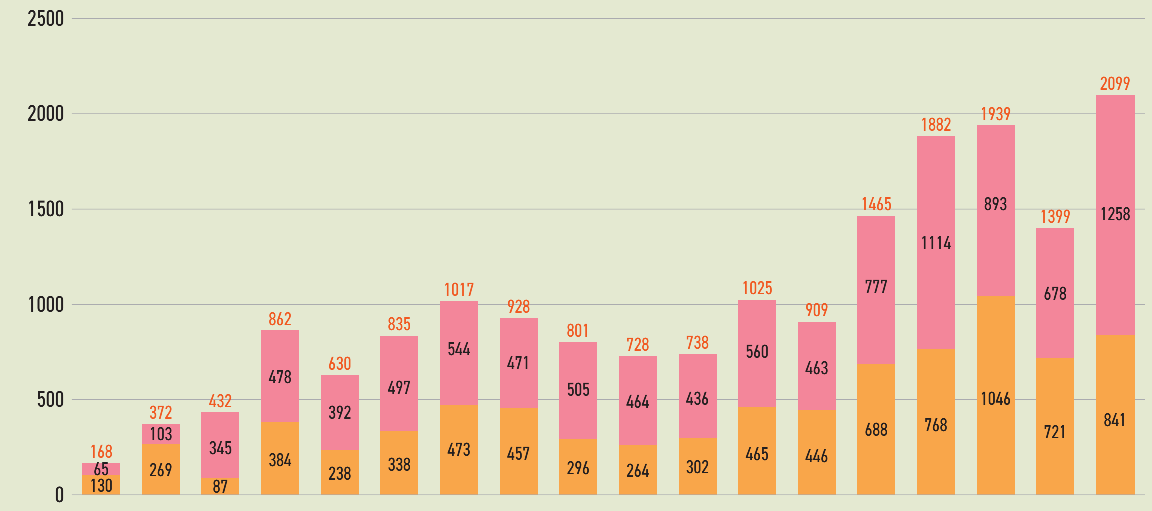
	Oct.2007	Mar.2008	Mar.2009	Mar.2010	Mar.2011	Mar.2012	Mar.2013	Mar.2014	Mar.2015	Mar.2016	Mar.2017	Mar.2018	Mar.2019	Mar.2020	Mar.2021	Mar.2022	Mar.2023	Mar.2024	Mar.2025
Researchers	18	63	125	165	194	209	236	245	255	259	252	274	279	280	291	265	266	251	267
Research Support Staffs	0	10	22	27	25	28	27	30	32	31	29	27	28	29	27	27	28	27	27
Administrative Staffs	3	7	11	10	11	10	10	10	10	10	10	10	11	11	11	11	11	11	10
Total	21	80	158	202	230	247	273	285	297	300	291	311	318	320	329	303	305	289	304

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	Mar.2022	Mar.2023	Mar.2024	Mar.2025
Overseas	5	17	60	92	100	79	105	98	105	90	102	111	136	118	135	119	124	111	123
Domestic	13	46	65	73	94	130	131	147	150	169	150	163	143	162	156	146	142	140	144
% of Overseas	28	27	48	56	52	38	44	40	41	35	41	41	49	42	46	45	47	44	46
% of Female	0	2	5	6	5	2	5	5	6	4	6	8	9	10	9	12	12	15	15
Total number	18	63	125	165	194	209	236	245	255	259	252	274	279	280	291	265	266	251	267

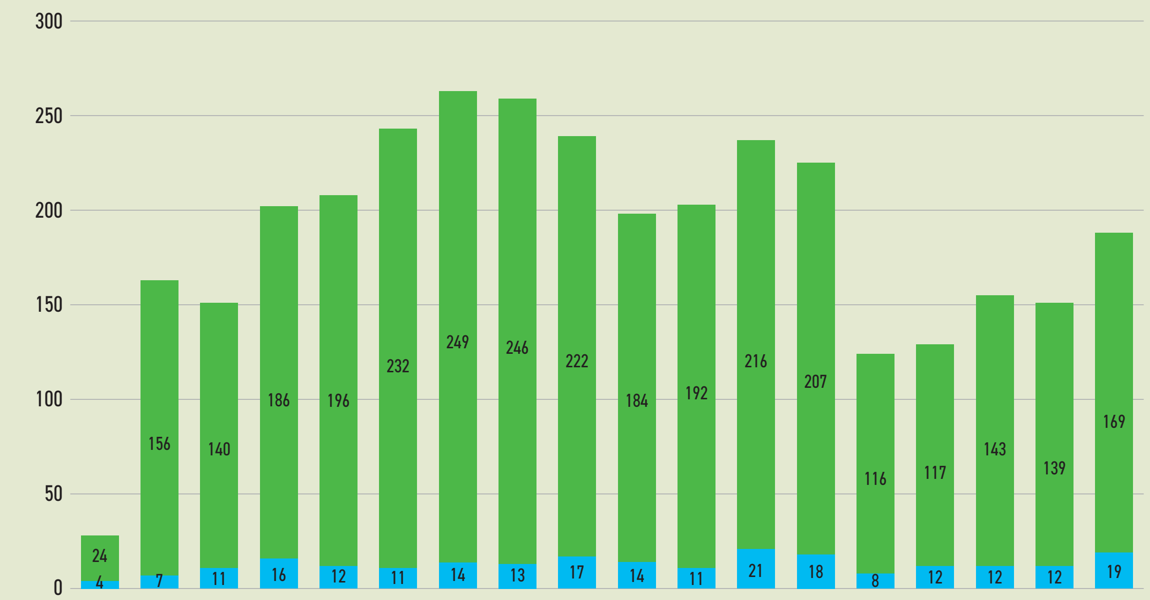
Research Activities



	FY2007	FY2008	FY2009	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024
Visitors (Overseas)	65	103	345	478	392	497	544	471	505	464	436	560	463	777	1114	893	678	1258
Visitors (Domestic)	103	269	87	384	238	338	473	457	296	264	302	465	446	688	768	1046	721	841
Visitors (Total)	168	372	432	862	630	835	1017	928	801	728	738	1025	909	1465	1882	1939	1399	2099

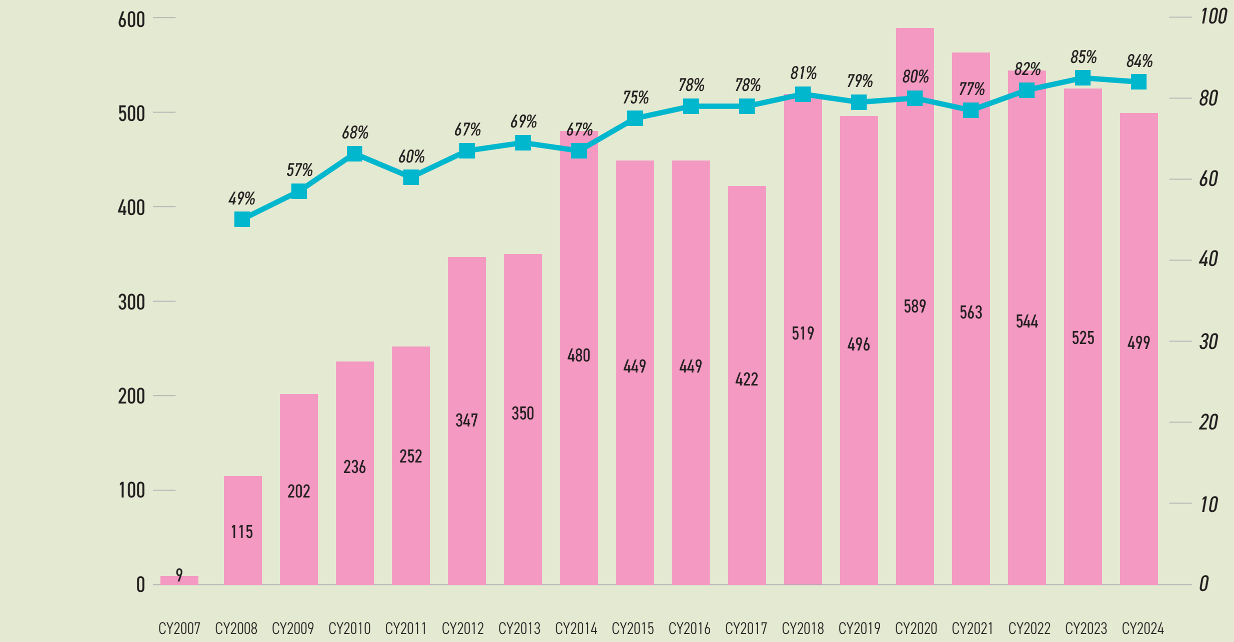
The total number of visitors is listed from FY2023 onward.
*Number of participants for online conferences are included from FY2020 onward.

Seminars and Conferences



	FY2007	FY2008	FY2009	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024
Seminars	24	156	140	186	196	232	249	246	222	184	192	216	207	116	117	143	139	169
Conferences	4	7	11	16	12	11	14	13	17	14	11	21	18	8	12	12	12	19

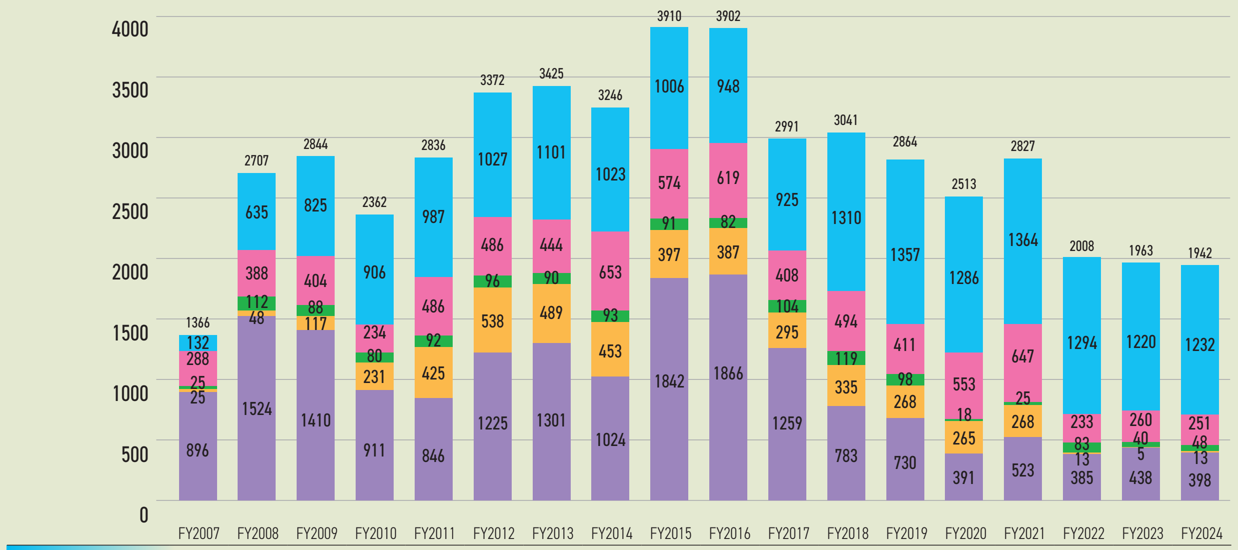
Publications



	CY2007	CY2008	CY2009	CY2010	CY2011	CY2012	CY2013	CY2014	CY2015	CY2016	CY2017	CY2018	CY2019	CY2020	CY2021	CY2022	CY2023	CY2024
Publications	9	115	202	236	252	347	350	480	449	449	422	519	496	589	563	544	525	499
% of int'l collabolation		49	57	68	60	67	69	67	75	78	78	81	79	80	77	82	85	84

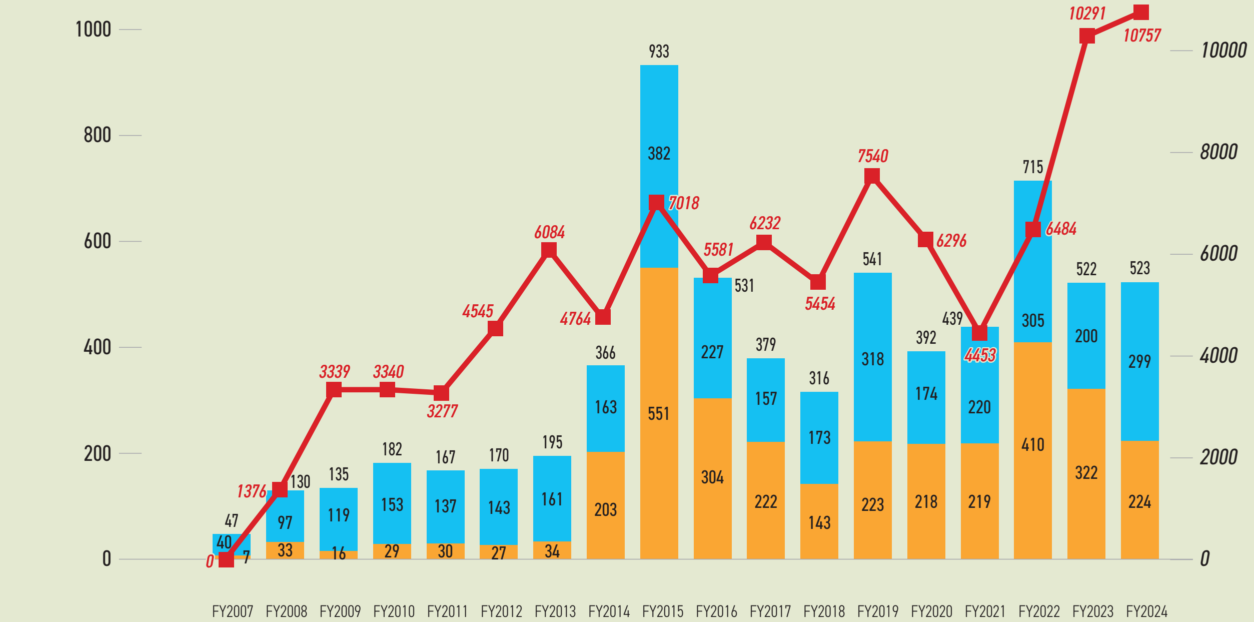
Total Expenditure

(1,000,000 JPY)



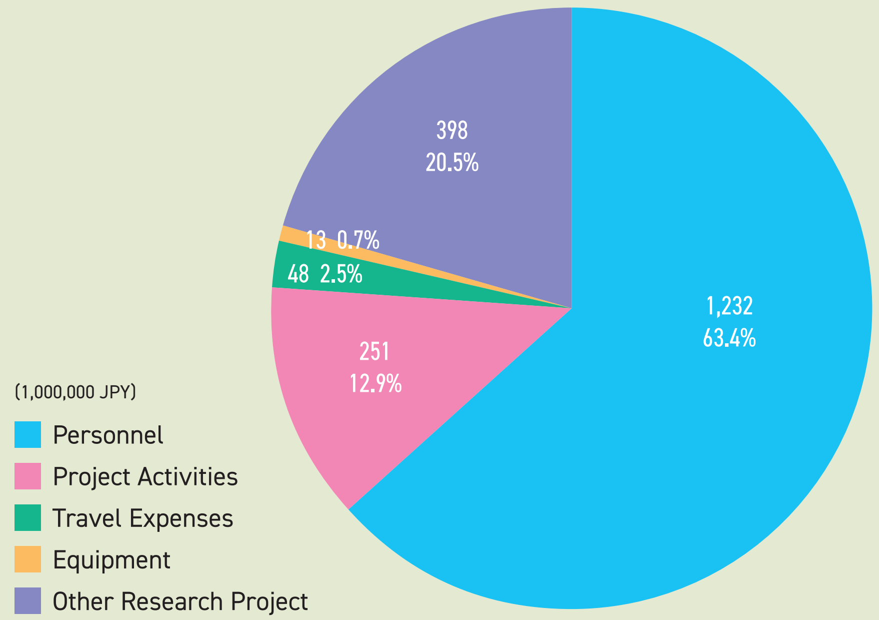
	FY2007	FY2008	FY2009	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024
Personnel	132	635	825	906	987	1027	1101	1023	1006	948	925	1310	1357	1286	1364	1294	1220	1232
Project Activities	288	388	404	234	486	486	444	653	574	619	408	494	411	553	647	233	260	251
Travel Expenses	25	112	88	80	92	96	90	93	91	82	104	119	98	18	25	83	40	48
Equipment	25	48	117	231	425	538	489	453	397	387	295	335	268	265	268	13	5	13
Other Research Project	896	1524	1410	911	846	1225	1301	1024	1842	1866	1259	783	730	391	523	385	438	398
Total	1366	2707	2844	2362	2836	3372	3425	3246	3910	3902	2991	3041	2864	2513	2827	2008	1963	1942

Media Coverages and Outreach Activities



	FY2007	FY2008	FY2009	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	FY2016	FY2017	FY2018	FY2019	FY2020	FY2021	FY2022	FY2023	FY2024
Participants in Outreach Activities	0	1376	3339	3340	3277	4545	6084	4764	7018	5581	6232	5454	7540	6296	4453	6484	10291	10757
Media Coverages (Domestic)	40	97	119	153	137	143	161	163	382	227	157	173	318	174	220	305	200	299
Media Coverages (International)	7	33	16	29	30	27	34	203	551	304	222	143	223	218	219	410	322	224

Breakdown of FY2024 Total Expenditure



2 News & Events

April 2024 - March 2025

APRIL

- Earliest twin quasars irradiated young universe
- Naoki Yoshida receives the 2024 Philipp Franz von Siebold Award
- Prime Focus Spectrograph (PFS) In final phase of commissioning
- Baryons in the Universe 2024
- Kavli IPMU x ICRR 30th Joint Public Lecture: Hyper-Kamiokande Experiment & Singularities
- Maria Mylova named 2024 Emmy Noether Fellow

MAY

- Towards Realistic Physics at Large Quantum Number
- The case of the missing black holes

JUNE

- Workshop on Galaxy and Black-hole Evolution
- Hitoshi Murayama awarded Miller Senior Fellowship

JULY

- Hirosi Ooguri appointed Louis Michel Chair
- LLP2024: Fourteenth Workshop of the Long-Lived Particle Community
- Reconstructing Our View of the Universe with JWST and COSMOS-Web
- First measurement of a nuclear recoil signal from solar neutrinos with XENONnT
- Hirosi Ooguri receives the Frontier of Science Award
- Science Cafe 2024: Universe

AUGUST

- Tadashi Takayanagi receives the 2024 ICTP Dirac Medal
- Dancing galaxies make a monster at the cosmic dawn
- Energy transmission in quantum field theory requires information

SEPTEMBER

- Masahiro Takada appointed new deputy director of Kavli IPMU
- MEXT Minister Masahito Moriyama visits Kavli IPMU
- Shigeki Matsumoto awarded the 2024 Particle Physics Medal
- Science Cafe 2024: Universe
- Focus Week on Non-equilibrium Quantum Dynamics

OCTOBER

- Saeko Hayashi appointed new Administrative Director of Kavli IPMU
- Misao Sasaki named Benjamin Lee Professor
- Kavli Foundation President Cynthia Friend visits Kavli IPMU
- *p*-adic Cohomology and Arithmetic Geometry
- 27th International Conference on Particle Physics and Cosmology (COSMO2024)
- Hirosi Ooguri to deliver the Ta-You Wu Lecture
- Kashiwa Open Campus 2024
- Kashiwa-no-ha Dark Matter and Cosmology Symposium: Satellite Workshop of COSMO2024

NOVOMBER

- Masayuki Nakahata receives Medal with Purple Ribbon
- Researchers uncover link between quantum information theory and particle and condensed matter physics
- T2K Analysis Workshop
- Focus Week on Primordial Black Holes 2024
- 13th Annual WPI Science Symposium: A World Made Bigger With Science
- Probing the Genesis of Supermassive Black Holes: Emerging Perspectives from JWST and Expectation Toward New Wide-Field Survey Observations
- Kavli IPMU Annual Report 2023 released

DECEMBER

- Hitoshi Murayama elected to Vice Chair of Division of Particles and Fields under American Physical Society
- Astronomers witness the in situ spheroid formation in distant submillimetre-bright galaxies
- Yukari Ito elected as the next president of the Asian-Oceanian Women in Mathematics
- Kavli IPMU x ICRR Joint Public Lecture: The Mystery of Massive Quantities
- Hitoshi-fest: From Particle Physics, Cosmology to Instrumentation

JANUARY

- PFS Collaboration Meeting
- Prime Focus Spectrograph on Subaru Telescope is about to begin its scientific operations
- Minh Nguyen named a recipient of the 2024 Buchalter Cosmology Prize
- LiteBIRD Face-to-Face Meeting at Kavli IPMU
- 10th Kavli IPMU/ELSI/IRCN Joint Public Lecture: A Question of Origins

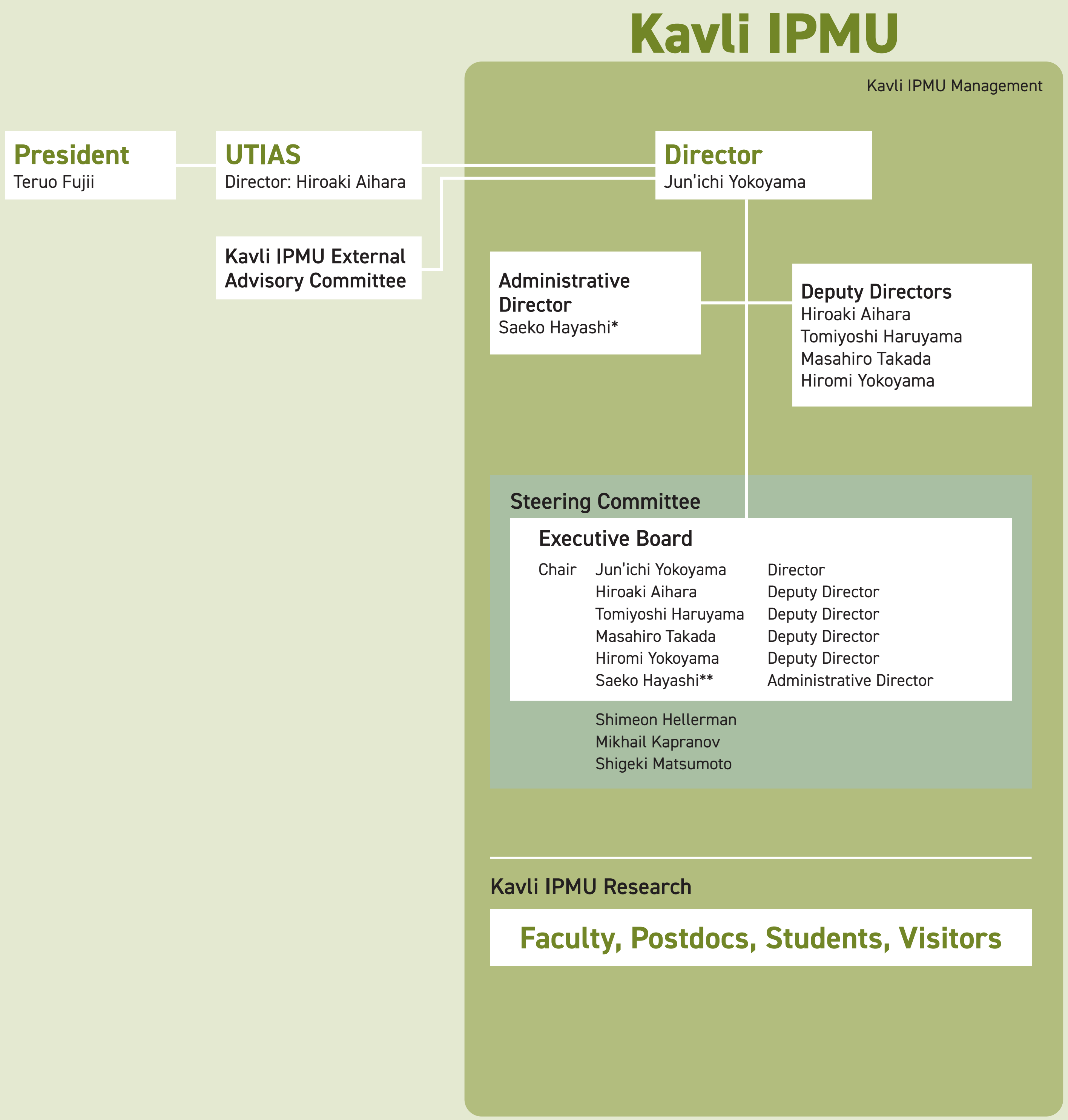
FEBRUARY

- Categorical and Analytic Invariants in Algebraic, Symplectic And Complex Geometry
- Researchers find dark matter dominating in early universe galaxies
- Tomiyoshi Haruyama receives the Koshiba Prize and 2025 Samuel C. Collins Award
- Belle II Upgrade Workshop
- Miho Katsuragawa awarded 2025 Fumiko Yonezawa Memorial Award
- Kavli IPMU and Fukushima Institute for Research, Education and Innovation sign MOU to further research collaboration

MARCH

- Enumerative Geometry, Representation Theory, and Physics
- The Quantum Frontier of Machine Learning

3 Organization



* Tomiyoshi Haruyama (till 2024/9/30)
** Saeko Hayashi (from 2024/10/1)

The Kavli IPMU has a distinctive organizational structure. 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 crossdisciplinary interactions.

The Director is appointed by the Director of the University of Tokyo Institutes for Advanced Studies (UTIAS). The Director has complete authority to hire research staff and administrative staff. He is also solely responsible for making all other decisions. He is assisted by the four Deputy Directors and the Administrative Diretor. They constitute the Executive Board (EB) and regularly meet to ensure the smooth operation of the Institute. The EB has close relation with the Office of the President for consultations on both scientific and administrative matters.

The Director is required to report new faculty appointments to the Director of UTIAS. In addition, to be in line with the university's formal procedures for faculty hiring, the Institute's decisions must be endorsed by the Kavli IPMU Steering Committee.

Instead of having a separate category, all the Full Professors at Kavli IPMU are regarded as equivalent to PIs.

The External Advisory Committee (EAC), appointed by the Director of the Kavli IPMU, reviews the scientific achievement and activities of the Institute and advises the Director on scientific properties and the research activities to keep the Institute stay on the course of the objectives.

The External Advisory Committee Members (April 2024)

Joshua Frieman	SLAC, USA	Cosmology
Shin'ya Aoki	RIKEN, Japan	Theoretical Physics
François Bouchet	IAP, France	Cosmology
John Ellis	King's College, London, UK	Phenomenology
Shirley Ho	Flatiron Inst./Princeton U, USA	Data Science
Sakura Schafer-Nameki	U of Oxford, UK	Mathematical Physics
Yongbin Ruan	Zhejiang U, China	Geometry and Physics
Michitoshi Yoshida	NAOJ, Japan	Astronomy

The main laboratory building on the Kashiwa Campus provides a basis for our researchers. Even most of experimental ists who are involved in Kamioka experiments and astro nomical 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 Études Scientifiques (IHES), France

Collaborating Institutions (domestic)

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

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

4 Staff

Director

Jun'ichi Yokoyama, Cosmology

Deputy Directors

Hiroaki Aihara (U Tokyo, School of Sci.), High Energy Physics
Tomiyoshi Haruyama, High Energy Physics (till 2025/3/31)
Masahiro Takada, Cosmology (from 2024/9/1)
Hiromi Yokoyama, Science and Society (till 2025/3/31)

Senior Fellows

Alexey Bondal (Steklov Math. Inst.), Mathematics
Takaaki Kajita (U Tokyo, ICRR), Neutrino Physics
Eiichiro Komatsu (MPI for Astrophysics), Cosmology
Alexander Kusenko (UCLA), Particle Theory
Masayuki Nakahata (U Tokyo, ICRR), Astroparticle Physics
Mihoko Nojiri (KEK), Particle Theory
Andrei Okounkov (Columbia U), Mathematics
Naoshi Sugiyama (Nagoya U), Cosmology

Faculty Members

Tomoyuki Abe, Mathematics
Hiroaki Aihara (U Tokyo, School of Sci.), High Energy Physics
Linda Blot, Astrophysics
Alexey Bondal (Steklov Math. Inst.), Mathematics (2024/9/1- 2025/2/15)
Patrick De Perio, Neutrino Physics
Enrico Garaldi, Astrophysics (from 2025/1/16)
Elisa Gouvea Mauricio Ferreira, Cosmology
Tomiyoshi Haruyama, High Energy Physics
Saeko Hayashi, Astronomy
Simeon John Hellerman, String Theory
Takeo Higuchi, High Energy Physics
Kentaro Hori, String Theory
Yukari Ito, Mathematics
Kookhyun Kang, High Energy Physics (2024/8/16- 2025/2/28)
Mikhail Kapranov, Mathematics
Khee-Gan Lee, Astronomy
Jia Liu, Cosmology
Kai Uwe Martens, Experimental Physics
Shigeki Matsumoto, Cosmology
Tomotake Matsumura, Experimental Physics
Thomas (Tom) Edward Melia, Particle Theory
Todor Eliseev Milanov, Mathematics
Hitoshi Murayama (UC Berkeley), Particle Theory
Hiraku Nakajima, Mathematics
Toshiya Namikawa, Cosmology
Hirosi Ooguri (CALTECH), Mathematical Physics
Tadashi Orita, Experimental Physics (till 2025/3/31)
Misao Sasaki, Cosmology
Jingjing Shi, Cosmology
Satoshi Shirai, Particle Theory
John David Silverman, Astronomy
Yuji Tachikawa, Particle Theory
Masahiro Takada, Cosmology
Tadayuki Takahashi, Experimental Physics
Shinichiro Takeda, Experimental Physics (till 2025/3/31)
Leander Friedrich Thiele, Astrophysics
Yukinobu Toda, Mathematics
Mark Robert Vagins, Astroparticle Physics
Taizan Watari, Theoretical Physics
Atsushi Yagishita, Experimental Physics (till 2024/5/31)
Masaki Yamashita (U Tokyo, NNSO), Astrophysics
Masahito Yamazaki (U Tokyo, School of Sci.), String Theory
Naoki Yasuda, Astronomy
Hiromi Yokoyama, Science and Society
Jun'ichi Yokoyama, Cosmology
Naoki Yoshida (U Tokyo, School of Sci.), Astrophysics

Project Researchers

Konstantin Aleshkin, Mathematics (from 2024/9/1)
Hugo Michel Jean Allaire, Astrophysics (from 2024/6/16)
Joaquin Andres Armijo Torres, Cosmology
Sebastian Bahamonde, Cosmology
Jiakang Bao, Mathematics
Rahool Kumar Barman, Particle Theory
Jahmall Matteo Bersini, Theoretical Physics
Philip Ewen Boyle Smith, Theoretical Physics (till 2024/9/15)
Weiguang Cao, Theoretical Physics (2024/10/1-11/30)
Anqi (Angela) Chen, Cosmology (till 2024/10/31)
Sunjin Choi, Theoretical Physics (from 2024/9/1)
Ioana Alexandra Coman Lohi, Theoretical Physics
Andrew Thomas Eberhardt, Cosmology
Daniela Galarraga Espinosa, Cosmology (from 2025/1/16)
Vaibhav Gautam, Theoretical Physics (from 2024/11/16)
Nivedita Ghosh, Particle Theory (from 2024/11/17)
Wahei Hara, Mathematics
Anamaria Hell, Cosmology
Shunichi Horigome, Theoretical Physics (till 2025/3/31)
Benjamin Aaron Horowitz, Theoretical Physics
Sagharsadat Hosseinisemnani, Theoretical Physics
Cesar Jesus Valls, Neutrino Physics
Baptiste Jost, Cosmology
Boris Sindhu Kalita, Astrophysics (till 2025/2/28)
Kookhyun Kang, High Energy Physics (till 2024/8/15)
Dogancan Karabas, Mathematics (till 2025/3/31)
Clement Leloup, Cosmology
Qiuyue Liang, Theoretical Physics
Huaxin (Henry) Liu, Mathematics
Kaloian Dimitrov Lozanov, Cosmology
Lluis Marti Magro, Astroparticle Physics
Dmytro Matvieievskyi, Mathematics
Katherine Alston Maxwell, Mathematics
Kevin Spencer McCarthy, Astronomy (from 2024/9/1)
Yuan Miao, Theoretical Physics
Marta Monelli, Cosmology (from 2024/10/16)
Hayato Morimura, Mathematics
Maria Mylova, Theoretical Physics
Yue Nan, Cosmology (till 2025/3/31)
Emily Margaret Nardoni, Theoretical Physics (till 2024/7/31)
Nhat Minh Nguyen, Cosmology (from 2024/10/1)
Ippei Obata, Theoretical Physics (till 2025/3/31)
Masafusa Onoue, Astronomy (till 2025/3/31)
Guillermo Pascual Cisneros, Cosmology (from 2025/1/16)
Xue (Sherry) Song, Cosmology (from 2024/5/2)
Tomoko Suzuki, Astronomy (till 2024/9/30)
Ka Ming Tsui, Neutrino Physics
Kateryna Vovk, Astronomy
Yu Watanabe, Particle Theory (till 2025/3/31)
Junjie Xia, Neutrino Physics (till 2024/10/31)
Mengxue Yang, Mathematics
Vicharit Yingcharoenrat, Cosmology (till 2024/4/30)
Si-Yue Yu, Astrophysics
Jiaxi Yu, Cosmology (from 2025/2/1)
Hao Zhang, Theoretical Physics
Yi Zhang, Theoretical Physics (from 2024/12/1)
Yu Zhao, Mathematics (till 2024/7/2)
Lutian Zhao, Mathematics (from 2024/8/16)
Yehao Zhou, Mathematical Physics (till 2025/1/15)
Tianyu Zhu, Astrophysics (from 2024/12/1)

Cross Appointments

Masashi Hazumi (KEK), High Energy Physics (till 2025/3/31)
Hitoshi Murayama (UC Berkeley), Particle Theory
Hirosi Ooguri (CALTECH), Mathematical Physics
Masahito Yamazaki (U Tokyo, School of Sci.), String Theory (from 2025/1/1)
Naoki Yoshida (U Tokyo, School of Sci.), Astrophysics

Affiliate Members

Ko Abe (U Tokyo, ICRR), Astroparticle Physics
Shunsuke Adachi (Kyoto U), Experimental Physics (from 2024/9/1)
Shin'ichiro Ando (U Amsterdam), Astroparticle Physics
Susumu Ariki (U Osaka), Mathematics
Yoichi Asaoka (U Tokyo, ICRR), Experimental Physics
Laura Baudis (UZH), Astroparticle Physics
Melina Bersten (CONICET), Astronomy
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5 Research Highlights

5.1 Connecting supermassive black holes to their host galaxies and larger dark matter halos

John Silverman

The first billion years of our universe are a laboratory for investigating the initial assembly of massive galaxies and their black holes. The James Webb Space Telescope (JWST), along with the Atacama Large Millimeter Array (ALMA), has opened this landscape of the early universe for observation. At Kavli IPMU, John Silverman's research group is leading science on the connection between the first supermassive black holes (SMBHs), their surrounding host galaxies, and dark matter halos. A key open question is whether the formation of SMBHs preceeds, follows, or goes along with their host galaxies. This line of investigation is motivated by the close relationship between the mass of SMBHs and the stellar mass of their hosts seen for galaxies in the nearby universe. We are asking how SMBHs and their host galaxies migrate onto this local mass relation, akin to the chicken and egg problem, i.e., which came first?

A remarkable breakthough has come with the detection of starlight under the glare of luminous accreting SMBHs at earlier cosmic times than previously feasible (Ding, Onoue, Silverman et al. 2023). This is now possible given the great stability of the telescope and its instruments at the Sun-Earth Lagrange Point 2, far away from the thermal impact of the Earth's atmosphere, which limited similar observations with the Hubble Space Telescope (HST).

Working our way up to the distant universe, Takumi Tanaka, a master degree student in the Silverman lab, performed image decomposition of 109 Active Galactic Nuclei at $0.7 < z < 2.5$ from COSMOS-Web, the largest imaging survey with JWST. He fit the images with models of the unresolved AGN emission and the underlying host galaxy to accurately measure the mass in stars of their host galaxies. This required careful construction of a library of empirical models of stars for use as an unresolved component (i.e., the AGN). After removing the AGN emission, the images revealed, not only their stellar content, but their distribution in the form of galaxy disks with spiral arms and central bars in some cases (**Figure 1**), each of these opening future investigations on their importance in driving gas to fuel a central SMBH. Takumi then reported on a very mild or non-existent evolution in the relation between the SMBH mass and galaxy stellar mass, thus indicating a scenario where SMBHs and their host galaxies grow in tandem.

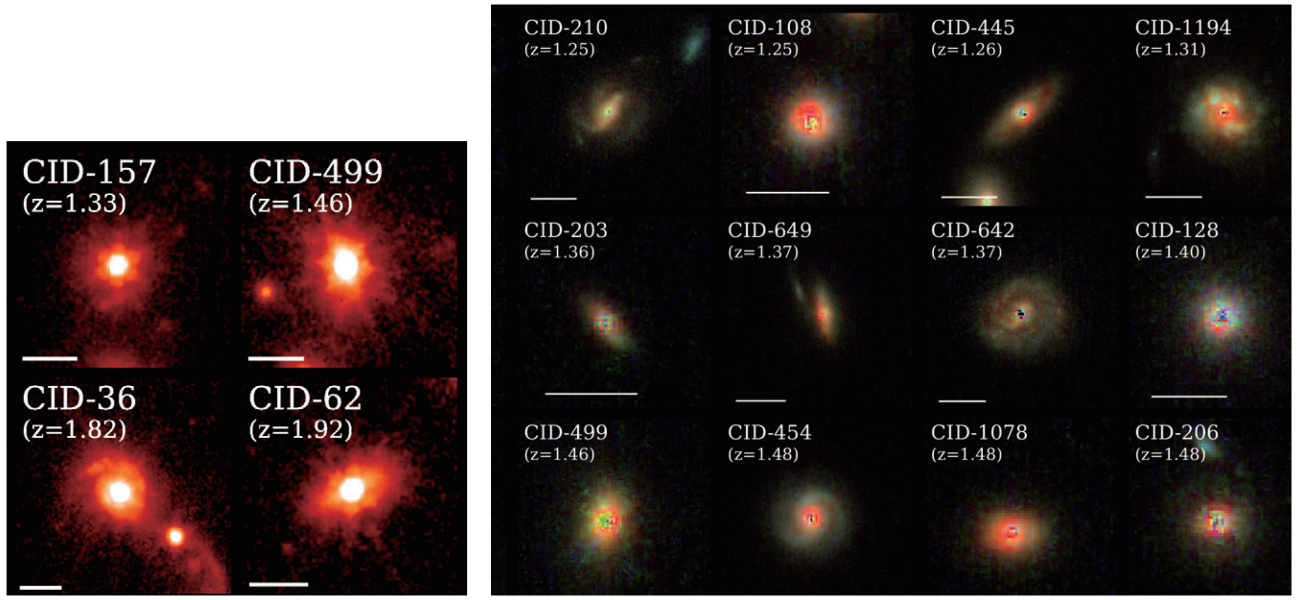


Figure 1: JWST images of quasars ($z > 1$) in the COSMOS-Web field. Left Original science frames at 2.77 μm with the quasar emission still present. Right Composite color images of quasar host galaxies after removal of the central unresolved quasar emission (Tanaka et al. 2025). The stellar emission is clearly visible with rich structures including spiral arms and bars, previously seen only at lower redshifts ($z < 1$) with HST.

However, differences between the masses of SMBHs and their hosts are expected to be largest in the early universe ($z \sim 6$) based on published hydrodynamic simulations. These early stages of growth are more sensitive to the initial seed mass for the black hole with formation channels including a rapid direct collapse of gas to a SMBH or a slower channel with lower mass seeds in the environment of a nuclear star cluster.

With JWST finding overly massive black holes at early cosmic times and works claiming a heavy-seed channel of formation, John Silverman and Junyao Li, a past visiting student in his lab, demonstrated that observational selection effects and measurement uncertainties lead to incorrect conclusions on the intrinsic relation between SMBHs and their host galaxies (Li, Silverman, Shen et al. 2025). After forward-modeling the galaxy population and their SMBHs, it is shown that the observed distribution in the SMBH-galaxy mass plane can be expected if following the local relation (**Figure 2**). This then predicts a large missing population of galaxies with undermassive black holes yet to be identified; hence, the observed samples are just the tip of the iceberg. This work was motivated by the need to construct analysis tools for the final evaluation of the evolution of SMBHs and their host galaxies with 12 quasars observed by JWST from the Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs) program being led by Kavli IPMU scientists including Masafusa Onoue (Principal Investigator) and John Silverman (Co-investigator).

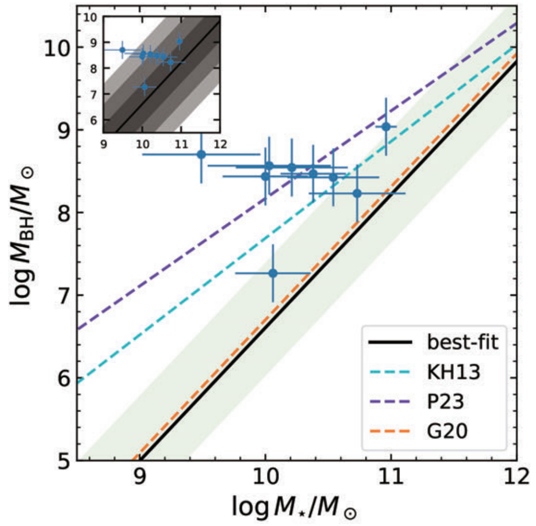


Figure 2: Best-fit (intrinsic) $z > 6$ relation between the mass of SMBHs and the stellar mass of their host galaxies (black line and green shaded confidence interval). The high-z relation is consistent with the local ($z \sim 0$) relations as indicated by dashed lines, except being inconsistent with a recently published analysis using a similar high-z sample shown in purple. The difference is due to incorrect selection function in the previously published result. Data point shows the observed quasar and AGN samples. These results demonstrate a co-evolution between SMBHs and their host galaxies even up to $z > 6$.

Expanding on studies on SMBHs at early cosmic time, a research team led by Kavli IPMU visiting researcher and Peking University graduate student Qinyue Fei, and including John Silverman, the University of Texas Austin's Dr. Seiji Fujimoto, and Peking University Kavli Institute for Astronomy and Astrophysics Associate Professor Ran Wang, have studied the dark matter content of supermassive black holes about 13 billion light years away. This study gives new insight into the relationship between dark matter and SMBHs when the universe was still very young, and how galaxies have evolved until today.

Made possible using data from ALMA and the ionized carbon (C+) emission line, the researchers were able to uncover the gas dynamics of two quasar host galaxies at redshift 6. By studying the rotation curves of each galaxy (**Figure 3**), they found dark matter made up about 60 per cent of its total mass. Velocity changes with radius in the galaxy are captured by blue-shifted gas (moving towards the researchers), and the red-shifted gas (moving away).

Interestingly, the rotation curves in the distant universe from past studies reveal a decrease in the galaxy outskirts, meaning a low fraction of dark matter. But the data taken by Fei and Silverman's team shows a flat rotation curve, similar to the massive disk galaxies close to Earth, which indicates more dark matter is required to explain the high velocities.

The team's findings shed light on the intricate relationship between dark matter and SMBHs. They offer a crucial piece of the puzzle in understanding how galaxies evolved from the early universe to the structures we observe today.

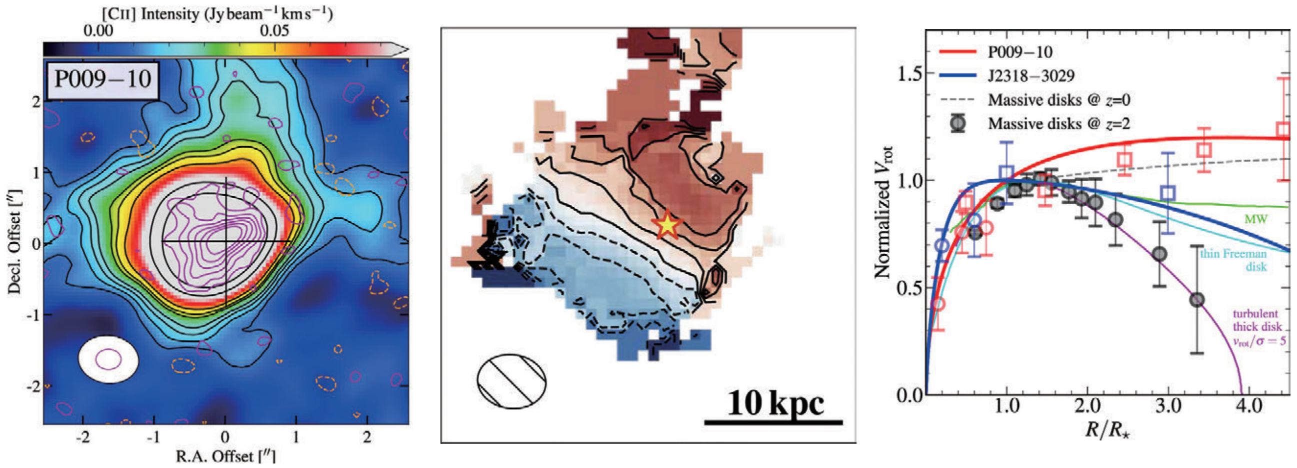


Figure 3. Left Gas distribution of ionized carbon (C+) on the halo scale of P009-10 as shown by the color image and black contours. Nuclear gas distribution, centered on the quasar (large black cross), is shown by the magenta contours. Middle: Velocity field of the C+ emission from -200 (in blue; moving towards us) to +200 (in red; moving away from us) km/s indicating coherent rotation in a massive dark matter halo. Right: Rotation curves of distant galaxies. Fei et al. data, in red and blue, remains relatively flat (i.e., high), similar to local massive disk galaxies at z~0 (dashed grey line) that need extended dark matter to explain their high velocities. The results from other galaxies at redshift~2-3 (in gray data points) show a rotation curve that decreases at the outskirts. This leads to a low dark matter fraction. (Credit: Fei et al.)

References:

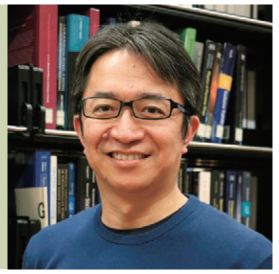
[1] The MBH - M* relation up to z ~ 2 through decomposition of COSMOS-Web NIRCam images
Tanaka, T., Silverman, J. D., Ding, X. et al., ApJ, 979, 215

[2] Tip of the iceberg: over massive black holes at 4 < z < 7 found by JWST are not inconsistent with the local MBH - M* relation
Li, J., Silverman, J. D., Shen, Y. et al. 2025, ApJ, 981, 19

[3] Assessing the dark matter content of two quasar host galaxies at z ~ 6 through gas kinematics
Fei, Q., Silverman, J. D., Fujimoto, S. et al., 2025, ApJ, 980, 84

5.2 Subaru Prime Focus Spectrograph Project takes off!

Masahiro Takada



The instrument, the Prime Focus Spectrograph (PFS), finally began its scientific operations in March 2025. The PFS is one of the flagships, next-generation instruments on the 8.2m Subaru Telescope, at 4,200m summit of Maunakea in Hawaii. Taking advantage of the ultrawide field of view of the Subaru Telescope, approximately 1.3 degrees in diameter at the prime focus, and large light-gathering power, the PFS will position 2,400 fibers to collect light from celestial objects and simultaneously obtain spectra across the entire visible light range and part of the near-infrared band (see **Figure 1**). Just like the compound eyes of insects, each facet (fiber) focuses on a different direction to cover a wide area while perceiving the colors of light from that direction. This highly ambitious instrument dramatically enhances the Subaru Telescope's spectroscopic observation efficiency.

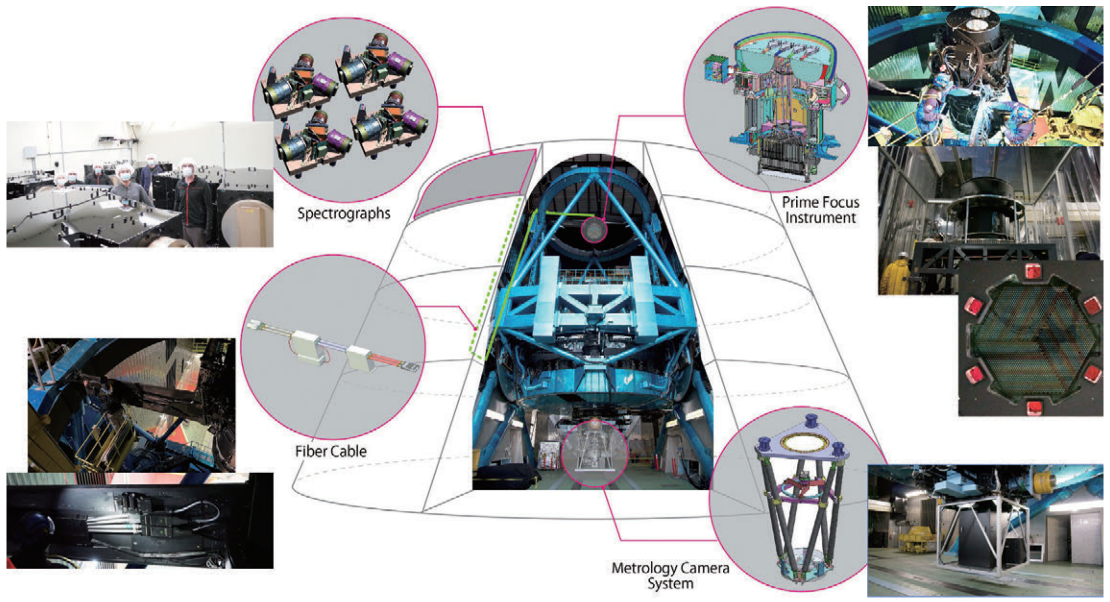


Figure 1: Schematic of the PFS instruments. It is composed of multiple subsystems installed at various locations on the telescope and throughout the enclosure. Approximately 2,400 optical fibers are distributed within the field of view of the Subaru Telescope's primary focus, precisely directed towards the stars and galaxies to be observed with an accuracy of about 20 micrometers corresponding to about 0.2 arcseconds on the sky. The light captured by these fibers from celestial objects is sent to the spectrograph system, consisting of four identical modules each of which is equipped with three cameras – "blue", "red", and "near-infrared" –and is simultaneously spectroscopically observed over a wide wavelength range, from 380 nanometers to 1,260 nanometers. (Credit: PFS Project/Kavli IPMU/NAOJ)

Spanning nearly 15 years with support from industrial partners around the world, the development of the PFS has been led by an international collaboration of over 20 research institutions spanning Japan, China, Brazil, France, Taiwan, Germany, and the United States. This collaboration has been ongoing for nearly 15 years, with various domestic and international industrial partners working together. Notably, the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) has taken the lead in proposing and developing the instrument as well as planning large-sky survey observations, with the goal of testing various theoretical models about the formation of the Universe. Meanwhile, the National Astronomical Observatory of Japan (NAOJ) has also played a central role, participating in the development of the instrument and overseeing the coordination of the project, while also being responsible for the acceptance and operation of the instrument. After overcoming the difficult period due to the COVID-19 pandemic, the PFS is finally ready to begin operations.

The PFS team plans to carry out large-sky survey programs over the next five or so years, utilizing a total of 360 nights of telescope time. By creating a 3D map of the universe and understanding its time evolution, they aim to uncover the nature of dark energy, which is driving the accelerated expansion of the universe. In addition, by doing spectroscopic surveys of numerous galaxies, much like a census, they will reveal the physical processes of galaxy formation and evolution over the 13.8-billion-year history of the universe. Furthermore, they will spectroscopically observe hundreds of thousands of stars in the Milky Way and Andromeda galaxies, investigating the dynamics of stars to determine the strength of gravity, thus exploring the nature of dark matter and the physical processes that have governed the growth of the galaxies. In this way, PFS will enable the observational study of dark energy, dark matter, and the history of galaxies based on an overwhelming amount of spectroscopic data, shedding light on their roles throughout the 13.8-billion-year history of the universe.

Figure 2 demonstrates the unique capability of PFS by presenting its images of Andromeda Galaxy – the largest neighbor of our Milky Way – taken during the commissioning observation in 2024. PFS enable us to obtain spectra of up to 2400 objects simultaneously over a wide solid area, covering the entire region of Andromeda Galaxy in this example. The six inset figures show the spectra of blue and red stars, an ionized interstellar gas (H II) region, a nova candidate region, and a planetary nebula. The spectra show the emission and/or absorption lines, as well as the continuum, of each object over a wide range of wavelengths. The spectroscopic capability of PFS can be compared with the rectangle in the lower left, which represents the field of view of the Keck telescope's spectrograph and allows spectra to be obtained for up to about 100 objects within that area.

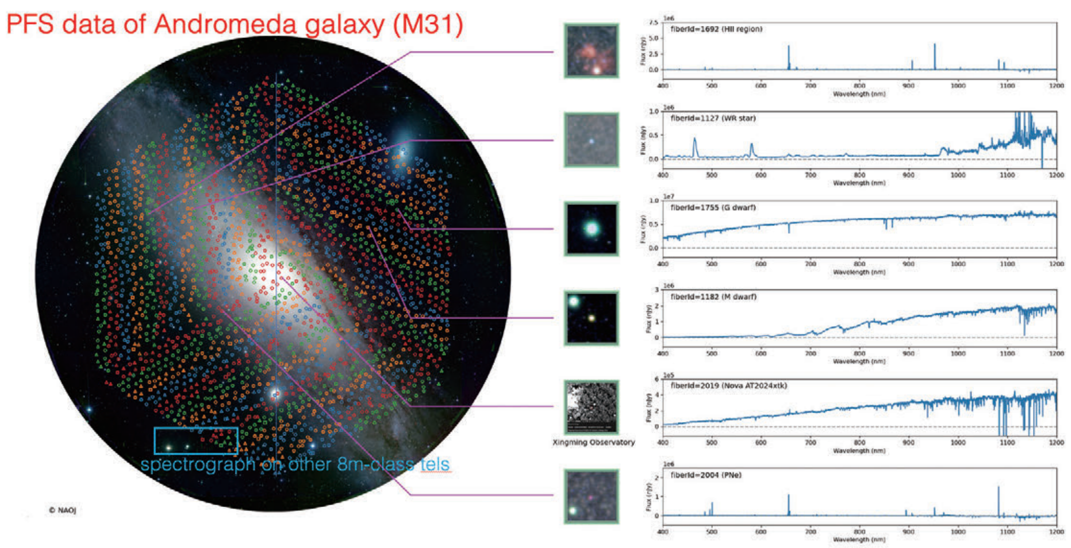


Figure 2: Example of data obtained by PFS observing celestial objects in the Andromeda Galaxy region. On the left, the positions of the PFS fibers configured to observe individual celestial objects are marked by circles (stars and galaxies for science), squares (bright stars for calibration purposes), and triangles (just to take sky spectra) on an image of the Andromeda Galaxy taken with HSC (Hyper Suprime-Cam) (Credit: HSC Project/NAOJ). The cyan rectangle represents the field of view of the multi-object spectrograph DEIMOS in operation at W. M. Keck Observatory for comparison. On the right, a magnified image of the observed celestial object is shown, along with the spectra obtained by PFS. (Credit: PFS Project/Kavli IPMU/NAOJ)

Figure 3 compares the spectra of the same galaxy obtained with the Subaru PFS and the Dark Energy Spectroscopic Instrument (DESI) on the 4 m Mayall Telescope. This galaxy is taken from the public Data Release 1 (DR1) of DESI and is known to be an [O II] emission-line galaxy at z = 1.13. The figure clearly shows that the PFS spectrum provides a higher signal-to-noise detection of the [O II] doublet than the DESI spectrum. In addition, the near-infrared spectrograph allows us to detect Hβ and [O III], other prominent emission lines from star-forming galaxies, which further improve the determination of redshift. We have assessed the quality of PFS spectra for [O II] emission-line galaxies and hope to begin full scientific operations of the PFS cosmology survey as soon as possible. One of the primary scientific goals of the PFS Cosmology program is to perform an independent test of the dynamical dark energy reported recently by the DESI collaboration. If the dynamical dark energy is confirmed, it will be a big discovery and will significantly advance our understanding of the expanding Universe.

Furthermore, we have taken a lot of PFS spectra for stars in the Milky Way dwarf galaxies and various types of galaxies at low and high redshifts. Each science working group has carefully assessed the data quality and refined the survey strategy to maximize scientific return. Please stay tuned for the exciting scientific results from PFS.

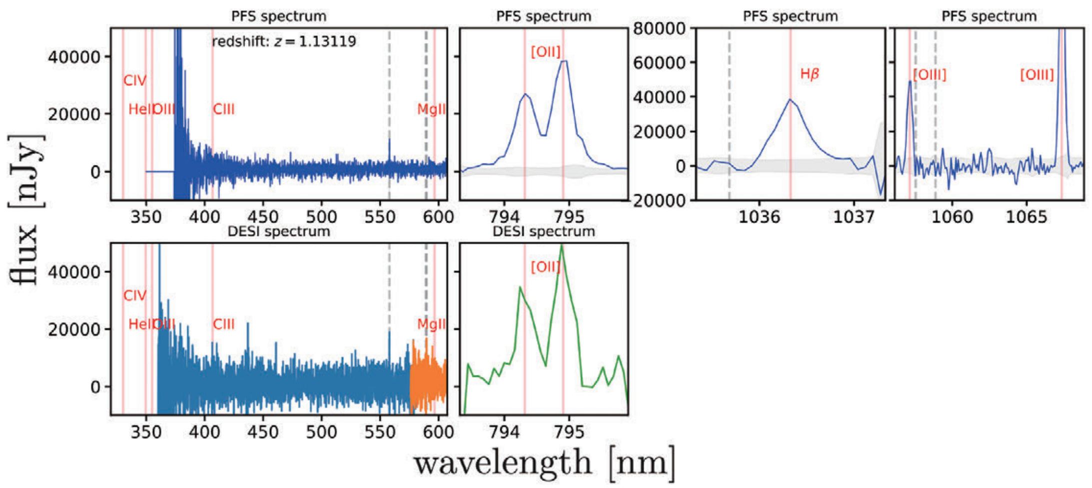


Figure 3: Another example of PFS data, for a star-forming galaxy at redshift z = 1.13. This galaxy was also observed by the US-led Dark Energy Spectroscopic Instrument (DESI) survey, whose data are publicly available. The four panels in the top row show zoomed-in PFS spectra covering the wavelength ranges where redshifted emission lines are expected to appear, as indicated by the vertical red line. Here, the exposure time for PFS is 1,800 seconds, while the DESI spectrum comes from the nominal exposure of 1,000 seconds. The two panels in the bottom row present the DESI spectra for the same galaxy, over the same wavelength ranges as the corresponding upper panels.

5.3 A new link between quantum field theory and quantum information theory

Masaki Okada and Yuji Tachikawa

In physics, symmetry provides an important clue to the properties of the system under investigation. Suppose, for example, we consider a system made of magnets. If we reverse the direction of every magnet by exchanging the north pole and the south pole of each magnet all at once, the forces on various objects and the energy stored in the magnetic field remain the same. This is because the equations describing the magnetic field are symmetric with respect to the operation of swapping the north and south poles.

Over the past few years, the concept of symmetries has received generalization in various directions in the theoretical study of quantum field theory, a unifying framework underlying both particle physics and condensed matter physics which is based on quantum mechanics. One such generalization is non-invertible symmetries. A conventional symmetry operation is always invertible. Equivalently put, there exists a reverse operation to undo it. Non-invertible operations in quantum field theory are more exotic, although a couple of such examples were known from the twentieth century, the earliest of which was the duality operation of the Ising model introduced by Kramers and Wannier in 1941. It was only in the last couple of years that such non-invertible operations are found to be ubiquitous in systems in various spacetime dimensions, and furthermore, can be considered as generalizations of the concept of symmetries, where we allow certain non-invertibility in such symmetry operations. The study of non-invertible symmetries is now an extremely active area of research, both in particle physics and in condensed matter physics, where many new and interesting results are rapidly being uncovered.

Another field increasingly getting the attention of physicists in recent years has been quantum information theory. It is the theory that makes up the foundation of quantum computers. A fundamental concept in quantum computation is to perform various operations on quantum memories called quantum bits, also known as qubits. Now, quantum mechanics is based on the concept of vector spaces and linear maps. Among those linear maps, any operation which can be undone is formulated by mathematical operations called unitary operators.

Non-invertible operations, where there are no reverse operations, are also important, such as the measurement of quantum bits. General linear maps cannot be used to describe them, partly because of the need to guarantee the positivity of probability. The linear maps satisfying the type of positivity required for consistency is mathematically known as complete positive maps. This means that any sensible operation on a quantum system is a complete positive map. Due to its importance in quantum information theory, complete positive maps are also known simply as quantum operations.

Let us come back to the topic of symmetries in quantum mechanics and quantum field theory. Ordinary, traditional symmetries are invertible. As such, they are implemented by unitary operators in quantum mechanics, as was uncovered in the early days of quantum mechanics more than 100 years ago. We are then naturally led to the question of what describes non-invertible symmetry operations in quantum mechanics and quantum field theories. An answer, naturally suggested from our discussions so far, is that they should be described by quantum operations. The discussions so far are summarized in **Figure 1**.

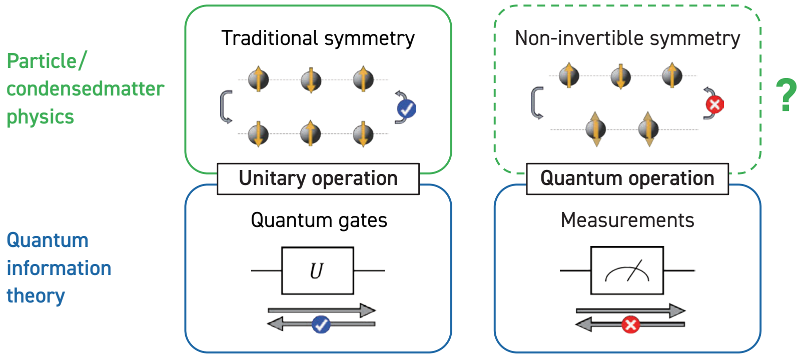


Figure 1: Traditional, invertible symmetries in particle and condensed-matter physics are known to correspond to unitary operations in quantum mechanics. In quantum information theory, non-invertible operations on a quantum system correspond to more general operations known as quantum operations. It is then natural to wonder if non-invertible symmetries on the side of particle physics and condensed-matter physics are described by quantum operations.

This is exactly what two physicists from Kavli IPMU, a graduate student Masaki Okada and his adviser Yuji Tachikawa, demonstrated in a paper [1] published in Physical Review Letters as an Editor's suggestion in the autumn of 2024. A precursor to this was a paper [2] by a mathematician Marcel Bischoff and his collaborators from several years ago where the same observation was made, although in a mathematical framework unfamiliar to most physicists and in a way applicable only to a rather restricted class of systems. The main novelty of [1] was that this general property was established only using widely used frameworks and methods in particle physics and condensed matter physics, in a way clearly applicable to a very general class of systems. The key step in the derivation is shown in **Figure 2**, which is taken from [1].

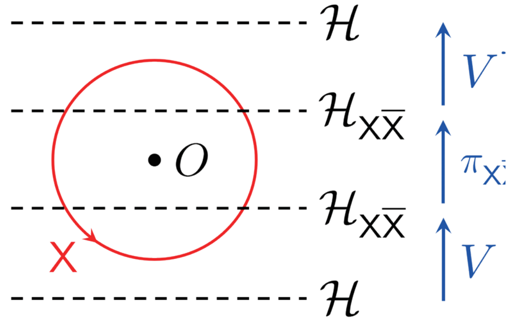


Figure 2: The key step in the derivation that non-invertible symmetry operations are quantum operations. Here the horizontal direction represents the spatial dimensions of the system, and the vertical direction represents the passage of time, or equivalently the order of the operations. As shown there, a non-invertible symmetry X acts by (1) transitioning via a map V from the original space H of quantum states to a new space, HXX , decorated by X, (2) acting by O, and (3) finally coming back to H by the adjoint V† of V. This sequence of V, then O, and then V†, is a standard form of quantum operations known as the Stinespring representation.

It is true that quantum information theory has already played an important role in the study of quantum field theory, mostly in the context of the analysis of quantum entanglement of the systems under investigation. Still, the concept of quantum operations, which plays such an important role in quantum information theory, had not been introduced or utilized on the side of quantum field theory very much. It is hoped that this work by two physicists from Kavli IPMU would become a new bridge between these two thriving fields of study.

Kavli IPMU made a press release on this work [3]. As is proper for such a press release in the 21st century, it comes with an accompanying YouTube video [4], which are recorded by the researchers themselves.

References:

[1] Masaki Okada and Yuji Tachikawa, "Non-invertible symmetries act locally by quantum operations", Physical Review Letters 133 191602 (2024), DOI: 0.1103/PhysRevLett.133.191602 , https://arxiv.org/abs/2403.20062

[2] M. Bischoff, S. Del Vecchio, and L. Giorgetti, "Quantum operations on conformal nets", Reviews in Mathematical Physics 35 235007 (2023), DOI: 10.1142/S0129055X23500071 , https://arxiv.org/abs/2204.14105

[3] "Researchers uncover link between quantum information theory and particle and condensed matter physics", IPMU press release,
English version: https://www.ipmu.jp/en/20241128-Quantum
Japanese version: https://www.ipmu.jp/ja/20241128-Quantum

[4] "Researchers uncover link between quantum information theory and particle and condensed matter physics", a YouTube video.
English version:
https://www.youtube.com/watch?v=iHLnMqz5ZjQ
Japanese version:
https://www.youtube.com/watch?v=P8ilgQx4uLI

5.4 A Universal Inequality Linking Energy and Information

Hirosi Ooguri

A collaboration including Hirosi Ooguri of the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) discovered a surprisingly simple and universal relationship between two fundamental processes in physics: energy and information transmission. The team published their results in Physical Review Letters in August 2024.

In both particle and condensed matter physics, one often encounters situations in which two quantum systems are brought into contact. The boundary between them, called an interface, plays a crucial role in determining how physical quantities flow from one side to the other. In condensed matter systems, for example, interfaces determine how electrical currents or thermal energy pass through junctions between different materials. In particle physics, interfaces arise in the study of domain walls, which are objects that separate distinct quantum phases or vacua of a quantum field theory. Despite their importance, the fundamental laws governing energy and information transfer across such interfaces have remained elusive. Both quantities are difficult to compute, especially in strongly coupled systems. Until now, no general relationship between the two was known.

The team studied two-dimensional conformal field theories (CFTs)—models with scale invariance that provide ideal environments for rigorous calculations—to investigate this relationship. The team identified three quantities that characterize an interface:

1. Energy Transmittance: How much energy can cross the interface? This property is encoded in the two-point correlation function of the energy-momentum tensor across the interface.
2. Information transmittance: How much quantum information (i.e., entanglement) is shared across the interface? This is captured by entanglement entropy, which defines the effective central charge.
3. Effective Hilbert space size: The growth rate of the number of states at high energy is bounded by the smaller of the two theories' central charges on either side of the interface.

At first, these three quantities seem unrelated. However, Ooguri and his colleagues discovered a universal inequality linking them:

[energy transmittance] ≤ [information transmittance] ≤ [size of the Hilbert space].

The energy transmitted across an interface cannot exceed the information transmitted, and information transmitted cannot exceed the effective size of the Hilbert space. In other words, energy transmission requires information transmission, and both require an ample supply of quantum states.

A crucial aspect of the result is that the inequalities are sharp—they cannot be improved upon. The team constructed examples where the bounds are exactly saturated.

- For trivial interfaces (complete decoupling), both energy and information transmission vanish.
- For topological interfaces (transparent connections), both energy and information transmission reach their maximum.
- In between, partially transmissive interfaces always lie within the inequality but never beyond it.

These results demonstrate that the inequalities cannot be strengthened. Their inequalities are the strongest that apply to any system.

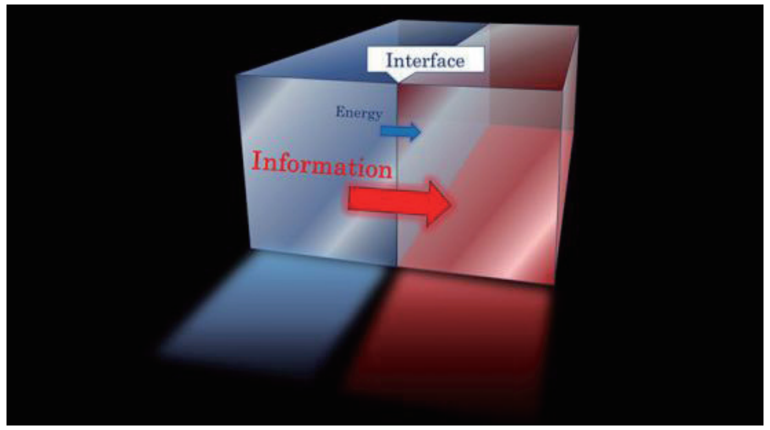
Energy and information are both cornerstones of physics. One of the most basic laws of nature is energy conservation. Quantified by entanglement and correlations, information has taken on a central role in quantum information science and the study of black holes. This work unites these two foundational concepts under a single framework by proving that energy transmission is always limited by information transmission.

The results also connect to practical problems. In condensed matter physics, for example, they clarify the theoretical limits of energy and entanglement transport in quantum materials.

This study was conducted in two-dimensional systems where conformal symmetry imposes powerful constraints. The authors suggest extending their results to higher dimensions. If analogous inequalities could be established in four-dimensional quantum field theories, the consequences would be significant for particle physics and quantum gravity.

The methods developed here also shed light on related quantities, such as pseudo-entropy and weak measurements, which are becoming important tools in quantum information science. Another promising direction is using lattice simulations to numerically test these predictions, bridging the gap between abstract theoretical results and computational experiments.

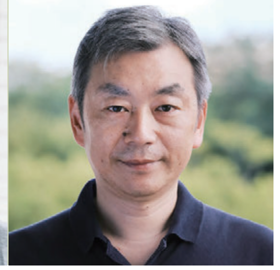
The discovery of this universal inequality demonstrates that, even within the intricate domain of quantum field theory, fundamental and elegant principles can emerge. By clarifying the deep relationship between energy and information, Ooguri and his collaborators advance the mathematical structure and conceptual foundations of modern physics.



(Credit: Yuya Kusuki)

5.5 XENONnT Research Highlights in FY2024

Kai Uwe Martens and Masaki Yamashita



Great strides were made by our XENONnT experiment throughout 2024, culminating in the publication of our "*Physical Review Letters collection of the year 2024*" featured paper "First Indication of Solar ^{8}B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT" in November [1]. This paper was followed by the "First Search for Light Dark Matter in the Neutrino Fog with XENONnT" in March 2025, also published in the Physical Review Letters (PRL) [2]. Both papers made PRL's "EDITOR'S SUGGESTION" roster and follow our XENON collaboration's proud tradition of doing blind analyses. The foundational framework for our "blind analysis" methodology was published in Physical Review D, also in March [3]. You may ask what it was that catapulted a coherent elastics neutrino-nucleus scattering (CEvNS) paper into the "*Physical Review Letters collection of the year*", PRL's "*most concentrated distillation of some of the most important and interesting papers*". Well, our paper documents the first measurement of astrophysical neutrinos via CEvNS, a scattering process for neutrinos predicted 50 years before our paper's publication and first verified experimentally 7 years ago using accelerator induced high-intensity neutrino bursts in a dedicated laboratory experiment. Having the lowest background at low energies among currently operating liquid xenon Time Projection Chambers (TPCs), we expect to continue to lead astrophysical neutrino measurements, including neutrinos from nearby core-collapse supernovae.

Another important XENONnT milestone in 2024 was the publication in August of the detector paper itself [4]. One important innovation of great importance for future detectors' design and operation is its new neutron veto, in which Gadolinium(Gd)-loaded ultra-pure water replaces highly flammable Gd-loaded liquid scintillator, while maintaining neutron tagging efficiency. This new approach to neutron veto design for ultra-low background experiments adapts the EGADS Gd-water technology developed for Super-Kamiokande (Super-K) to the background requirements of water shields for detectors chasing signals at or below the keV level – as opposed to much larger signals at MeV level and above pursued by Super-K. At the end of 2023 decisions delaying a currently ongoing intervention necessary to restore XENONnT's drift field to its design value allowed us to verify our neutron veto's new design and simplified Gd-water purification system with 1/10th of its design Gd-concentration. This turned out to become a resounding success. With only 0.02% Gd by weight dissolved in the water, various neutron calibration methods – including a neutron generator and sources containing neutron emitting isotopes – ascertained our new neutron veto design's fitness-for-purpose. With 77% neutron tagging efficiency measured with only 0.02% Gd in the water we verified that its final performance will be comparable to that of its traditional, liquid scintillator based rivals. As one of the main drivers in our effort to adapt and implement our Japanese Super-K water-Cherenkov neutron tagging technology as a new type of neutron veto for an ultra-low background experiment, one of us (K. M.) is currently documenting this success as a writer of the respective forthcoming XENON collaboration paper. Using (so far) only 10% of our available ultra-high purity Gd salt – acquired with the help of Super-Kamiokande from their original source, many thanks to them! – will allow us to run with our full target neutron veto efficiency when XENONnT's liquid xenon TPC has its full drift field restored, and thus both detector components finally reach their full potential. It is also worth mentioning that accessing the TPC to restore its drift field would have been much more time consuming and difficult had the older ideas prevailed and its neutron veto relied on liquid scintillator rather than simply being the optically separated inner part of its water shield. At the time of writing TPC repair is completed, and we are looking forward to re-installing the neutron veto in XENONnT's water tank – and finally dissolving the Gd-salt needed to reach our new neutron veto's design sensitivity.

Another one of us (M.Y.) serves the XENON collaboration as one of two co-chairs of its Collaboration Board and was the driving force behind its liquid-phase xenon purification effort since the start of XENONnT. In FY2024 his insights led to a successful remedy for an unexpected sudden increase in background from photoionization in XENONnT's liquid xenon, which appeared as the experiment doubled the efficiency of its continuous online radon removal. Masaki was the first to point to the right culprit, proceeded to identify the means to continually remove it from the detector's xenon, and thus brought photoionization in its TPC under control again. The collaboration thanked him by the rare awarding of a "XENON medal".

Our Kavli IPMU team for XENONnT data analysis is led by our Postdoctoral Fellow Tianyu Zhu, who joined us at Kavli-IPMU's Kamioka Branch in December 2024 and works closely with Kai's PhD student Caio Ishikawa, the youngest member of Kavli IPMU's XENON team. Tianyu is also XENONnT analysis Team Leader for analyses involving nuclear recoils – the signature by which XENONnT detects solar neutrinos and hopefully soon also dark matter particles. While our analysis effort's current focus still is on the data taken before TPC repair work started, we are also actively preparing for new analyses of new data that we expect to profit from achieving our detector's design drift field and neutron veto efficiency. In short, we concentrate on XENONnT's main competitive advantage among the current generation of dual-phase liquid xenon TPCs: its ultra-low radiogenic background. Fully exploiting our Super-Kamiokande-inspired neutron veto's projected neutron tagging efficiency will be essential to pushing this edge. And at Kavli IPMU we have the unique advantage of having first class theorists and phenomenologists in-house to help us identify new targets for our XENONnT rare event searches – targets that are both promising and relevant – and to refine our search strategies with their advice. Continuing to leverage this distinctive Kavli IPMU feature will remain a distinct advantage for our current XENONnT and XLZD group at Kavli IPMU – all the way deep down into the neutrino fog.

As for our future in XLZD (**X**ENON, **L**UX-**Z**EPLIN, **D**ARWIN):
In 2024 XLZD made a decisive step forward when it transitioned from a consortium to an active collaboration. XLZD plans to build the next generation xenon observatory with an active liquid xenon target mass of 60 tons to search for dark matter and neutrinoless double beta decay and measure astrophysical neutrinos. The "XLZD design book" was uploaded to arXiv in October 2024 – Kai and Masaki are members and authors. Masaki serves on XLZD's elected 10-person Executive Board, and Kai is the University of Tokyo's Institutional Board representative.

[1] E. Aprile et al., Phys. Rev. Lett. 133 191002 (2024): Editor's suggestion & PRL 2024 Collection
[2] E. Aprile et al., Phys. Rev. Lett. 134 111802 (2025): Editor's suggestion
[3] E. Aprile et al., Phys. Rev. D 111, 062006 (2025)
[4] E. Aprile et al., Eur. Phys. J. C 84, 784 (2024)

Figure 1: XENONnT's 700-ton water shield tank from the back of Hall B at the Gran Sasso Underground Laboratory (LNGS). On the left part of the Gd-water system sticks out from behind the gray cleanroom guarding the installation port of that water tank. Photo by Kai Martens.

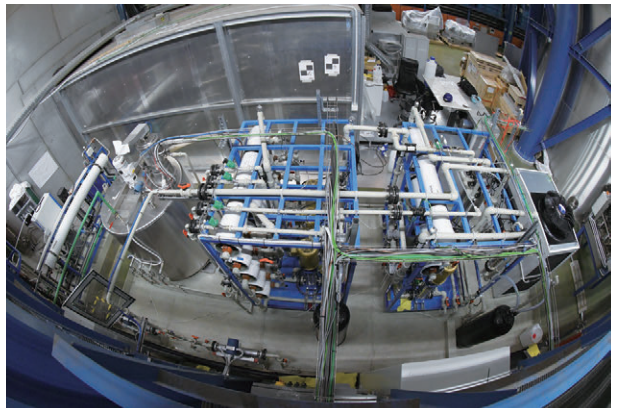
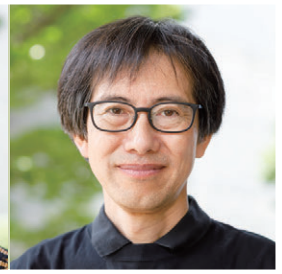


Figure 2: The XENONnT Gadolinium-water purification system - a simplified version of the original EGADS Gd-water system developed for Super-Kamiokande at the Kamioka Observatory of the Institute of the Cosmic Ray Research, University of Tokyo. Photo by Kai Martens.

5.6 Were Primordial Black Holes Formed?

Jason Kristiano and Jun'ichi Yokoyama



Since the discovery of gravitational waves from a binary black hole merger by the Advanced LIGO detector in 2015, numerous black hole merger events have been observed by the LIGO–Virgo–KAGRA collaboration. These observations have revealed that our universe hosts a large number of black holes with masses exceeding several tens of times that of the Sun. Because it is not easy to form such massive black holes through the collapse of ordinary stars, attention has been drawn to the possibility that they may, in fact, be primordial black holes formed in the very early universe shortly after the Big Bang. Primordial black holes are also considered promising candidates for dark matter, which constitutes nearly 30% of the universe's energy content.

Primordial black holes can form if there were significant inhomogeneities in the energy density of the early universe, which was filled with hot radiation right after the Big Bang. The moment a region with unusually large energy density than elsewhere comes within the Hubble horizon, it can collapse into a black hole. The most compelling mechanism for generating such energy-density inhomogeneities—i.e., fluctuations—is quantum fluctuations produced during the inflationary epoch, when the universe underwent rapid expansion before the Big Bang became observable. Quantum fluctuations always exist on microscopic scales, but during inflation their wavelengths are stretched dramatically, re-entering the observable universe after inflation as large-scale perturbations.

The nature of these primordial fluctuations has been well constrained by observations of the cosmic microwave background (CMB). The long-wavelength fluctuations probed by the CMB are very small, with deviations from uniform density to the order of one part in 100,000. This empirical fact is beautifully explained by models of so-called slow-roll inflation, in which the inflaton field—responsible for driving inflation—rolls slowly down a potential slope.

However, in ordinary slow-roll models, short-wavelength fluctuations remain equally small, making it impossible to generate the high-density regions required for primordial black hole formation. For this reason, many researchers, including Yokoyama in his younger days, have worked to construct models capable of generating large fluctuations on scales relevant to primordial black holes. The most actively studied model today is the ultra-slow-roll inflation model, of which Yokoyama is one of the original proposers. The dynamics of inflation can be likened to the motion of a ball rolling down a slope defined by the scalar field potential. In the ultra-slow-roll model, a flat plateau is introduced along the slope, causing the ball's motion to decelerate rapidly. During this deceleration, quantum fluctuations are amplified relative to its classical motion, generating large density perturbations temporarily. This is because in this regime, the would-be decaying mode actually grows rapidly even outside the Hubble horizon. Hence the conventional wisdom that perturbation remains constant after the horizon exit does not apply even at the linear level. As a result, primordial black holes can form on the scales corresponding to the wavelengths of these amplified fluctuations.

Because this amplification is only temporary, it had long been believed that such small-scale phenomena would not affect the large-scale fluctuations observed in the CMB. In our work, however, we carried out the first detailed calculation of one-loop corrections—arising from quantum interactions among large-amplitude small-scale fluctuations—within the framework of quantum field theory, in inflation models that realize primordial black hole formation. We found that such large fluctuations generated at small scales can, in fact, influence large-scale fluctuations observed in the CMB (see Fig. 2). In particular, we demonstrated that models predicting sufficiently large fluctuations to explain black holes with tens of solar masses (as suggested by gravitational-wave observations) or to account for dark matter as primordial black holes would inevitably produce temperature fluctuations on large scales that exceed those observed in the CMB. This creates a clear inconsistency with observations [1].

Because this conclusion overturns the conventional wisdom, it has prompted a number of rebuttal studies. However, many of these employed improper renormalization procedures or developed quantum theory using inappropriate variables involving surface terms, ultimately leading to incorrect conclusions [2,3].

Our result implies that in order to explain gravitational wave events or cold dark matter by primordial black holes, we need to adopt more complicated inflation models involving multiple fields or consider different mechanisms of fluctuation formation.

References:
[1] Jason Kristiano and Jun'ichi Yokoyama, Physical Review Letters 132(2024)221003
[2] Jason Kristiano and Jun'ichi Yokoyama, Physical Review D109(2024)103541
[3] Jason Kristiano and Jun'ichi Yokoyama, Journal of Cosmology and Astroparticle Physics 10 (2024) 036.

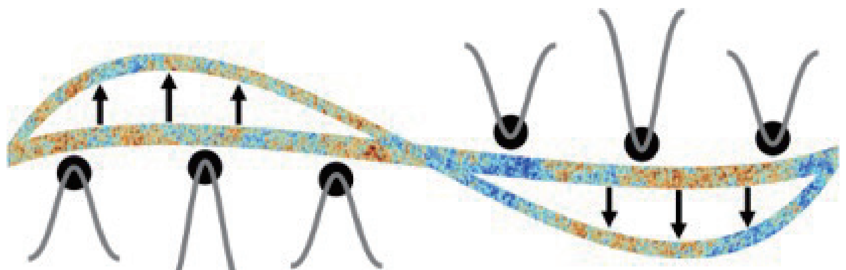


Figure 1: The study finds how large amplitude fluctuations generated on small scales can amplify large-scale fluctuations observed in the cosmic microwave background. (©2024 ESA/Planck Collaboration, modified by Jason Kristiano CC-BY-ND)

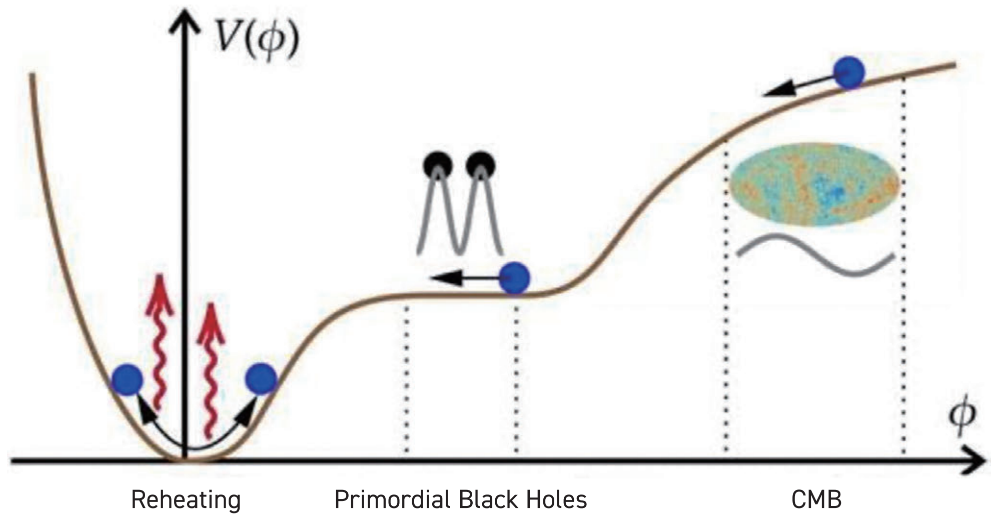


Figure 2: Simple potential of the inflaton realizing primordial black hole formation.

5.7 A Derived-categorical aspect of crepant resolution of singularities

Wahei Hara

My research focuses on singularities in algebraic geometry, with particular interest in the derived-categorical aspects of crepant resolutions and flops.

In algebraic geometry, the canonical class of a variety, which is related to differential forms, is regarded as a fundamental invariant. A crepant resolution is a resolution of singularities that preserves the canonica class. If $f : X \to Y = \operatorname{Spec} R$ is a crepant resolution of Y with trivial canonical class, then X is a local (i.e. non-compact) Calabi-Yau variety, which plays an important role not only in algebraic geometry but also in mathematical physics. A flop is a birational operation that modifies a codimension-two locus of a variety while preserving its canonical class. Crepant resolutions do not always exist, and when they do, they are not necessarily unique. Nevertheless, any two distinct crepant resolutions are connected by a sequence of flops.

In 2024, my joint work with Michael Wemyss titled "Spherical objects in dimensions two and three" was published from Journal of the European Mathematical Society. A spherical object in the derived category is an object with "sphere-like cohomology", and is regarded as important for various reasons, including
(i) it induces an autoequivalence of a category called spherical twist,
(ii) it can be seen as a kind of "generalized simple object" in representation theory, and
(iii) under mirror symmetry, spherical objects correspond to Lagrangian submanifolds, and the associated spherical twist corresponds to the Dehn twist.

The classification of spherical objects is expected to exist in local Calabi-Yau settings. Namely, if $f : X \to \operatorname{Spec} R$ is a crepant resolution of a given normal Gorenstein singularity $\operatorname{Spec} R$, then spherical objects may admit a classification. My paper with Wemyss established a method to classify "generalized simple objects" that works in various geometric settings including the minimal resolutions of Kleinian singularities, as well as in silting discrete contexts in representation theory. The classification of spherical objects in the derived category $\mathrm{D^b}(\operatorname{coh} X)$ was studied by Ishii-Uehara around 2004 in the case when $f : X \to \mathbb{C}^2/G$ is the minimal resolution of type A Kleinian singularities. Even for type D or E Kleinian singularities, the classification of spherical objects in $\mathrm{D^b}(\operatorname{coh} X)$ has not yet been established. As the geometric case, our work classified "spherical-like" objects in the smaller category

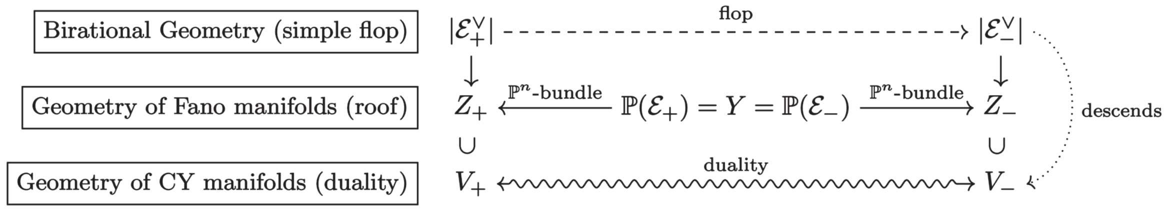
$$\mathcal{C} := \{x \in \mathrm{D^b}(\operatorname{coh} X) \mid Rf_* x = 0\} \subset \mathrm{D^b}(\operatorname{coh} X)$$

when $f : X \to \operatorname{Spec} R$ is a partial crepant resolution of a Kleinian singularity or a threefold flopping contraction where X has only Gorenstein terminal singularities. Although our proof of the classification does not extend to the whole category $\mathrm{D^b}(\operatorname{coh} X)$ immediately, at least for the category $\mathcal{C}$, it works much more generally than Ishii-Uehara's. Another noteworthy aspect of our proof is that the method also works with the derived categories $\mathrm{D^b}(\operatorname{mod} A)$ of silting discrete algebras A, which is an important class of algebras in representation theory. I presented a plenary talk in International Conference on Representations of Algebras (ICRA 21, 2024) about this work.

Regarding ongoing work, I mainly studied the derived-categorical aspect of simple flops. A simple flop is a flop that can be described by a single smooth blow-up followed by a smooth blow-down. The class of simple flops serves as a natural generalization of the Atiyah flop and the Mukai flops, the most fundamental examples of flops. Simple flops are important not only for their simplicity and the wealth of examples they provide in birational geometry, but also for their connections with the geometry of Fano manifolds and (projective) Calabi-Yau manifolds.

Namely, let us consider two smooth Fano manifolds Z_+, Z_- have vector bundles E_+, E_- such that $W = \mathbb{P}(E_+) \simeq \mathbb{P}(E_-)$. If $E_\pm$ are ample vector bundles of the same rank and satisfy $c_1(E_\pm) = c_1(Z_\pm)$, then W is a Fano manifold admitting two different $\mathbb{P}^{r-1}$-bundle structures, where $r := \operatorname{rank}(E_\pm)$, and such W is called a roof. Given pairs $(Z_\pm, E_\pm)$ that give a roof, there is a simple flop $|E_+^\vee| \dashrightarrow |E_-^\vee|$ between the total spaces of the dual bundles. In addition, choosing general sections $s_\pm \in H^0(Z_\pm, E_\pm)$ gives projective Calabi-Yau manifolds $V_\pm \subset Z_\pm$ as zero-loci. If two sections $s_\pm$ correspond to each other by a natural isomorphism $H^0(E_+) \simeq H^0(E_-)$, then two Calabi-Yau manifolds V_+ and V_- are called dual to each other.

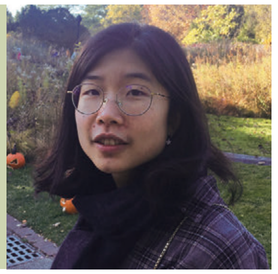
Dual Calabi-Yau manifolds are not birational to each other in general, but are expected to share many important invariants including their derived categories. By the theory of matrix factorizations, an equivalence $\mathrm{D^b}(\operatorname{coh}|E_+^\vee|) \simeq \mathrm{D^b}(\operatorname{coh}|E_-^\vee|)$ descends to an equivalence $\mathrm{D^b}(\operatorname{coh} V_+) \simeq \mathrm{D^b}(\operatorname{coh} V_-)$. Thus there are three interconnected levels of geometry.



In 2024, I studied many examples of simple flops, including those of type A_4^G, D_4 and $G_2^\dagger$, partly with W. Donovan, M. Kapustka and M. Rampazzo. The simple flop of type A_4^G associates a particular class of Calabi-Yau threefolds, and those of type D_4 and $G_2^\dagger$ associate K3 surfaces of degree 12. The results I established for those simple flops reveal new aspects of these (projective) Calabi-Yau manifolds from the viewpoint of higher-dimensional birational geometry.

5.8 Correspondences in higher Teichmüller theory

Mengxue Yang



1 Introduction

Broadly speaking my research interest lies in exploring correspondences between Higgs bundles, flat connections (e.g.opers), and representations on a Riemann surface. Examples of such correspondences include the famous non-abelian Hodge correspondence ([Hit87],[Sim92],[Don87],[Cor88]) and the Riemann–Hilbert correspondence, which bridge between the geometric, topological, and algebraic objects listed above. In 2014, Gaiotto proposed an ħ-conformal limit [Gai14], creating a new path between Higgs bundles and opers with physical motivation. The Cayley correspondence for G^R-Higgs bundles ([Hit92],[Got01],[AABC+19],[AABC+19],[BCG+24]) reveals new and profoundly interesting topological properties about the moduli space for a real simple Lie group G^R. These are all inspirational foundations for my studies as shown in the following projects.

2 Generalized opers (past)

To give some background, I will recall my past work on generalizing opers. Classically an oper is a repackaging of the data of an n'th order linear differential operator with nonvanishing symbol on a Riemann surface. More precisely, a G-oper on a Riemann surface Σ is a holomorphic connection on a principal G bundle that satisfies Griffiths transversality and nondegeneracy conditions with respect to a holomorphic reduction of structure group to a Borel subgroup $B < G$. This reformulation from linear differential operator to connection has the advantage that it is global, coordinate-free, and it facilitates the study of opers in families. When Beilinson–Drinfeld ([BD05],[BD]) proposed the first version of the geometric Langlands conjecture as an equivalence of categories:

$$\mathrm{D\text{-}mod}(\mathrm{Bun}_G(\Sigma)) \simeq \mathrm{DCoh}(\mathrm{Loc}_{G^\vee}(\Sigma)),$$

they gave evidence by verifying the claim on the space of G-opers, showcasing their usefulness.

A (G, P)-oper [CS21] is a natural generalization of a G-oper, by extending the reduction of structure group to allow arbitrary parabolic subgroups $P < G$. When $P = B$ is a minimal parabolic, we return to the definition of a G-oper. In past work with professor Indranil Biswas and professor Laura Schaposnik, we studied special types of (G, P)-opers in explicit vector bundle formulation called generalized B-opers [BSY20] and generalized SO(2n,C)-opers [BSY21]. Independently, I showed that our generalization is indeed a special case of the (G, P)-opers [Yan22].

3 Conformal limit and Θ-positive opers

From a geometric perspective, the Teichmüller space of a topological surface S is the space parametrizing marked conformal structures on S. For a compact surface with genus $g \geq 2$, the conformal structures on S are equivalent to hyperbolic metrics. An equivalent, but more algebraic incarnation of the Teichmüller space is the character variety $X(\pi_1(S), \mathrm{PSL}(2,\mathbb{R}))$ of holonomy representations of the marked hyperbolic metrics up to conjugacy. These representations are characterized by the property of

"forming a connected component of discrete and faithful representations in $Hom(\pi_1(S), PSL(2,\mathbb{R}))/\sim$*".*

A *higher* Teichmüller space is then naturally a union of connected components consisting entirely of discrete and faithful representations in $\mathrm{Hom}(\pi_1(S), G^R)/\sim$, *for* G^R *a higher* rank Lie group.

In 1992, Hitchin first generalized this picture of Teichmüller space as a representation variety into PSL(n,R) using Higgs bundles built from the data of a principal $\mathfrak{sl}_2$-triple [Hit92]. These are called Hitchin components (also Hitchin section), and they were shown to be discrete and faithful by Labourie [Lab06] and Fock–Goncharov [FG06]. In 2010, Guichard and Wienhard found a sufficient topological condition to impose on the representations so that they form higher Teichmüller spaces [GW10]. Such representations are called maximal, and they were shown to have interesting dynamical properties. Most recently, Guichard and Wienhard developed an algebraic structure called Θ-positivity, which conjecturally classifies all real simple Lie groups that admit higher Teichmüller spaces [GW24]. From a Θ-positive structure, we may obtain a Θ-principal $\mathfrak{sl}_2$-triple, which can be used to build Higgs bundles that give rise to higher Teichmüller spaces via the non-abelian Hodge correspondence. This perspective directly generalizes the Hitchin components, and also includes the maximal components.

In the context of 4d $N = 2$ gauge theories compactified on a circle, Gaiotto conjectured that a certain ħ-conformal limit takes Higgs bundles in the Hitchin components to the special flat connections that admit an oper structure [Gai14]. Inspired by higher Teichmüller theory, we showed that the conformal limit (applied to flat connections arising from Higgs bundles):

$$\lim_{R\to 0} [\hbar^{-1}\Phi + D_{h(R)} + R^2\hbar\Phi^{\dagger_{h(R)}}]$$

establishes a bijection between Higgs bundles that give rise to higher Teichmüller spaces and Θ-positive opers (which include special cases of generalized B-opers). Here (E, Φ) is a Higgs bundle on a compact Riemann surface Σ of genus at least two, $h(R)$ is a Hermitian metric solving Hitchin's equations, $D_{h(R)}$ is the Chern connection, and $\hbar \in \mathbb{C}^*$ is a fixed constant.

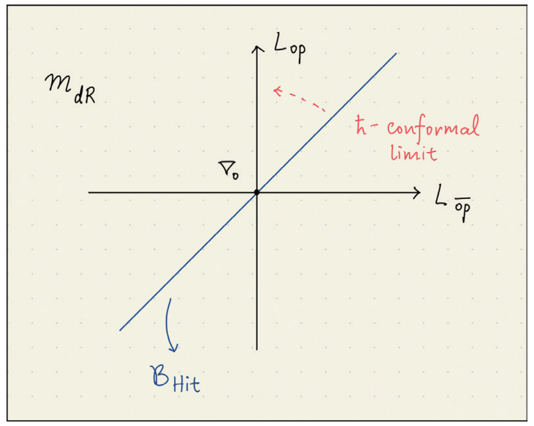


Figure 1: a local picture of the ħ-conformal limit on the Hitchin section B_{Hit} to the space of opers L_{op} in the moduli space of flat connections M_{dR} at a uniformizing connection ∇_0. We denote by L_{op} the space of anti-opers.

More specifically, we first identify the correct base space that generalizes the Hitchin base:

$$\mathcal{B}_{(\mathcal{P}_C,\psi)} = H^0(\Sigma, \mathcal{P}_C(\widetilde{\mathfrak{m}}) \otimes K^{m+1}) \oplus \bigoplus_i H^0(\Sigma, K^{l_i+1}),$$

where (P_C, ψ) is a stable C^*-fixed point for some C-Higgs bundle, where C is the centralizer of a given Θ-principal $\mathfrak{sl}_2$-triple (f, h, e), K is the canonical line bundle of Σ, and the symbols, $\widetilde{\mathfrak{m}}$, m, l_i are all Lie theoretic data associated to the $\mathfrak{sl}_2$-triple.

Together with professor Georgios Kydonakis in [KY24], we showed that for $u \in B_{(P_C,\psi)}$, Q reductions of structure group to the maximal compact subgroup, ρ the Lie algebra involution preserving Q, and $\Phi_u = f + \psi + u$,

$$\lim_{R\to 0} [\hbar^{-1}\Phi_u + D_{\mathcal{Q}(R,u)} - R^2\hbar\rho_{\mathcal{Q}(R,u)}(\Phi_u)] = [\hbar^{-1}\Phi_u + D_{\mathcal{Q}_0} - \hbar\rho_{\mathcal{Q}_0}(\Phi_0)].$$

Moreover the right hand side of the equation are isomorphism classes of flat connections with the structure of a (G, P_Θ)- oper, which we call Θ-positive opers. In particular, we generalized Gaiotto's conjecture about Hitchin components to all higher Teichmüller components.

4 Stacky Cayley correspondence and Langlands duality

On the Higgs bundles side of higher Teichmüller theory, an important result that unifies years of research on counting connected components in the moduli space of G^R-Higgs bundles is the general Cayley correspondence of [BCG+24]. Their work conjecturally solves the question of classifying additional connected components (e.g. higher Teichmüller components) for all simple real Lie groups G^R. This is done by studying **magical $\mathfrak{sl}_2$-triples**, which are in some sense equivalent to the Θ-principal triples from the previous section. In short, we can think of their theorem as the existence of an injective, open and closed map:

$$\Psi : \mathcal{M}_{K^{m+1}}(\widetilde{G}^{\mathbb{R}}) \times \bigoplus_i H^0(\Sigma, K^{l_i+1}) \to \mathcal{M}(G^{\mathbb{R}}).$$

Here $M_L(G^R)$ is the moduli space of L-twisted G^R-Higgs bundles on Σ. The key takeaway of this map is that it is a correspondence on connected components. In particular for $\widetilde{G}^R$ some other real group, $\pi_1(\widetilde{G}^{\mathbb{R}})$ provides additional

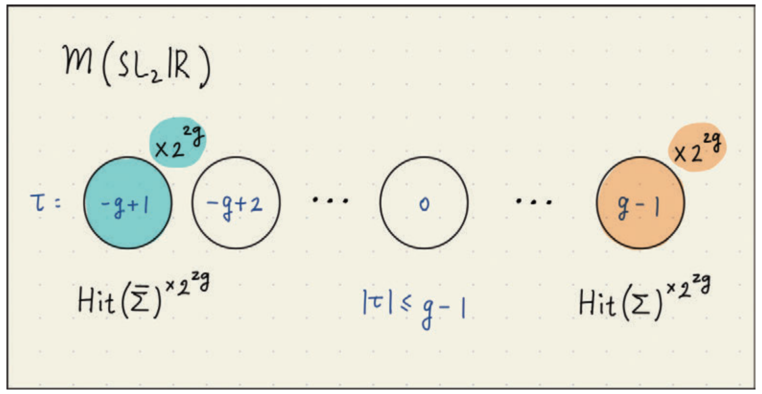


Figure 2: two collections of connected components are distinguished in the moduli space of SL_2R-Higgs bundles$M(SL_2R)$ by the maximal Toledo invariant $|\tau| = g - 1$. They are the Hitchin components $Hit(\Sigma) \simeq Teich(\Sigma) \simeq R^{6g-6}$ and the Hitchin components for $\overline{\Sigma}$.

topological invariants to $\pi_1(G^R)$, which will distinguish connected components in $M(G^R)$. In addition, the image of Ψ are identified with higher Teichmüller spaces via the non-abelian Hodge correspondence.

In recent work with Eric Y. Chen and Enya Hsiao [CHY25][1], we reinterpreted the general Cayley correspondence as a stacky morphism of Lagrangians over the Hitchin moduli stack. The construction of these Lagrangians turns out to be a special case of Gaiotto's Lagrangians in the context of boundary conditions of some 4d $N = 4$ gauge theories [Gai18]; they are also closely related to the recent program of relative Langlands [BSV].

Roughly speaking, Gaiotto's Lagrangian is a functorial construction that takes a graded Hamiltonian G-space M and produces a derived Lagrangian in the moduli stack of G-Higgs bundles Lag(M). We apply this abstract machinery to two Hamiltonian G-spaces associated to a magical sl_2-triple, M^0_{CS} and M_{G^R} , and obtain two Lagrangian stacks generalizing the domain and codomain of Ψ respectively. In fact, M_{CS} is the Hamiltonian G-space underlying a Higgs bundle version of [CS21]'s (G, P)-opers from above; M_{G^R} is the one giving rise to G^R-Higgs bundles. Then given the natural morphism $\varphi : M^0_{CS} \to M_{G^R}$, we showed that the stacky Cayley morphism

$$\mathrm{Lag}(\phi) : \mathrm{Lag}(M^0_{\mathrm{CS}}) \to \mathrm{Lag}(M_{G^{\mathbb{R}}})$$

is an isomorphism on tangent complexes and universally closed. Moreover, when we restrict to the classical moduli spaces, Lag(∅) recovers the open and closed properties of the Cayley correspondence Ψ.

In the context of S-duality/mirror symmetry or relative Langlands program, we expect there to be a duality between some 2-categories of boundary conditions (e.g. BAA/BBB branes), which consist of quasi-coherent sheaves on Lagrangians over the Hitchin moduli stack on the A-side. The Cayley correspondence gives examples of *morphisms* in these categories, which are a priori very hard to understand. Now we may be able to describe not just duality between some objects, but also duality between some morphisms. This is checked explicitly over the regular Hitchin fibration for the real form PU(n, n).
We rediscovered a theorem of Hitchin's about dual branes associated to PU(n, n)/Sp(2n,C) [Hit13], and supplemented it with a new conjecture about dual morphisms and provided evidence for the duality using the Fourier–Mukai transform.

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6 Awards & Honors

Credit: Naoki Yoshida

Naoki Yoshida receives the 2024 Philipp Franz von Siebold Award

Project Professor Naoki Yoshida from The Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), The University of Tokyo, has been named the recipient of this year's Philipp Franz von Siebold Award.
The Philipp Franz von Siebold Award was established in 1978 by Walter Scheel, the Federal President of Germany at the time, and recognizes the outstanding contributions by a Japanese researcher or academic in improving the mutual understanding of culture and society in Germany and Japan.

Credit: Kavli IPMU

Maria Mylova named 2024 Emmy Noether Fellow

Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) Project Researcher Maria Mylova has been named a 2024 Simons Emmy Noether Fellow, it was announced on April 25 by the Perimeter Institute.
The Simons Emmy Noether Fellows Program at Perimeter Institute honors the legacy of Emmy Noether, a mathematician whose work more than a century ago became a fundamental concept in mathematical physics. Partnered with the Simons Foundation, the program supports and encourages early- and mid-career women researchers in physics and related areas.

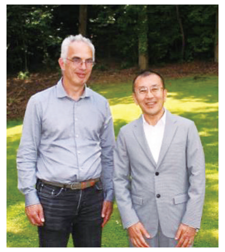
Credit: Hitoshi Murayama

Hitoshi Murayama awarded Miller Senior Fellowship

Hitoshi Murayama, Professor at the University of California, Berkeley, and Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), has been appointed as the 2024 Miller Senior Fellow, it was announced by UC Berkeley's Miller Institute for Basic Research in Science.
The Miller Institute is dedicated to research and investigation into basic science, and was established in 1943 following the donations by former UC Berkeley Economics professor Adolph C. Miller and his wife Mary Sprague Miller.
The Miller Senior Fellowship was established in 2008, and invites a selected group of UC Berkeley faculty members into the institute to enhance their interaction with other Fellows, particularly young scientists at the postdoctoral stage, and provides him or her with significant discretionary research funds.

Hitoshi Murayama elected to Vice Chair of Division of Particles and Fields under American Physical Society

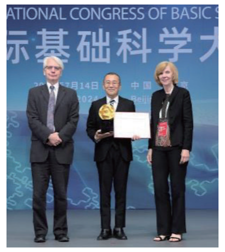
Hitoshi Murayama, Professor at the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), has been named the incoming Vice Chair of the Division of Particles and Fields (DPF) under the American Physical Society, it was announced by the DPF executive committee.
The American Physical Society (APS) is a non-profit organization established in 1899 for professionals in physics and related fields, to advance and diffuse physics knowledge. Today it is made up of about 50,000 members with 17 divisions for each subfield, including the DPF. The APS also publishes more than a dozen scientific journals including Physical Review. The DPF was established in 1967, and is dedicated to studying fundamental particles and fields, their structure, their interactions and interrelationships, the design and development of high energy accelerators, and the design and development of instrumentation techniques for high energy physics. The DPF has about 5000 members today.



Credit: Fanny Dufour, IHES

Hirosi Ooguri appointed Louis Michel Chair

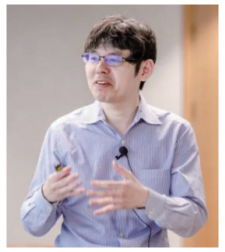
Hirosi Ooguri, Professor at the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), has been appointed the Louis Michel Chair at the Institut des Hautes Études Scientifiques (IHÉS) in France.
Founded in 1958 and located in a suburb of Paris, IHÉS is a world leader in mathematics, theoretical physics, and all related sciences. It offers exceptional scientists a place where they can devote themselves entirely to their research, free from teaching and administrative obligations. To date, 8 of the 12 permanent professors at IHÉS have received the Fields Medal.
The Louis Michel Chair, established in 2000, is an academic chair for distinguished long-term visitors in theoretical physics. It is named after the late Louis Michel, a leading figure in particle physics and the first professor in physics at IHÉS from 1962 to 1992.



Credit: ICBS 2024

Hirosi Ooguri receives the Frontier of Science Award

Professor Hirosi Ooguri of the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) at the University of Tokyo received the Frontier of Science Award in Theoretical Physics at the International Congress for Basic Science (ICBS) in Beijing, China.
Ooguri is being recognized for the paper he co-authored with Daniel Harlow of the Massachusetts Institute of Technology entitled "Symmetries in Quantum Field Theory and Quantum Gravity," which was published in Communications in Mathematical Physics in 2021.
The Frontiers of Science Award is given to papers published in the last ten years in these areas of science that are of the highest scientific merit and originality and have had a significant impact on their fields.



Credit: Tadashi Takayanagi

Tadashi Takayanagi receives the 2024 ICTP Dirac Medal

Kyoto University Yukawa Institute for Theoretical Physics Professor and Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) Visiting Senior Scientist Tadashi Takayanagi is one of four physicists who have received this year's ICTP Dirac Medal, announced the International Centre for Theoretical Physics (ICTP).
The ICTP Dirac Medal was established in 1985, and is named after the pioneering theoretical physicist of the 20th century Paul Dirac. The medal recognizes important contributions to theoretical physics, and this year it has recognized achievements in quantum entropy in gravity and quantum field theory. Recipients were announced on August 8, the same day as Dirac's birthday.

Credit: Kavli IPMU

Misao Sasaki named Benjamin Lee Professor

The University of Tokyo Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) Project Professor Misao Sasaki has been named this year's Benjamin Lee Professor, it was announced by the Asia Pacific Center for Theoretical Physics (APCTP) in South Korea.
The Benjamin Lee Professorship was established by the APCTP in honor of Korean-born theoretical physicist Benjamin Lee, who had a distinguished career in particle physics theory, and is awarded to researchers who have made significant contributions in physics internationally. Sasaki has been recognized for his contributions to early universe research and the general theory of relativity.

Credit: Kavli IPMU

Shigeki Matsumoto awarded the 2024 Particle Physics Medal

The University of Tokyo Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) Professor Shigeki Matsumoto has been named one of the recipients of this year's Particle Physics Medal, awarded by the Japan Particle and Nuclear Theory Forum.
Matsumoto is receiving the medal as part of a three-person team, and his co-recipients are also affiliates of Kavli IPMU: High Energy Accelerator Research Organization (KEK) Professor and Kavli IPMU Senior Fellow Mihoko Nojiri, and Nagoya University Graduate School of Science Professor and Kavli IPMU Visiting Senior Scientist Junji Hisano.
The Particle Physics Medals has been awarded annually since 2000, and was established to further inspire research in particle physics, nuclear physics and related fields. Members of the Japan Physical Society's Particle Theory Committee select the recipients. The researchers they choose are ones who have made significant contributions to particle theory and its surrounded fields. By recognizing the efforts by these researchers, the society aims to encourage the next generation of researchers to pursue their own original research.

Credit: ICRR

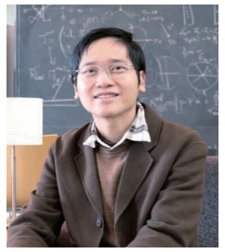
Masayuki Nakahata receives Medal with Purple Ribbon

The University of Tokyo Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) Senior Fellow and Institute for Cosmic Ray Research Professor Masayuki Nakahata has been named one of the recipients of the Medal with Purple Ribbon, it was announced on November 3 by the government of Japan as part of their Autumn Honors list.
The Medal with Purple Ribbon was established in 1881, but when the Medal with Yellow Ribbon was established in 1955, the Medal with Purple Ribbon was adjusted to recognize individuals who have made significant contributions to discovery or development in science and technology, sports or arts.
Nakahata is being recognized for his work as an active leader in solar neutrino and supernova neutrino research, heading several underground experiments in neutrino physics and astrophysics. In 2014 he became the representative of the Super-Kamiokande, and even after the Super-Kamiokande's upgrade and the introduction of gadolinium into the detector's water tank, Nakahata remains an active member of supernova neutrino background research.


Credit: Yukari Ito

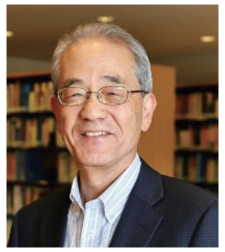
Yukari Ito elected as the next president of the Asian-Oceanian Women in Mathematics

The University of Tokyo Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) Professor Yukari Ito has been elected as the next President of the Asian-Oceanian Women in Mathematics (AOWM), it was announced on December 8 during the AOWM Workshop in New Zealand. The AOWM was established in 2022, after the Committee for Women in Mathematics (CWM), under the International Mathematics Union, received a call for its development. It is the first Asia-Oceania group of mathematicians dedicated to providing support and education for women mathematicians in the region. Ito has been involved with the group as an executive committee member since its establishment.


Credit: Kavli IPMU

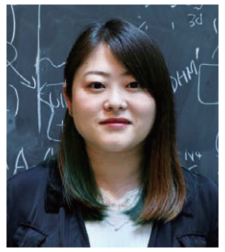
Minh Nguyen named a recipient of the 2024 Buchalter Cosmology Prize

Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) Project Researcher Minh Nguyen has been awarded Third Prize for the 2024 Buchalter Cosmology Prize, it was announced on January 16 at the 245th Meeting of the American Astonomical Society in the US.
The Buchalter Cosmology Prize was established in 2014 by Ari Buchalter, an astrophysicist-turned-entrepreneur who remains keenly interested in cosmology. First, Second and Third Prizes are awarded to new ideas or discoveries that have the potential to produce breakthrough advances in our understanding of the origin, structure, and evolution of the universe beyond current standard cosmological models.
Nguyen is being recognized for work he carried out as Leinweber Fellow at the University of Michigan before joining Kavli IPMU in 2024.


Credit: Kavli IPMU

Tomiyoshi Haruyama receives the Koshiba Prize and 2025 Samuel C. Collins Award

Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) Deputy Director Tomiyoshi Haruayama has been selected as both the 2024 Koshiba Prize and 2025 Samuel C. Collins Award recipient, it was announced by the Foundation for High Energy Accelerator Science on 7 February 2025, and Cryogenic Engineering Conference Awards Committee on 28 January 2025, respectively.
The Koshiba Prize was established by Japan's High Energy Accelerator Science Foundation in honor of Japanese physicist Masatoshi Koshiba, who received the 2002 Nobel Prize in Physics for his pioneering work in neutrino astronomy, which he carried out using the Kamiokande detector.
The award recognizes researchers who have achieved outstanding originality and made internationally acclaimed achievements in the development and research of measuring instrument technology in the field of elementary particles and other basic sciences.
The Samuel C. Collins Award was established in honor of American physicist Samuel C. Collins, inventor of the first commercially available helium liquefier, and recognizes researchers who have identified and resolved cryogenic engineering problems and subsequently served the cryogenic community with their professional service and leadership.
For the Koshiba Prize, Haruyama his being recognized for his contributions to the "Development of a Pulse Tube Cryocooler for Large-Scale Liquid Xenon Particle Detection Experiments." During his time as a researcher at Japan's High Energy Accelerator Research Organization, Haruyama successfully developed an original pulse-tube cryocooler to cool large liquid xenon particle detectors used in particle physics experiments to 165 Kelvin.


Credit: Kavli IPMU

Miho Katsuragawa awarded 2025 Fumiko Yonezawa Memorial Award

Kyoto University Graduate School of Science Assistant Professor and The University of Tokyo Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) Visiting Associate Scientist Miho Katsuragawa has been named a recipient of the 2025 Fumiko Yonezawa Award, it was announced by The Physical Society of Japan in February.
The prize was established by The Physical Society of Japan in 2019 to commemorate the achievements of theoretical physicist Fumiko Yonezawa, and is awarded to women researchers in the JPS to honor and encourage their landmark studies and activities.
Katsuragawa has been recognized for her contributions to "interdisciplinary research based on hard x-ray space observation technologies and their applications to accelerator experiments," particularly for using cadmium telluride (CdTe) semiconductor detectors developed for hard X-ray observations in space to improve the accuracy of non-destructive elemental analysis technology using low-energy negative muon beams. She also contributed to the development of new methods for accurately and simultaneously imaging radionuclides in vivo in small animals.

7 Conferences

Conference Title Date, Place	Attendees (from abroad)
Baryons in the Universe 2024 April 8-12, 2024, Lecture Hall, Kavli IPMU	147 (121)
Towards Realistic Physics at Large Quantum Number May 13-17, 2024, Lecture Hall, Kavli IPMU	27 (16)
Workshop on Galaxy and Black-hole Evolution June 3-7, 2024, Lecture Hall, Kavli IPMU	41 (30)
LLP2024: Fourteenth Workshop of the Long-Lived Particle Community July 1-5, 2024, Koshiba Hall, Hongo Campus, The University of Tokyo	80 (62)
Reconstructing Our View of the Universe with JWST and COSMOS-Web July 8-12, 2024, Lecture Hall, Kavli IPMU	98 (62)
Focus Week on Non-equilibrium Quantum Dynamics September 30-October 4, 2024, Lecture Hall, Kavli IPMU	82 (17)
p-adic Cohomology and Arithmetic Geometry October 21-25, 2024, Tohoku University	88 (25)
27th International Conference on Particle Physics and Cosmology (COSMO2024) October 21-25, 2024, Kyoto University	507 (358)
Kashiwa-no-ha Dark Matter and Cosmology Symposium: Satellite Workshop of COSMO2024 October 28-November 1, 2024, Lecture Hall, Kavli IPMU	290 (168)
T2K Analysis Workshop November 6-8, 2024, Lecture Hall, Kavli IPMU	26 (23)
Focus Week on Primordial Black Holes 2024 November 13-15, 2024, Lecture Hall, Kavli IPMU	43 (19)
Probing the Genesis of Supermassive Black Holes: Emerging Perspectives from JWST and Expecta-tion Toward New Wide-Field Survey Observations November 18-21, 2024, Lecture Hall, Kavli IPMU	97 (55)
Hitoshi-fest: From Particle Physics, Cosmology to Instrumentation December 16-20, 2024, Lecture Hall, Kavli IPMU	113 (15)
PFS Collaboration Meeting January 7-9, 2025, Lecture Hall, Kavli IPMU	176 (67)
LiteBIRD Face-to-Face Meeting at Kavli IPMU January 20-24, 2025, Lecture Hall, Kavli IPMU	140 (100)
Categorical and Analytic Invariants in Algebraic, Symplectic And Complex Geometry February 3-7, 2025, Lecture Hall, Kavli IPMU	55 (8)
Belle II Upgrade Workshop February 24-25, 2025, Lecture Hall, Kavli IPMU	60 (45)
Enumerative Geometry, Representation Theory, and Physics March 3-7, 2025, Lecture Hall, Kavli IPMU	88 (46)
The Quantum Frontier of Machine Learning March 11, 2025, Lecture Hall, Kavli IPMU	60 (11)

8 Conference Presentations & Seminar Talks

Invited talks given by the Kavli IPMU researchers (Selected 12 of 350)

Presenter	Presentation title	Conference name and date
Masahiro Takada	Weak Lensign Cosmology	Cosmology in the Adriatic -- From PT to AI July 18, 2024
Hitoshi Murayama	US P5 Vision and Strategic Plan	ICHEP2024 July 23, 2024
Elisa G. M. Ferreira	How to Build a Dark Matter Model: Evidences and the Landscape of Dark Matter Candidates	EXPLORE 2024 August 23, 2024
Anamaria Hell	Aspects of Massive Gauge Fields	Corfu 2024 – The Dark Side of the Universe September 10, 2024
Mark Vagins	Hyper-Kamiokande Looks to the Heavens	Towards the Detection of Diffuse Supernova Neutrinos Workshop September 19, 2024
Shigeki Matsumoto	Mediator Decay through Mixing with Degenerate Spectrum	The 4th Asian-European-Institutes (AEI) Workshop for BSM October 10, 2024
Hiromi Yokoyama	Measuring Trust in AI for Policy Implementation: Demand for AI in Medicine Accelerates AI Use in Japan	Chinese Academy of Sciences October 14, 2024
Jun'ichi Yokoyama	Quantum Aspects of Inflationary Cosmology	2024 ICTP-AP Winter School on Theoretical Physics November 28, 2024
Todor Milanov	K-Theoretic Heisenberg Algebras and Permutation-Equivariant GW Theory	Enumerative Geometry in East Asia December 16, 2024
Masahito Yamazaki	Crystal Melting and Quiver Algebras	Strings 2025 January 7, 2025
Hiraku Nakajima	Duality of Nilpotent Orbits for Classical Groups	The 2025 Annual Meeting of Mathematical Society of the Republic of China (TMS) January 14, 2025
Leander Thiele	Cosmic Voids	Voids @ CPPM February 15, 2025

9 Outreach and Public Relations

Event Title	Date	Venue	Number of Participants
30th Kavli IPMU x ICRR Hybrid Joint Public Lecture: Hyper-Kamiokande Experiment & Singularities	April 20, 2024	Kashiwanoha Conference Center & Online	400
Science Cafe in English: Universe 2024 "A pillar of precision cosmology in the 21st century: wide-field perturbation statistics"	July 20, 2024	Tamarokuto Science Center	31
Science Cafe in English: Universe 2024 "Knot invariants: How can we represent and study objects around us as mathematicians"	September 22, 2024	Tamarokuto Science Center	27
Open Campus Kashiwa 2024	October 25-26, 2024	Kashiwa Campus, The University of Tokyo & Online	4,627
The 13th WPI Science Symposium	November 16, 2024	Clock Tower Centennial Hall, Kyoto University	301
9th Of Course I Love Physics: Careers for Girls in Physics	November 23, 2024	Online	30
31th Kavli IPMU x ICRR Joint Online Public Lecture: The Mystery of Massive Quantities "Dark Matter and Ultra High Energy Gamma Rays"	December 8, 2024	Yasuda Auditorium, The University of Tokyo & Online	800
10th Kavli IPMU/ELSI/IRCN Joint Public Lecture: A Question of Origins	January 25, 2025	SHIBUYA QWS Scramble Hall & Online	541
2025 AAAS Annual Meeting	February 13-15, 2025	Hynes Convention Center, USA	4,000