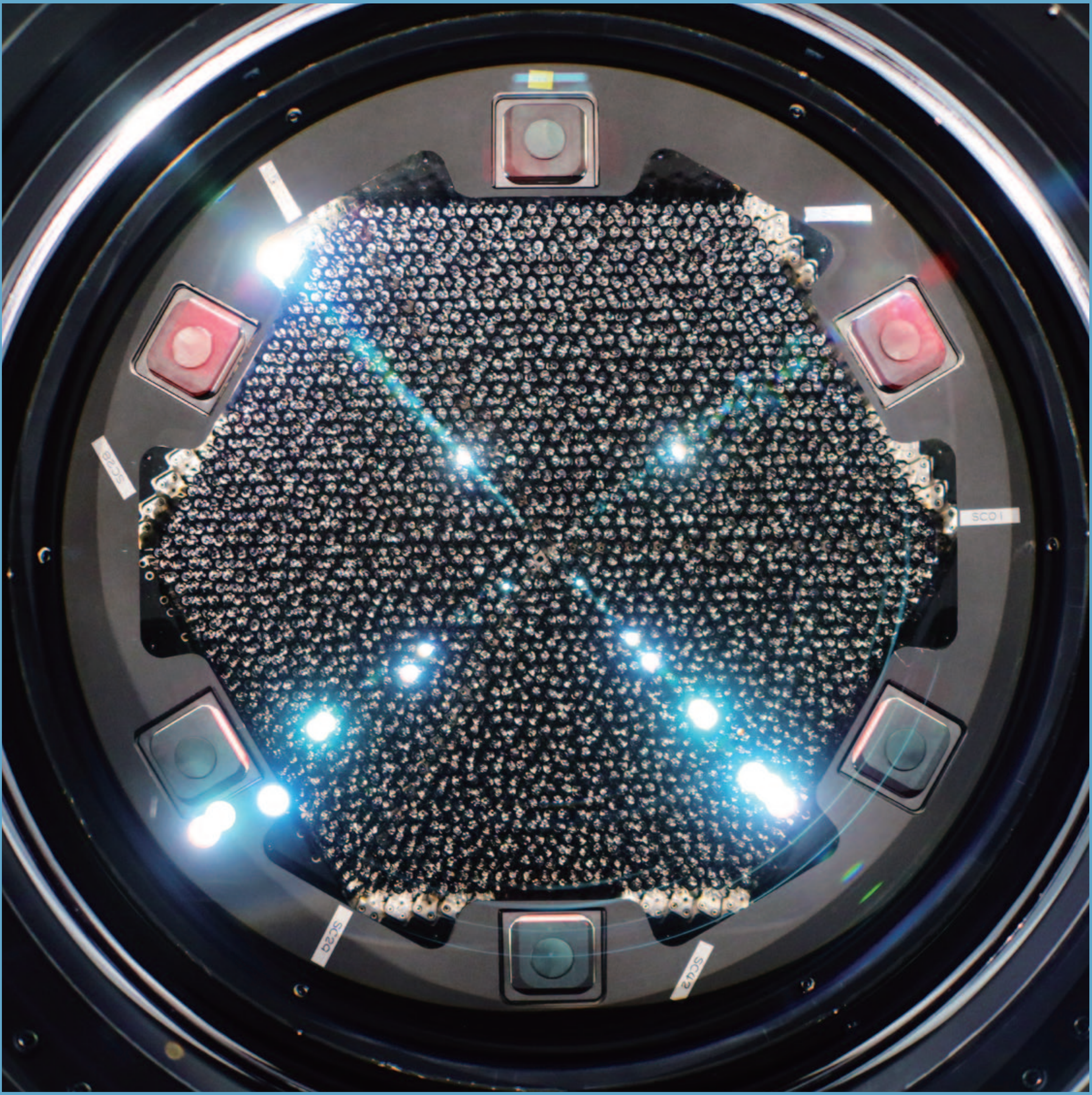


April 2021–March 2022

Kavli IPMU

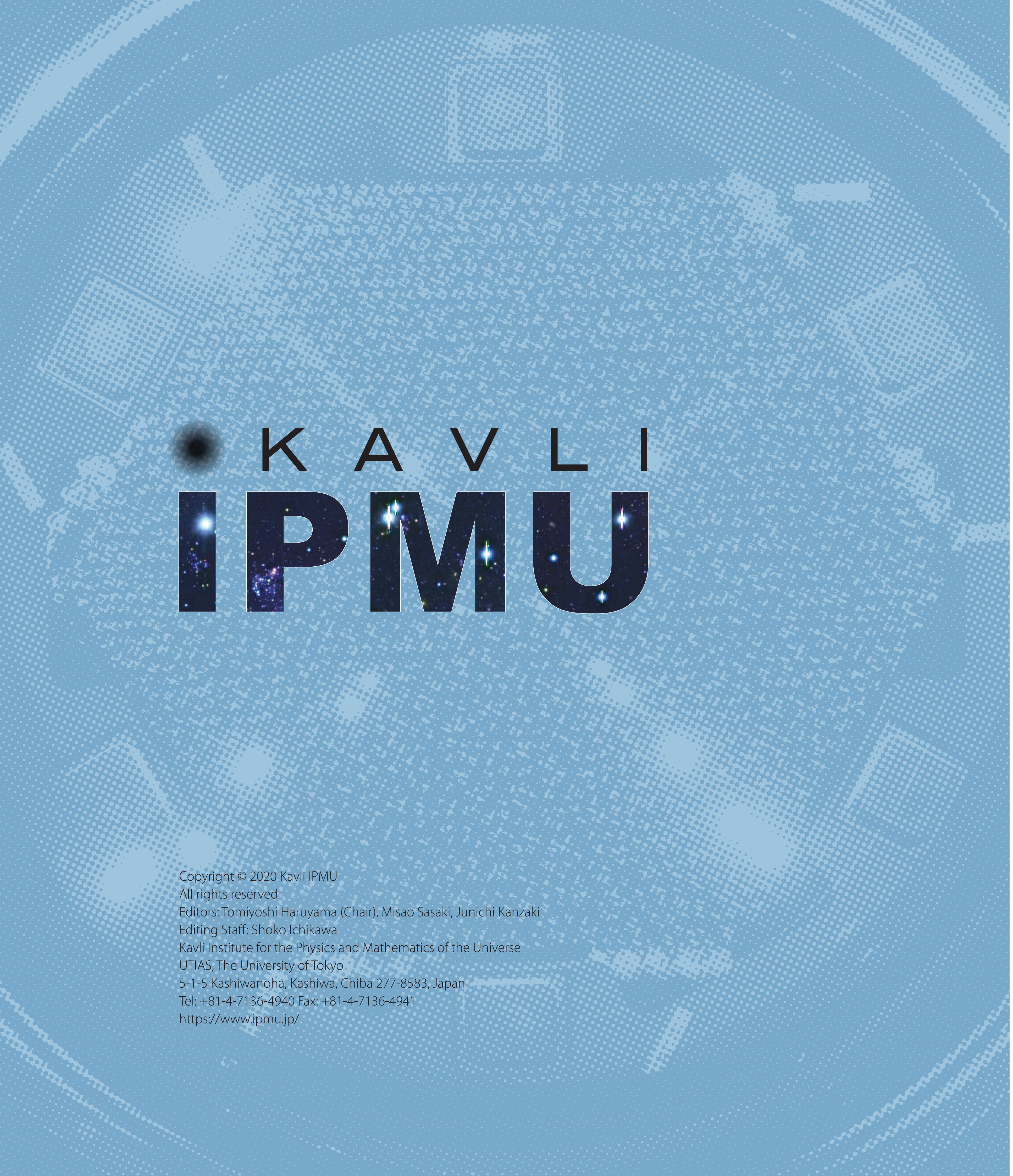
ANNUAL REPORT 2021

THE UNIVERSITY OF TOKYO

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

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

wpi World Premier International Research Center Initiative



KAVLI IPMU

Editors: Tomiyoshi Haruyama (Chair), Misao Sasaki, Junichi Kanzaki
Editing Staff: Shoko Ichikawa
Kavli Institute for the Physics and Mathematics of the Universe
UTIAS, The University of Tokyo
5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan
Tel: +81-4-7136-4940 Fax: +81-4-7136-4941
https://www.ipmu.jp/

CONTENTS

On the cover:
This is the focal plane of Prime Focus Spectrograph (PFS) on the Subaru telescope prime focus. Many small dots distributed in the hexagonal area are fiber positioners called "Cobra" each of which is integrated with an optical fiber and a microlens that receives photons from the sky and feeds them to the spectrograph. There are about 2400 of them in total, which can be moved individually and very accurately to the positions around them where astronomical objects such as stars and galaxies of interest are imaged on the focal plane. Meanwhile, the six square devices around the hexagonal area are the CCD cameras to measure the positions of bright stars on the images for the telescope auto guiding and field acquisition (Credits: PFS project).

FOREWORD

Hirosi Ooguri
Director

By the time you read this Annual Report, I hope the COVID-19 pandemic is in our rear view or at least stays in a manageable level. In October, the Japanese government resumed visa waiver programs for 68 countries and regions Tuesday, lifting COVID-19-induced restrictions. At the Kavli IPMU, we have resumed in-person seminar series, workshops, and conferences and are welcoming back visitors from abroad.

We are pleased to welcome Patrick de Perio, Elisa Ferreira, and Jia Liu as our new tenure-track faculty members. Patrick works on underground high energy experiments including T2K, Super-Kamiokande, and Hyper-Kamiokande. Elisa works in the interface between cosmology, astrophysics, and high energy physics, with focus on the dark sector of the Universe. Jia works on the large-scale structures to elucidate fundamental physics, such as the nature of dark energy and neutrino mass, using cosmological observations of the cosmic microwave background and galaxies together with state-of-the-art numerical simulations.

I am also pleased to report that Hiraku Nakajima, one of our professors in mathematics, is the next President of the International Mathematical Union (IMU). IMU represents mathematical societies of more than 80 countries around the world, organize the International Congress of Mathematicians, and awards the Fields Medals. It is a significant recognition of his achievements and stature in mathematics. I applaud him for taking on this important responsibility and look forward to his leadership at IMU.

"M" of the Kavli IPMU stands for "mathematics." We include mathematics in our name since we believe that mathematics plays an essential role in our mission to solve fundamental questions about our Universe. Hiraku exemplifies this mission. When I was a faculty member in Kyoto University and invited Edward Witten to Japan in 1994, he wanted to meet Hiraku. It turned out that mathematical formulas Hiraku derived in 1993 played an essential role in Witten's work with Cumrun Vafa on quantum gauge theory in four dimensions, which was published a couple of months after his meeting with Hiraku. Hiraku's works over the last three decades have had enormous impacts on physics as well as on mathematics. Among his many honors and recognitions, he is a recipient of the Cole Prize in Algebra from the American Mathematical Society and the Japan Academy Prize. The fact that he has been chosen to lead IMU for the next four years validates the founding vision of the Kavli IPMU that, by integrating mathematics with physics and astronomy, we make advances and open new directions of research in mathematics as well as in physics and astronomy.

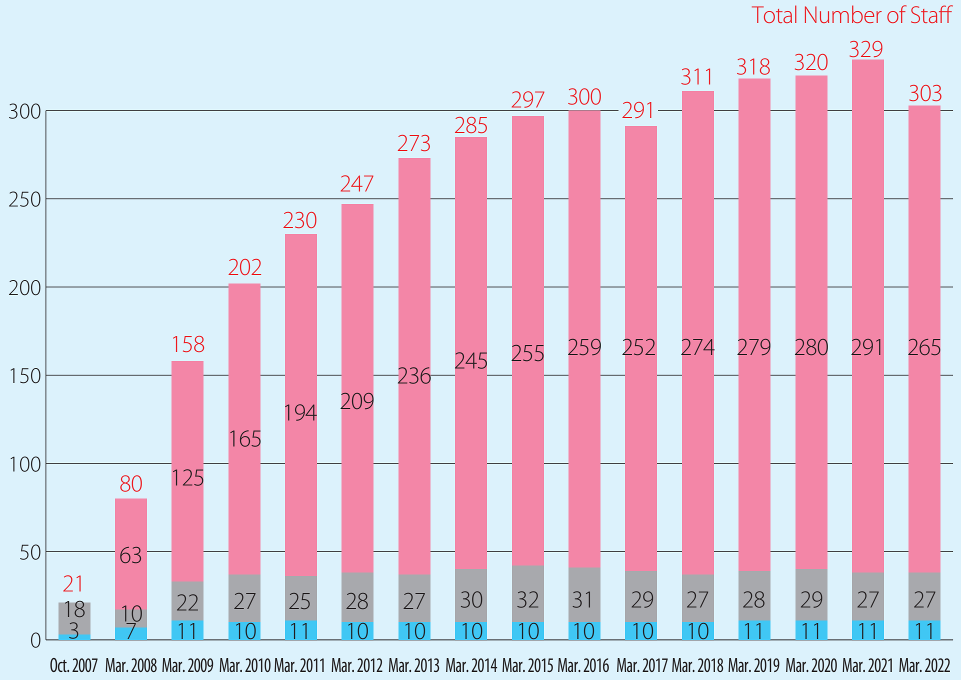
We are also making great progress in experiments and observations. Super-Kamiokande Gadolinium Project, initiated by our own Mark Vagins, is expecting the first physics results in 2023. Hyper-Kamiokande construction is on schedule, and its tunnel excavation has reached the center of the cavern dome. At Subaru Telescope, Hyper Suprime-Cam survey completed its observation and will release cosmology parameters this year, and Prime Focus Spectrograph expects to complete all deliveries and test by 2023 and start its scientific observations in 2024. LiteBIRD, the satellite to detect CMB polarizations, is working on its mission definition review.

In my inaugural address as the Director of the Kavli IPMU in October 2018, I stated my commitment to provide an inclusive and supportive environment to the diverse group of people in our community. Last year, we launched the Kavli IPMU Diversity Initiative to make progress in diversity, equity, and inclusion. We established the Chien-Shiung Wu Prize Postdoctoral Fellowship for female scientists, with the approval of the son and granddaughter of Chien-Shiung Wu, whose groundbreaking experiment proved that parity symmetry is broken by the weak interaction. The inaugural recipient of the prize is Man-Wai Cheung, who is a mathematician working on cluster algebras, mirror symmetry for cluster varieties, and the relation between representation theory and mirror symmetry. We are also offering leadership trainings to our members with focus on valuing diversity and leading inclusively, improving our communication on diversity issues to them, organizing outreach activities for female students in science, and offering childcare support for our conference participants. We are reviewing outcomes of these activities and striving to improve them.

Hirosi Ooguri

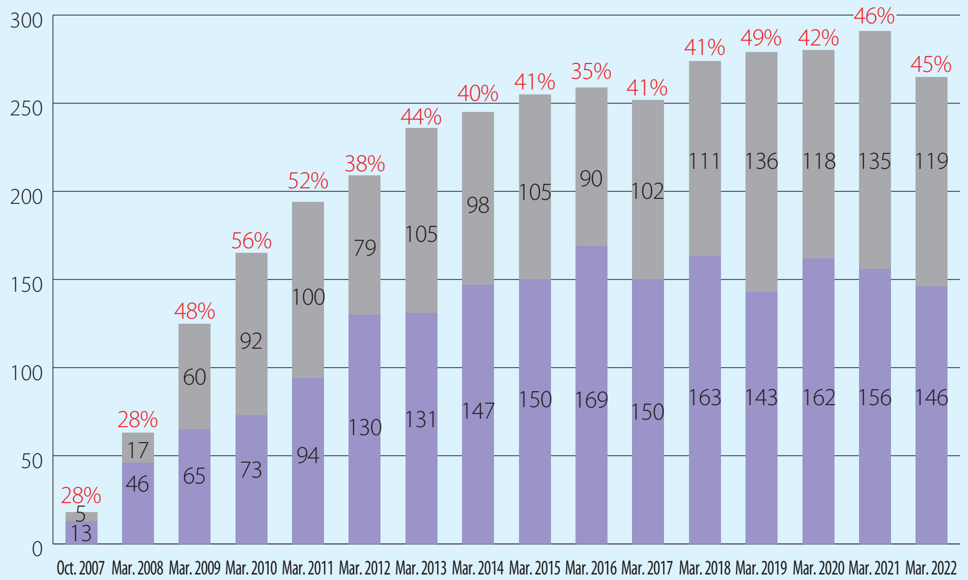
1 STATISTICS

STAFF



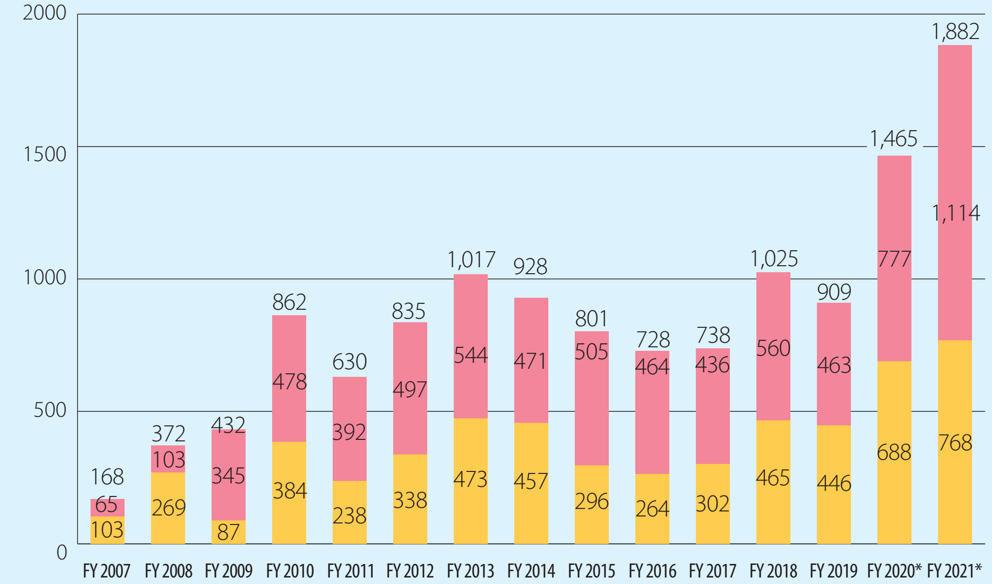
	Oct. 2007	Mar. 2008	Mar. 2009	Mar. 2010	Mar. 2011	Mar. 2012	Mar. 2013	Mar. 2014	Mar. 2015	Mar. 2016	Mar. 2017	Mar. 2018	Mar. 2019	Mar. 2020	Mar. 2021	Mar. 2022
🟥 Researchers	18	63	125	165	194	209	236	245	255	259	252	274	279	280	291	265
■ Research Support Staffs	0	10	22	27	25	28	27	30	32	31	29	27	28	29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

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
■ Overseas	5	17	60	92	100	79	105	98	105	90	102	111	136	118	135	119
■ Domestic	13	46	65	73	94	130	131	147	150	169	150	163	143	162	156	146
% of Overseas	28%	28%	48%	56%	52%	38%	44%	40%	41%	35%	41%	41%	49%	42%	46%	45%
% of Female	0%	2%	5%	6%	5%	2%	5%	5%	6%	4%	6%	8%	9%	10%	9.3%	11.7%

RESEARCH ACTIVITIES

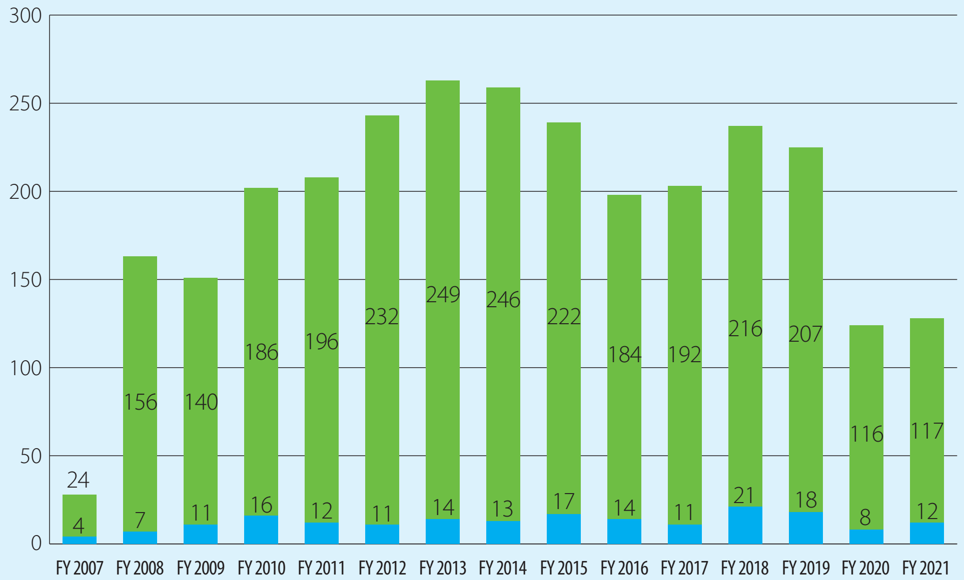


	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020*	FY 2021*
🟥 Visitors (Overseas)	65	103	345	478	392	497	544	471	505	464	436	560	463	777	1,114
🟨 Visitors (Domestic)	103	269	87	384	238	338	473	457	296	264	302	465	446	688	768
Visitors (Total)	168	372	432	862	630	835	1,017	928	801	728	738	1,025	909	1,465	1,882

Multiple visits in a given year are counted as one.

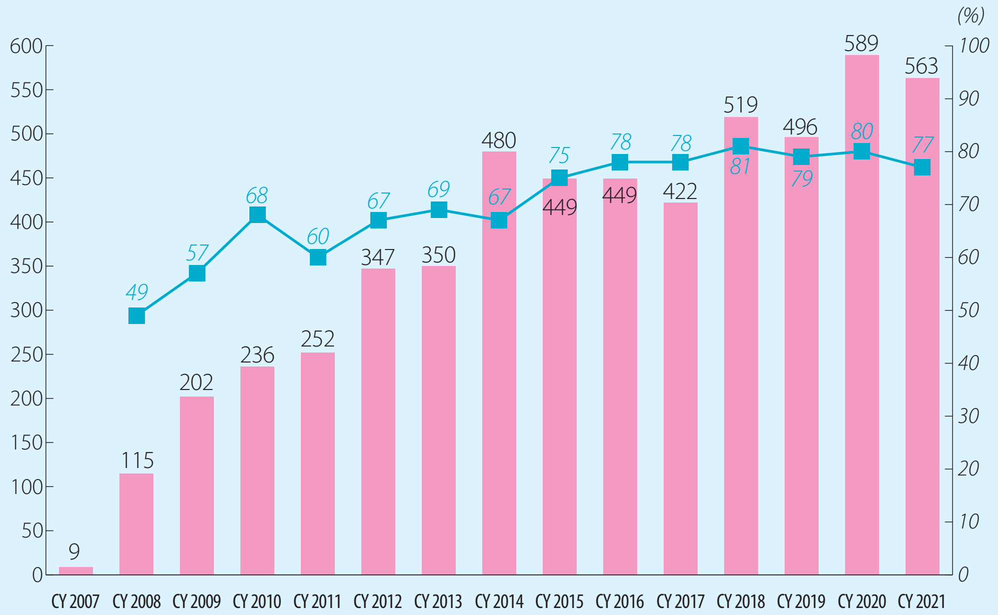
* Number of participants for online conferences are included from FY2020 onward.

SEMINARS & CONFERENCES



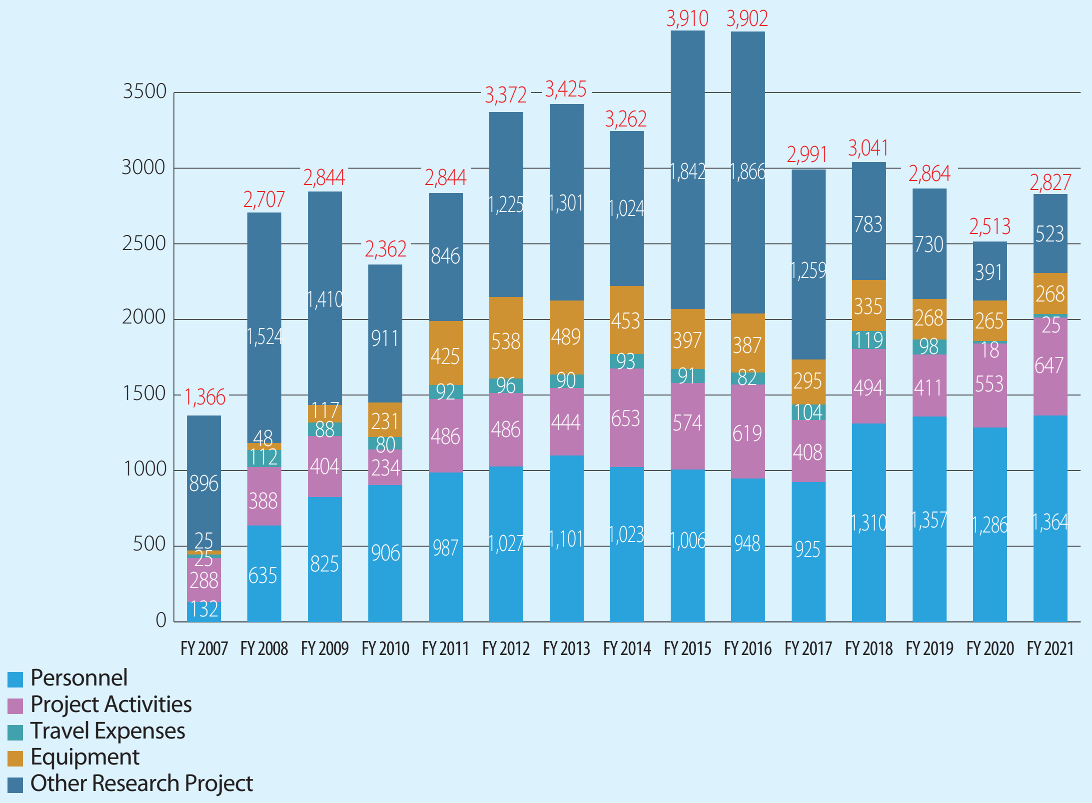
	FY 2007	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	FY 2021
🟩 Seminars	24	156	140	186	196	232	249	246	222	184	192	216	207	116	117
🟦 Conferences	4	7	11	16	12	11	14	13	17	14	11	21	18	8	12

PUBLICATIONS

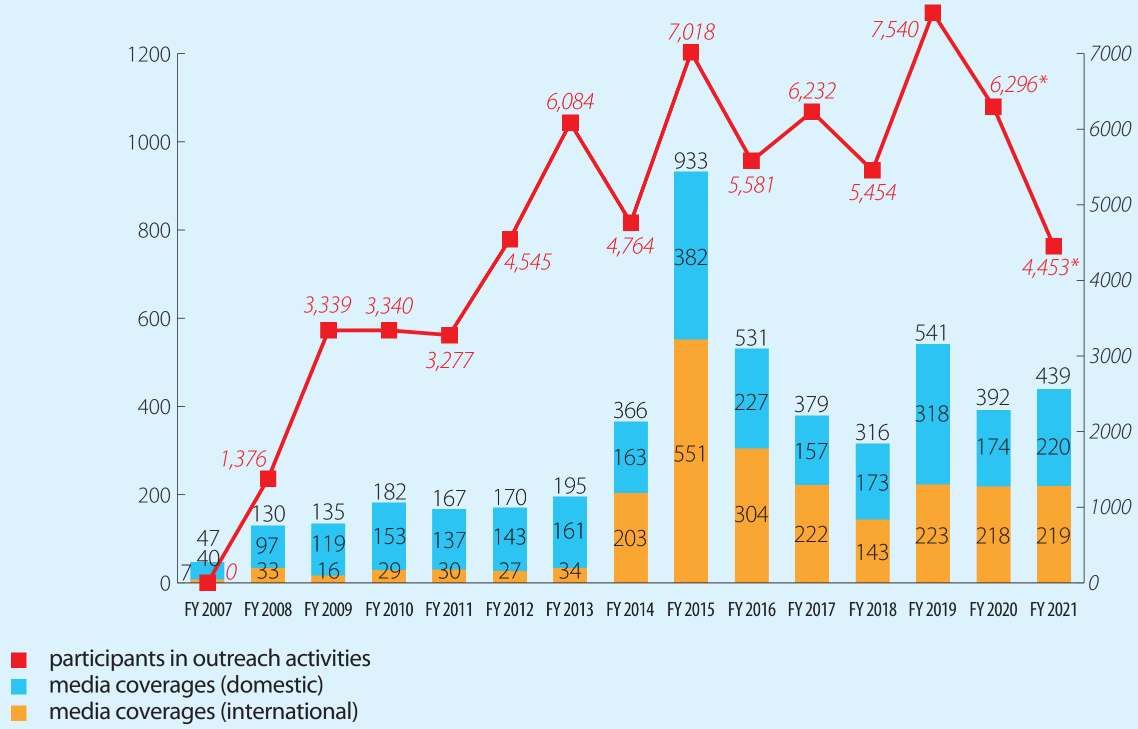


	CY 2007	CY 2008	CY 2009	CY 2010	CY 2011	CY 2012	CY 2013	CY 2014	CY 2015	CY 2016	CY 2017	CY 2018	CY 2019	CY 2020	CY 2021
Publications	9	115	202	236	252	347	350	480	449	449	422	519	496	589	563
% of international collaboration	49%	57%	68%	60%	67%	69%	67%	75%	78%	78%	81%	79%	80%	77%

TOTAL EXPENDITURE

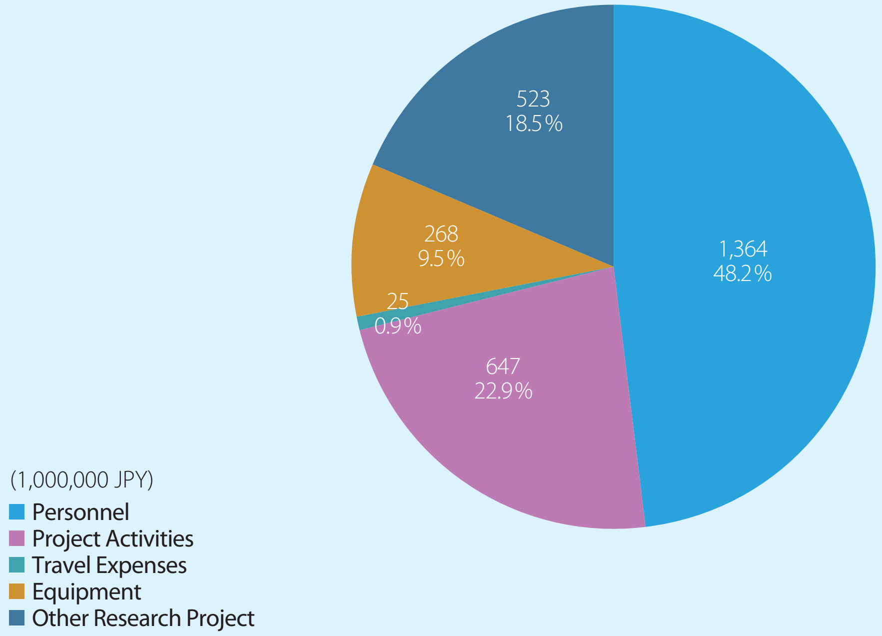


MEDIA COVERAGES AND OUTREACH ACTIVITIES



* Number of participants of the Kashiwa Campus Open day is not included in FY2020 and FY2021.

BREAKDOWN OF FY 2021 TOTAL EXPENDITURE



2 NEWS & EVENTS

April 2021 - March 2022

APRIL

- >> The 24th ICRR & Kavli IPMU public lecture “The wonders of a universe full of matter” [online]
- >> Research institutes in Japan and France establish new laboratory for astrophysics and particle physics
- >> COSMOS-Webb program to map earliest structure of the Universe selected by James Webb Space Telescope
- >> PFS can now successfully observe night sky spectra
- >> Film screening “Secrets of the Surface: The Mathematical Vision of Maryam Mirzakhani” [online]

JUNE

- >> Number Theory, Strings and Quantum Physics [online]
- >> Hyper-Kamiokande Collaboration Meeting [online]
- >> Quarkonia Meet Dark Matter [online]
- >> Fundamentalz Bazaar
- >> Axions could be the fossil of the Universe researchers have been waiting for
- >> A rogue in the “Cosmic Standard Candle”? - the relic of the densest white dwarf has been detected in the remnant of its supernova -
- >> Science Cafe “Universe” [online]
- >> Research into “Birth of Elements” awarded grant by the Leverhulme Trust
- >> Theoretical proof that a strong force can create light-weight subatomic particles
- >> A new type of supernova illuminates an old mystery

JULY

- >> Director Hirosi Ooguri gives summary talk at Strings 2021
- >> Parliamentary Vice-Minister of MEXT Hidehiro Mitani visits Kavli IPMU
- >> Director Hirosi Ooguri elected Chair of the Board of Trustees of the Aspen Center for Physics
- >> Leading xenon researchers unite to build next-generation Dark Matter Detector
- >> Split second behavior of muons in atoms uncovered for first time

AUGUST

- >> President of the Republic of Armenia Armen Sarkissian visits Kavli IPMU
- >> Astrophysicists, social scientists to probe the Universe’s deepest mysteries
- >> Hirosi Ooguri named Benjamin Lee Professor
- >> Focus Week on Quantum Mechanical Systems at Large Quantum Number [online]

SEPTEMBER

- >> Young-Kee Kim elected Vice President of the American Physical Society
- >> Science Cafe “Universe” [online]

OCTOBER

- >> Masashi Hazumi to become director of new research institute studying the universe and its particles
- >> Open Campus Kashiwa 2021 (Kavli IPMU: Oct 23 - 24) [online]

NOVEMBER

- >> 6th “Actually I Really Love Physics!”–Career Paths of Female Physics Graduates [online]
- >> Particle Acceleration in Solar Flares and the Plasma Universe --Deciphering Its Features Under Magnetic Reconnection-- [online]
- >> The World of Mathematical Physics II [online]
- >> Kavli IPMU x ICRR Joint Public Lecture: “A dream of modern mathematics. A cutting edge of physics” [online]

DECEMBER

- >> Dark Sectors of Astroparticle Physics (AstroDark-2021): Axions, Neutrinos, Black Holes and Gravitational Waves [online]
- >> Record-breaking simulations of large-scale structure formation in the Universe
- >> Gravitational waves could be key to answering why more matter was left over after Big Bang
- >> Researchers capture fastest optical flash emitted from a newborn supernova
- >> Eiichiro Komatsu awarded the Inoue Prize for Science
- >> Unveiling substructures at the edge of the Galaxy
- >> Kavli IPMU Annual Report 2020 released
- >> 10th Annual WPI Science Symposium: “To The Future NanoWorld” [online]

JANUARY

- >> New Observational Windows on the High-Scale Origin of Matter-Antimatter Asymmetry [online]
- >> Measuring trust in AI
- >> New theory finds upcoming satellite mission will be able to detect more than expected
- >> Researchers uncover model for extremely luminous and fast rising supernova
- >> Scientists make a new type of optical device using alumina
- >> Hitoshi Murayama named new AAAS fellow
- >> 7th Kavli IPMU/ELSI/IRCN Joint Public Lecture: “A Question of Origins” [online]

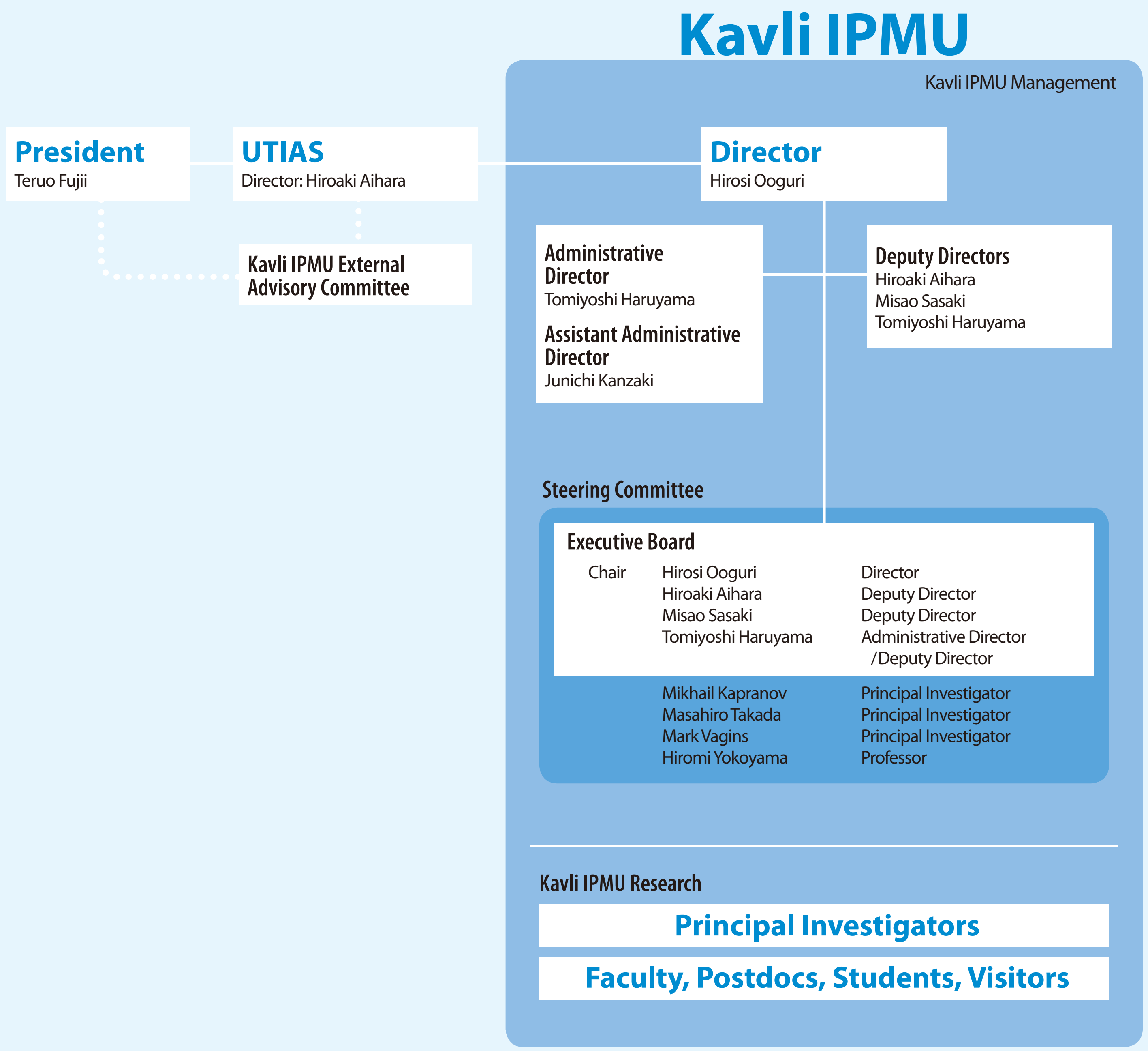
FEBRUARY

- >> Hyper-Kamiokande Collaboration Meeting

MARCH

- >> Fundamentalz Festival mini: An Exhibition of work by Artists and Researchers
- >> Cosmic Cartography 2022: Exploring the Cosmic Web and Large-Scale Structure [online]
- >> PFS 13th Collaboration Meeting [online]
- >> What Is Dark Matter? - Comprehensive Study of the Huge Discovery Space in Dark Matter - [online]

3 ORGANIZATION



Kavli IPMU

Kavli IPMU Management

President
Teruo Fujii

UTIAS
Director: Hiroaki Aihara

Kavli IPMU External Advisory Committee

Director
Hirosi Ooguri

Administrative Director
Tomiyoshi Haruyama

Assistant Administrative Director
Junichi Kanzaki

Deputy Directors
Hiroaki Aihara
Misao Sasaki
Tomiyoshi Haruyama

Steering Committee

Executive Board

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

Kavli IPMU Research

Principal Investigators

Faculty, Postdocs, Students, Visitors

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

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

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

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

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

The External Advisory Committee Members (March 2021)

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

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

Host Institute
(The Univ. of Tokyo)

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

Kavli IPMU
Kashiwa Campus
Kamioka Branch

Berkeley Satellite

Collaborating Institutions
(overseas)

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

Collaborating Institutions
(domestic)

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

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

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

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

4

STAFF

Director

Hirosi Ooguri, Mathematical Physics

Deputy Directors

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

Principal Investigators

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

Faculty Members

Tomoyuki Abe, Mathematics
Hiroaki Aihara(U Tokyo), High Energy Physics
Alexey Bondal(Steklov Math. Inst.), Mathematics (2021/8/1-2022/2/15)
Elisa Gouvea Mauricio Ferreira, Cosmology (from 2021/12/3)
Mark Patrick Hartz, Neutrino Physics
Tomiyoshi Haruyama, High Energy Physics
Simeon John Hellerman, String Theory
Takeo Higuchi, High Energy Physics
Chiaki Hikage, Cosmology
Kentaro Hori, String Theory
Shunsaku Horiuchi, Theoretical Physics (from 2021/8/10)
Yukari Ito, Mathematics
Mikhail Kapranov, Mathematics
Nobuhiko Katayama, High Energy Physics
Khee-Gan Lee, Astronomy
Jia Liu, Cosmology (from 2021/9/1)
Kai Uwe Martens, Experimental Physics
Shigeki Matsumoto, Cosmology
Tomotake Matsumura, Experimental Physics
Thomas Edward Melia, Theoretical Physics
Todor Eliseev Milanov, Mathematics
Hitoshi Murayama(UC Berkeley), Particle Theory
Hiraku Nakajima, Mathematics
Toshiya Namikawa, Cosmology (from 2021/8/1)
Andrei Okounkov(Columbia U), Mathematics (from 2021/9/1)
Hirosi Ooguri(CALTECH), Mathematical Physics
Tadashi Orita, Experimental Physics
Misao Sasaki, Cosmology
Satoshi Shirai, Particle Theory
John David Silverman, Astronomy
Yevgeny Stadnik, Theoretical Physics (till 2021/12/31)
Nao Suzuki, Astrophysics (till 2021/9/15)
Yuji Tachikawa, Particle Theory
Masahiro Takada, Cosmology
Tadayuki Takahashi, Experimental Physics
Shinichiro Takeda, Experimental Physics
Naoyuki Tamura, Astronomy
Yukinobu Toda, Mathematics
Mark Robert Vagins, Astroparticle Physics
Taizan Watari, Theoretical Physics
Atsushi Yagishita, Experimental Physics
Masaki Yamashita, Astrophysics
Masahito Yamazaki, String Theory
Naoki Yasuda, Astronomy
Hiromi Yokoyama, Science and Society
Naoki Yoshida(U Tokyo), Astrophysics

Project Researchers

Shunsuke Adachi, Experimental Physics (till 2021/9/30)
Meer Ashwinkumar, String Theory
Metin Ata, Cosmology
Tobias Binder, Theoretical Physics
Connor Hugh Bottrell, Astrophysics
Philip Ewen Boyle Smith, Theoretical Physics (from 2021/9/16)
Tuan Khai Bui, Experimental Physics
Yalong Cao, Mathematics (till 2021/7/15)
Anqi Chen, Cosmology (from 2021/11/1)
Thomas Rafael Czank, Experimental Physics (till 2021/11/30)
Anton Reyes De la Fuente, String Theory
Xuheng Ding, Astronomy
Zhiyuan Ding, Mathematics
Matthew Dodelson, String Theory (till 2021/9/30)
Joshua Armstrong Eby, Cosmology
Fatemeh Elahi, High Energy Physics (till 2021/5/10)
Dmitrii Galakhov, String Theory
Naoki Genra, Mathematics
Tommaso Ghigna, Experimental Physics
Ryuichiro Hada, Cosmology
Takashi Hasebe, High Energy Physics
Thuong Duc Hoang, Experimental Physics (from 2021/11/1)
Shunichi Horigome, Theoretical Physics (from 2021/6/1)
Seyed Morteza Hosseini, String Theory (till 2021/9/30)
Shuhei Iguro, Particle Theory (2021/4/1 -9/30)
Yuko Ikkatai, Science and Society (till 2021/9/30)
Derek Beattie Inman, Cosmology
Kazuhiro Ito, Mathematics (from 2021/12/2)
Jian Jiang, Astronomy
Kookhyun Kang, High Energy Physics (from 2021/8/16)
Miho Katsuragawa, Experimental Physics
Lalitwadee Kawinwanichakij, Astrophysics (till 2021/10/31)
Ilya Khrykin, Astrophysics
Yosuke Kobayashi, Cosmology (2021/4/1 - 8/31)
Takafumi Kokubu, Theoretical Physics (from 2021/10/1)
Robin Rinze Kooistra, Astronomy (till 2022/1/15)
Chiara La Licata, Experimental Physics (till 2022/1/15)
Yun-Tsung Lai, High Energy Physics
Hsueh-Yung Lin, Mathematics (till 2021/7/31)
Wentao Luo, Astrophysics (till 2021/5/16)
Oscar Macias, Astrophysics (till 2021/8/31)
Abhiram Mamandur Kidambi, Mathematical Physics
Mohammad Khaled Hashem Mardini, Astronomy (from 2021/7/1)
Rieko Momose, Astronomy (from 2021/8/1)
Yuki Moritani, Astronomy (till 2021/8/31)
Shigenori Nakatsuka, Mathematics
Emily Margaret Nardoni, Theoretical Physics (from 2021/10/1)
Hyunbae Park, Cosmology (till 2021/10/31)
Youngsoo Park, Cosmology
Samuel Charles Passaglia, Cosmology

Alexis Roquefeuil, Mathematics (till 2022/1/1)
Ipsita Saha, Particle Theory
Yuki Sakurai, Experimental Physics (till 2021/9/30)
Yuya Sakurai, Astrophysics
Jingjing Shi, Cosmology
Tomoko Suzuki, Astronomy (from 2021/10/1)
Volodymyr Takhistov, Theoretical Physics
Izumi Umeda, Medical Application of Gamma-ray Imaging
Valeri Vardanyan, Cosmology
John Welliaveetil, Mathematics (till 2021/5/31)
Graham Albert White, Particle Theory
Kenneth Christopher Wong, Astronomy (till 2021/6/30)
Kiyoto Yabe, Astronomy
Ryo Yamagishi, Mathematics
Lilan Yang, Astronomy (from 2021/11/4)
Hassen Yesuf, Astronomy
Wai Kit Yeung, Mathematics
Vicharit Yingcharoenrat, Cosmology (from 2021/11/1)
Yu Zhao, Mathematics (from 2021/7/3)
Yunqin Zheng, Theoretical Physics
Zijun Zhou, Mathematics

Joint Appointments

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

Affiliate Members

Kou Abe(U Tokyo, ICRR), Astroparticle Physics
Shin'ichiro Ando(U Amsterdam), Astroparticle Physics
Bruce Berger(LBL, Berkeley (LBNL)), Neutrino Physics
Melina Bersten(IALP CONICET-UNLP), Astronomy
Sergey Blinnikov(ITEP), Astronomy
Agnieszka Maria Bodzenta-Skibinska(U Warsaw), Mathematics
Kevin Allen Bundy(UC Santa Cruz), Astronomy
Andrew Bunker(U Oxford), Astrophysics
Scott Huai-Lei Carnahan(U Tsukuba), Mathematics
Cheng-Wei Chiang(Natl Taiwan U), Particle Theory
Yuji Chinone(U Tokyo), Astronomy
Neal K Dalal(Perimeter Institute), Astrophysics
Patrick De Perio, Neutrino Physics (from 2021/6/25)
Patrick Decowski(U Amsterdam/GRAPPA), Neutrino Physics
Jason Detwiler(U Washington, Seattle), Neutrino Physics
Mamoru Doi(U Tokyo, IoA), Astronomy
Chris Done(Durham U), Astrophysics
William Ross Goodchild Donovan(Tsinghua U, Beijing), Mathematics
Yuri Efremenko(U Tennessee), Neutrino Physics
Motoi Endo(KEK), Particle Theory
Sanshiro Enomoto(U Washington, Seattle), Neutrino Physics
Gaston Folatelli(IALP CONICET-UNLP), Astrophysics
Andreu Font-Ribera(IFAE-Barcelona), Cosmology
Brian Fujikawa(LBL, Berkeley), Neutrino Physics
Masataka Fukugita(U Tokyo), Astrophysics
Shao-Feng Ge(Shanghai Jiao Tong U), Theoretical Physics
Paolo Gondolo(U Utah), Cosmology (from 2021/4/22)
Lawrence J Hall(UC Berkeley), Particle Theory
Koichi Hamaguchi(U Tokyo), Particle Theory
Jiaxin Han(Shanghai Jiao Tong U), Astronomy
Tilman Hartwig(U Tokyo), Astrophysics
Tetsuo Hatsuda(RIKEN), Nuclear Physics
Yoshinari Hayato(U Tokyo, ICRR), Neutrino Physics
Katsuki Hiraide(U Tokyo, ICRR), Astroparticle Physics
Raphael Hirschi(Keele U), Astronomy
Junji Hisano(Nagoya U), Particle Theory
Kenta Hotokezaka(U Tokyo, School of Science), Astrophysics
Masahiro Ibe(U Tokyo, ICRR), Particle Theory
Kei Ieki(U Tokyo, ICRR), Neutrino Physics (from 2021/11/1)
Hirokazu Ikeda(JAXA), Experimental Physics
Motoyasu Ikeda(U Tokyo, ICRR), High Energy Physics
Shiro Ikeda(ISM), Mathematics
Yuko Ikkatai(Kanazawa U), Science and Society (from 2021/10/1)
Yoshiyuki Inoue(Osaka U), Astrophysics
Miho N. Ishigaki(NAOJ, Hawaii), Astronomy
Ken'ichi Izawa(Tokushima U), Particle Theory
Nicholas Kaiser(Ecole normale superieure), Cosmology
Jun Kameda(U Tokyo, ICRR), Neutrino Physics
Yousuke Kanayama(RIKEN), Experimental Physics
Amanda Irene Karakas(Monash U), Astronomy
Kazumi Kashiyama(Tohoku U), Astronomy (from 2021/5/1)
Yosuke Kataoka(U Tokyo, ICRR), Neutrino Physics (from 2021/11/1)
Akishi Kato(U Tokyo, Math Sci), Mathematical Physics
Yasuyuki Kawahigashi(U Tokyo, Math Sci), Mathematics
Edward T. Kearns(Boston U), Neutrino Physics
Sergey Ketov(Tokyo Metropolitan U), Theoretical Physics
Yasuhiro Kishimoto(Tohoku U), Neutrino Physics
Ryuichiro Kitano(KEK), Particle Theory
Chiaki Kobayashi(CAR, U of Hertfordshire), Astronomy
Masayuki Koga(Tohoku U), Neutrino Physics
Kazunori Kohri(KEK), Cosmology
Satoshi Kondo(Middle East Technical U), Mathematics
Yusuke Koshio(Okayama U), Neutrino Physics
Akito Kusaka(U Tokyo), Experimental Physics
Alexander Kusenko(UCLA), Particle Theory
Tatsuki Kuwagaki(Kyoto U), Mathematics
Alexie, Solange Leauthaud Harnett(UC Santa Cruz), Astrophysics
Shiu-Hang (Herman) Lee(Kyoto U), Astrophysics
Marco Limongi(INAF), Astrophysics
Kazuo Makishima(U Tokyo), High Energy Physics
Ryu Makiya(ASIAA), Astronomy
Brice Menard(Johns Hopkins U), Astrophysics
Makoto Minowa(U Tokyo), Experimental Physics
Makoto Miura(U Tokyo, ICRR), High Energy Physics
Hironao Miyatake(Nagoya U), High Energy Physics
Hiroshi Mizuma(RIKEN), Experimental Physics
Anupreeta Sadashiv More(IUCAA), Astronomy
Surhud Shrikant More(IUCAA), Astronomy
Yuki Moritani(NAOJ, Hawaii), Astronomy (from 2021/9/1)
Takeo Moroi(U Tokyo), Particle Theory
David Robert Morrison(UC Santa Barbara), Mathematics
Shinji Mukohyama(Kyoto U), Cosmology
Motohico Mulase(UC Davis), Mathematics
Dinakar Muthiah(U Glasgow), Mathematics
Kentaro Nagamine(Osaka U), Astrophysics
Yasuhiro Nakajima(U Tokyo, School of Science), Neutrino Physics
Kenzo Nakamura(KEK), Neutrino Physics
Tsuyoshi Nakaya(Kyoto U), High Energy Physics
Kazunori Nakayama(Tohoku U), Cosmology
Shoei Nakayama(U Tokyo, ICRR), Neutrino Physics
Takahiro Nishimichi(Kyoto U), Cosmology
Ken'ichi Nomoto(U Tokyo), Astronomy
Hirokazu Odaka(U Tokyo), High Energy Astrophysics
Masamune Oguri(Chiba U), Cosmology
Shinnosuke Okawa(Osaka U), Mathematics
Kimihiro Okumura(U Tokyo, ICRR), Neutrino Physics
Teppei Okumura(Academia Sinica), Cosmology
Yoshiyuki Onuki(U Tokyo, ICEPP), High Energy Physics
Domenico Orlando(INFN), String Theory
Masaki Oshikawa(U Tokyo, ISSP), Theoretical Physics
Masami Ouchi(U Tokyo, ICRR), Astronomy
Serguey Todorov Petcov(SISSA), Particle Theory
Shi Pi(Chinese Academy of Sciences), Astrophysics
Jason Xavier Prochaska(UC Santa Cruz), Astronomy
Anna Puskas(U Queensland), Mathematics
Robert Michael Quimby(San Diego State U), Astronomy
Susanne Reffert(U Bern), String Theory
Jason Rhodes(NASA JPL/Caltech), Cosmology
Joshua Thomas Ruderman(New York U), Particle Theory
Wiphu Rujopakarn(Chulalongkorn U), Astronomy
Kyoji Saito(Kyoto U), Mathematics
Ryo Saito(Yamaguchi U), Astrophysics
Shun Saito(Missouri U of Science and Technology), Cosmology
Yoshihisa Saito(Rikkyo U), Mathematics (from 2021/10/1)
Francesco Sala(U Pisa), Mathematics
Katsuhiko Sato(JSPS), Astroparticle Physics
Vadim Schechtman(U Toulouse III-Paul Sabatier), Mathematics
Christian Schnell(SUNY, Stony Brook), Mathematics
Kate Scholberg(Duke U), Neutrino Physics
Hiroyuki Sekiya(U Tokyo, ICRR), Neutrino Physics
Masato Shiozawa(U Tokyo, ICRR), High Energy Physics
Gary Shiu(U Wisconsin, Madison), String Theory
Aurora Simionescu(SRON Netherlands Institute for Space Research), Astrophysics
Michael Smy(UC Irvine), Neutrino Physics
Yevgeny Stadnik(U Sydney), Theoretical Physics (from 2022/1/1)
Samantha Lynn Stever(Okayama U), Astrophysics
James L. Stone(Boston U), High Energy Physics
Shigeki Sugimoto(Kyoto U), Theoretical Physics
Nao Suzuki(LBL, Berkeley (LBNL)), Astrophysics (from 2021/9/16)
Atsushi Takahashi(Osaka U), Mathematics
Fuminobu Takahashi(Tohoku U), Particle Theory
Tadashi Takayanagi(Kyoto U), String Theory
Atsushi Takeda(U Tokyo, ICRR), Astroparticle Physics
Yasuhiro Takemoto(U Tokyo, ICRR), Experimental Physics
Yasuo Takeuchi(Kobe U), Astroparticle Physics
Hidekazu Tanaka(U Tokyo, ICRR), Neutrino Physics
Masaomi Tanaka(Tohoku U), Astronomy
Atsushi Taruya(Kyoto U), Astrophysics
Nozomu Tominaga(NAOJ), Astrophysics
Werner Tornow(Duke U), Neutrino Physics
Akihiro Tsuchiya(Nagoya U), Mathematics
Sachiko Tsuruta(Montana State U), Astrophysics
Edwin L Turner(Princeton U), Astrophysics
Kazushi Ueda(U Tokyo, Math Sci), Mathematics
Hokuto Uehara(Tokyo Metropolitan U), Mathematics
Alexander Voronov(U Minnesota), Mathematics
Christopher W. Walter(Duke U), Neutrino Physics
Shin Watanabe(JAXA), Experimental Physics
Bryan Webber(U Cambridge), Particle Theory
Roger Alexandre Wendell(Kyoto U), Neutrino Physics
Marcus Christian Werner(Duke Kunshan U), Mathematical Physics
Benda Xu(Tsinghua U, Beijing), Experimental Physics
Tsutomu Yanagida(Shanghai Jiao Tong U), Particle Theory
Jun'ichi Yokoyama(U Tokyo, School of Science), Cosmology
Masashi Yokoyama(U Tokyo), High Energy Physics
Shuichiro Yokoyama(Nagoya U), Cosmology
Ying-li Zhang(Tongji U), Cosmology

Graduate Students

Yuto Arai, Mathematics
Weiguang Cao, Theoretical Physics
Laurence Cook(U Oxford), Neutrino Physics (till 2021/5/8)
Henrique De Campos Affonso, Mathematics
Sho Egusa, String Theory
Yuichi Enoki, Particle Theory
Linghu Fan, Mathematics
Saki Fujita, Experimental Physics (from 2021/10/1)
Kyosuke Higashida, Mathematics
Shunichi Horigome, Theoretical Physics (till 2021/5/31)
Yuxin Huang, Astronomy
Tomohiro Karube, Mathematics
Tenyo Kawamura, Experimental Physics
Tasuki Kinjo, Mathematics
Asahi Kojima, Particle Theory

Dan Kondo, Particle Theory
Toshiki Kurita, Theoretical Physics
Yasunori Lee, Particle Theory
Xiangchong Li(Carnegie Mellon U), Cosmology (till 2021/9/30)
Peijang Liu, Mathematics
Ryusei Maeda, Theoretical Physics
Tianle Mao, Mathematics
Takuro Matsumoto, Mathematics
Takahiro Minami, Experimental Physics
Kai Murai, Particle Theory
Colm Murphy, High Energy Physics (till 2021/9/30)
Shunsaku Nagasawa, Experimental Physics
Kanade Nishikawa, Particle Theory
Masaki Okada, Theoretical Physics
Fumiaki Otani, Experimental Physics
Tian Qiu, Cosmology
Yotaro Sato, Theoretical Physics
Yusuke Sato, Mathematics
Yuta Sato, Particle Theory
Tomoyuki Shimasaki, Experimental Physics
Ryota Shimoda, Theoretical Physics
Yusuke Suetake, String Theory
Sunao Sugiyama, Theoretical Physics
Shenli Tang, Astronomy
Takanori Taniguchi, Cosmology
Ryo Terasawa, Cosmology
Akira Tokiwa, Cosmology
Yutaka Tsuzuki, Experimental Physics
Yu Watanabe, Particle Theory
Yuki Watanabe, Cosmology
Xia Xiaokun, Mathematics
Goro Yabu, Experimental Physics
Chenghan Zha, Mathematics

Berkley satellite Members

Lawrence J Hall(UC Berkeley), Particle Theory
Yasunori Nomura(UC Berkeley), Particle Theory

Administration

Tomiyoshi Haruyama, Administrative Director, Project Professor
Junichi Kanzaki, Assistant Administrative Director, Project Lecturer
Isao Uehara, General Manager
Masayuki Tomita, Deputy General Manager

Accounting

Shigeru Kobayashi* (till 2021/6/30)
Masataka Tanaka* (from 2021/7/1)
Naoko Ishida
Hiromi Yoshida
Yukiko Yoshikawa

Budget Control

Daisuke Hamada*
Madoka Okamoto
Tomoko Shiga
Kaori Watanabe

Contract & General Purchasing

Kenji Irie* (till 2021/6/30)
Noboru Abe* (from 2021/7/1)
Yuri Kazama
Takako Okawa
Sachiko Shimada
Tomoko Yamanaka

General Management

Manabu Hirano*
Yuuko Enomoto
Mika Miura
Ayako Nakada
Mana Shindo
Rieko Tamura

International Relations and Researchers Support

Yuko Fukuda*
Rie Kohama
Masami Nishikawa
Hinaka Ochiai
Eri Shinoda

Network & Web Service

Satoko Inoshita
Masahiro Kawada

Planning & Assessment

Shoko Ichikawa

Public Relations

Motoko Kakubayashi
Marina Komori
Aya Tsuboi

Kamioka Branch

Fumitoshi Sakai*
Masako Ishikura
Yoshimi Kakioka
Hitoshi Nakagawa

(*section head)

5 RESEARCH HIGHLIGHTS

5.1 Impact of the COVID-19 Pandemic on Astronomy in the First Two Years

Jia Liu

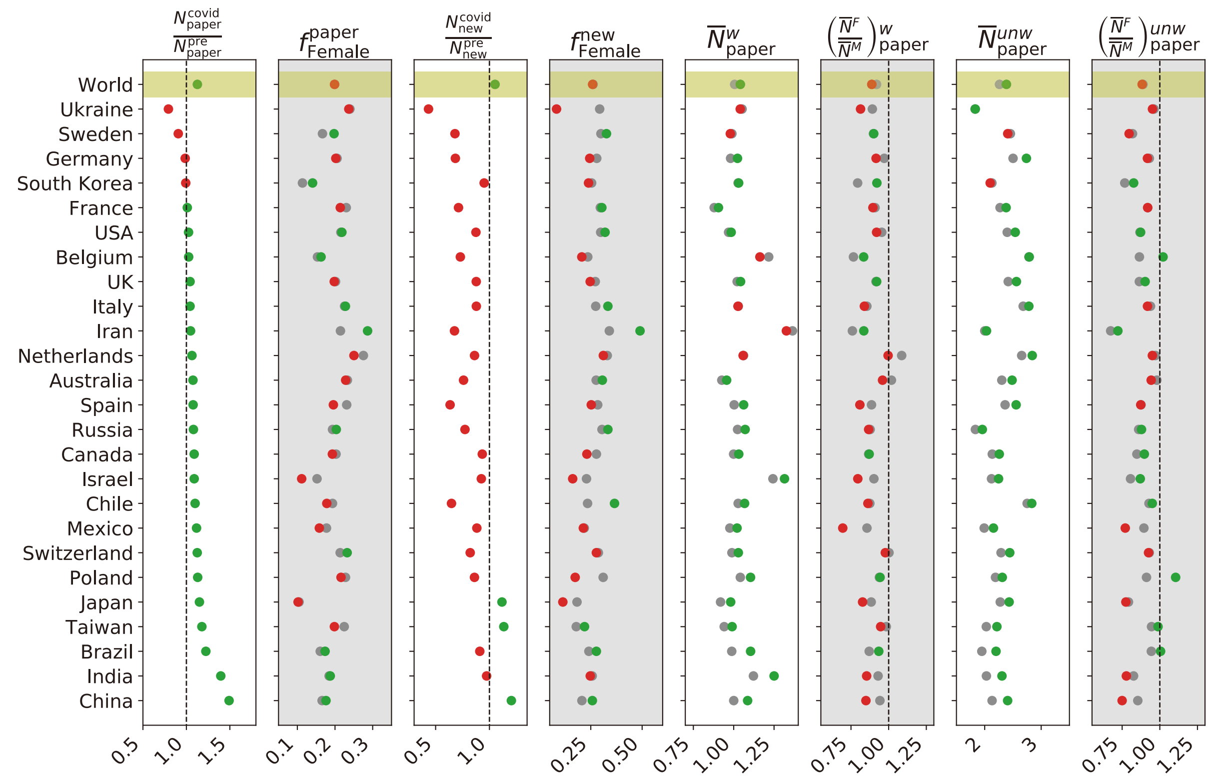
I arrived at Kavli IPMU during the COVID-19 pandemic. As a new mother and an early career scientist, my life has been heavily affected by the pandemic — lost childcare, dropped productivity, disconnection from my colleagues, and a tough job market. Thanks to the strong support I received from IPMU, I was able to settle in a new country smoothly. While rebuilding my research and life routines, I couldn't stop wondering: how are others in my field affected by the pandemic? Am I alone?

My colleague and friend Vanessa Böhm, who was a postdoc at UC Berkeley at the same time as me, had the same question. We did some literature search, but weren't satisfied with the limited studies we found, so we decided to answer this question by ourselves. We started meeting on Tuesday mornings (Monday afternoons for Vanessa). As computational cosmologists, we used the tools that we are trained well with — data mining. We downloaded all the astronomical publications since 1950, more than 1.2 million records from the SAO/NASA Astrophysics Data System, and analyzed the publication pattern by gender and by country. Of course, gender and citizenship are confidential information that we can't access. Instead, we assigned a gender probability to each author based on their given name and assigned a country based on their affiliation(s) listed in the paper. We searched for new trends during COVID that were not seen historically.

We found a surprising trend that the overall output of the field, measured by the yearly paper count, has increased. While one may assume that COVID has mostly negative impacts on the world, this positive phenomenon may not be hard to understand: COVID-induced changes such as increased flexibility in work arrangement, reduced commutes and business trips, as well as improved virtual technologies, among others, are potentially favorable for conducting scientific research.

However, the increase in overall output in the field could be due to two factors: (1) an increase in new researchers and/or (2) an increase in individual productivity. As we investigated further, we found that (2) is mainly responsible for the trend. When we counted the average number of papers each researcher produced, **we saw boosted individual productivity seen across most countries. Meanwhile, a decreasing number of incoming new researchers is seen in most of the countries we studied**. This result indicates larger barriers for new researchers to enter the field, or for junior researchers to complete their very first project during COVID.

Sadly, **the overall improvement in productivity seen in the field is not equally shared by female astronomers**. A smaller fraction of papers are written by women and fewer women are among incoming new researchers as compared to pre-pandemic trends, in 14 out of 25 countries we studied. Even though female astronomers also became more productive during COVID, the level of improvement is smaller than for men. Pre-COVID, female astronomers in countries such as the Netherlands, Australia, and Switzerland were equally as or even more productive than their male colleagues, demonstrating that female researchers are indeed as productive as men when provided with adequate support. During COVID, on average, no single country's female astronomers were able to be more productive than their male colleagues.



Our results are released in Böhm & Liu 2022 [1] and can be summarized by the figure above, which shows the impact of COVID-19 on astronomy by country measured in 4 statistics (white columns), each paired with a corresponding gender-disparity measurement (the adjacent gray column to the right). Gray points are pre-COVID and red (green) points are during COVID that are worse (better) than pre-COVID. The World statistics are shown in the first row. **(1) Overall output (Cols. 1 & 2)**: Ratio of the number of papers per year during COVID to pre-COVID, and corresponding fraction of female authors. **(2) New researchers (Cols. 3 & 4)**: Ratio of the number of new authors per year during COVID to pre-COVID, and corresponding fraction of new female authors. **(3) Individual productivity (Cols. 5 & 6)**: Weighted average number of papers per active author $N_{paper}^{weighted}$, where none-first author papers are down-weighted, and the corresponding ratio of that between female to male authors. **(4) Individual productivity irrespective of author position (Cols. 7 & 8)**: Unweighted average number of papers per active author $N_{paper}^{unweighted}$, where the author order is ignored, and the corresponding ratio of that between female to male authors.

Finally, we have only data from a limited period of time after the onset of the pandemic, while its impact is expected to be long-term. While we are able to study the quantitative outputs of the field during COVID, the quality of these papers is yet to be seen. It would be valuable to revisit this topic in a few years.

Reference

[1] V. Böhm and J. Liu, "Impact of COVID-19 on Astronomy: Two Years In", arXiv:2203.15621 [astro-ph.IM].

5.2 Towards the Post-COVID CMB Activity in Kavli IPMU

Tomotake Matsumura

My previous contribution to this annual report was in 2018. Since then, COVID has brought a completely different lifestyle to all, and the research activity related to CMB experiments at Kavli IPMU is no exception. Kavli IPMU CMB group members work on ongoing and upcoming CMB experiments, including LiteBIRD, Simons Observatory, POLARBEAR/SimonsArray, and CMB-S4. Unfortunately, during the COVID, we have limited lab access, no traveling, including going to the telescope site at Atacama, Chile, and no participation in any domestic or international in-person conference. These gave us a tremendous impact on research and education. However, we have now started to see the end of it (hopefully), and I will describe the progress related to the CMB experiences in FY2021.

For LiteBIRD, Kavli IPMU is in charge of developing the low-frequency telescope polarization modulator unit (PMU) and the data analysis. After LiteBIRD was selected as the second ISAS/JAXA Strategic Large-class mission in May 2019, we focused on developing the key technological challenges. We constructed the second-generation breadboard model of the PMU system led by the former IPMU postdoc, Y. Sakurai (now an assistant professor at Okayama Univ.). The test campaign is now led by the two postdocs, T. Hasebe and T. D. Hoang. The former IPMU postdoc, T. Ghigna (now a postdoc at QUP/KEK), characterized a superconducting detector with an external magnetic field. These are important milestones for the LiteBIRD development at this phase, and these activities resulted in the publishing of more than eight refereed papers in 2021-2022. One of the by-products of the LiteBIRD PMU development is the work led by the graduate student at the Univ. of Tokyo, R. Takaku; fabricating the laser machined moth-eye anti-reflection sub-wavelength structure on an infrared absorbing filter made of alumina (see Fig. 1). A moth-eye is known to have an array of tiny structures smaller than the wavelength, which functions as an anti-reflection layer to the incident radiation to its eye. We employ this moth-eye structure in our millimeter-wave optical component for CMB and astrophysical observations. We provide this successfully fabricated filter to the MUSTANG2 receiver on the Greenbank telescope as the world's first implementation of the laser-fabricated filter used in astronomical observation [1]. The preparation of the satellite project takes a long time (the currently scheduled LiteBIRD launch is in the late 2020s). However, the successful development of LiteBIRD now directly contributes to the ongoing astronomical observations in parallel.

Another highlight is providing the forebaffle for Simons Observatory (SO) Small Aperture Telescope (SAT). This is one of the telescope structures which will be integrated into SO-SAT in Atacama, Chile, and will prevent stray light to the telescope from the surroundings. The former IPMU postdoc, F. Matsuda (now an assistant professor at ISAS/JAXA), designed it, and we shipped it to Chile after being assembled on the Kashiwa campus. (see Fig. 2). Unfortunately, the time of the shipment coincided with the shortage of containers in international shipping during COVID and the corresponding increase in the shipping cost. Despite the challenges, tremendous administrative staff support in IPMU made it overcome this challenge, and we shipped the forebaffle in time successfully.

By looking into the future, LiteBIRD will continue to move forward with a solid international partnership. SO is expected to start observations in 2023. Last but not least, we now have new faculties, T. Namikawa, J. Liu, and E. Ferreira, who have expertise in theory, simulation, and data analysis. It is an exciting time, and we expect more integrated work among the instrumentation-based efforts, simulation, data analysis, and cosmology in the coming years.

Reference

[1] **R. Takaku et al., "Large diameter millimeter-wave low-pass filter made of alumina with laser ablated anti-reflection coating," Opt. Express 29, 41745-41765 (2021), see also** https://www.ipmu.jp/en/20220127-MUSTANG2

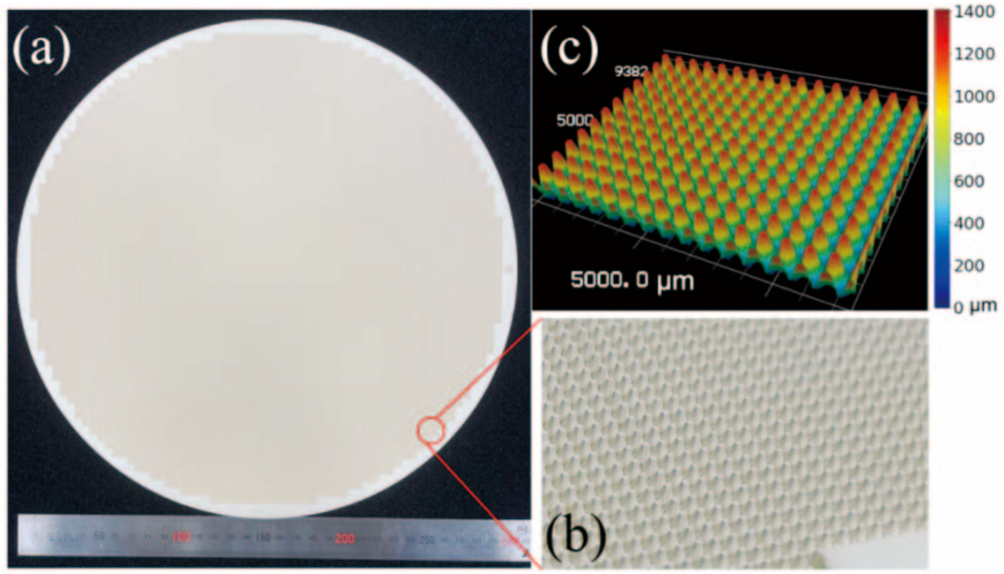


Fig. 1: Images of one side of the fabricated filter. The other side is identical. (a) A photograph of the entire filter. The ruler is graduated up to a length of 300 mm. (b) An enlarged area. (c) Rendering of confocal microscopy scanning of the SWS. (Credit: Takaku et al.)

Fig. 2: The forebaffle for the Simons Observatory Small Aperture Telescope carried by the IPMU CMB group member.

5.3 Confluence in Quantum K-Theory

Todor Eliseev Milanov

Gromov–Witten (GW) theory was introduced by Witten in [4] in order to give a mathematical definition of the correlation functions in a certain two-dimensional Quantum Field Theory (QFT) model. In particular, for every smooth projective variety X, the correlation functions give a set of symplectic invariants of X known as the GW invariants of X. In certain cases, if X is a Calabi–Yau manifold, the GW invariants can be identified with the Taylor series expansion of an appropriate family of period integrals that describe the deformations of complex structures of a certain complex manifold Y. The manifold Y is called the *mirror model* of X and usually there is an interesting duality between the complex geometry of Y and the symplectic geometry of X. Moreover, there is a proposal by Givental that every manifold X has a mirror model in the following sense: Y is non-compact, one has to fix a holomorphic function f on Y, and a holomorphic volume form ω on Y and consider the deformation theory of the triple (Y, f, ω). Respectively, the period integrals should be replaced with oscillatory integrals. Shortly after Witten, Givental proposed a K-theoretic version of GW theory. It is expected that by using Kawasaki's orbifold generalization of the Hirzebruch–Riemann–Roch formula, one can express the K-theoretic invariants in terms of the cohomological ones. However, the relation is very complicated and so far it is known only in genus 0 (see [2]). It is a very interesting problem to find the characterization of the K-theoretic GW invariants of X in terms of the mirror model (Y, f, ω) of X. The main motivation for our work with Alexis Roquefeuil [3] came from our attempt to understand the role of the K-theoretic J-function in mirror symmetry. More precisely, the J-functions in both K-theoretic and cohomological GW theory of a toric manifold can be identified with certain oscillatory integrals. The K-theoretic oscillatory integral is a q-oscillatory integral in the sense of Jackson and it has a limit as $q \longrightarrow 1$ which is the oscillatory integral corresponding to the cohomological J-function. One of the main motivations for our work is to test whether the K-theoretic J-function has a limit as $q \longrightarrow 1$. Our result is an indication that the mirror model (Y, f, ω), whenever it exists, should have a q-deformation.

Let X be a smooth projective variety. The Gromov–Witten (GW) invariants of X are by definition certain intersection numbers on the moduli spaces $M_{g,n}(X, d)$ of stable maps $f : C \longrightarrow X$, where C is a nodal Riemann surface of fixed arithmetic genus g, equipped with a fixed number n of marked points $z_1, \ldots, z_n$, and the map f is required to have a fixed degree $d = f_*[C] \in H_2(X)$. More precisely, we have evaluation maps $ev_i : M_{g,n}(X, d) \longrightarrow X$ defined by evaluating f at the marked points z_i and tautological line bundles formed by the cotangent lines $T^*_{zi}C$. Pulling back cohomology classes from X and taking characteristic classes of the tautological line bundles yields a huge supply of cohomology classes on $M_{g,n}(X, d)$. Integrating such cohomology classes against the virtual fundamental cycle of the moduli space yields a set of numbers known as the GW invariants of X. Using GW invariants, Givental introduced the so-called *small J-function* of X. It is a formal power series $J(Q_1, \ldots, Q_r)$ in certain variables $Q_1, \ldots, Q_r$, known as the *Novikov variables*. The number r here is the so-called Picard number of X which can be characterized as follows: there exists a set of r curve classes in $H_2(X)$, such that, every other curve class d decomposes uniquely as a linear combination with coefficients non-negative integers $(d_1, \ldots, d_r)$. The coefficient in front of $Q_1^{d1} \cdots Q_r^{dr}$ in the small J-function is a vector in $H^*(X)$ whose components are GW invariants defined via the moduli space $M_{0,1}(X, d)$. It is expected that in fact the small J-function is a convergent power series, that is, it is an analytic function in $Q_1, \ldots, Q_r$. The small J-function is a solution to a certain system of Ordinary Differential Equations (ODEs) known as the *small quantum differential equations* of X. In many examples, the small quantum differential equations can be solved in terms of period integrals associated to a family of analytic hypersurfaces. If this happens, then the parameters $Q_1, \ldots, Q_r$ can be interpreted as coordinates on a certain moduli space of complex structures and we usually say that the family of hypersurfaces is a *mirror model* of X.

The K-theoretic version of GW theory was proposed by Givental in [1]. Pulling back K-theoretic vector bundles from $K^0(X)$ and taking the K-theoretic classes of the tautological line bundles L_i yields a huge supply of K-theoretic vector bundles on $M_{g,n}(X, d)$. The K-theoretic GW invariants of X are defined as the Euler characteristic (K-theoretic pushforward to a point) of K-theoretic vector bundles on $M_{g,n}(X, d)$. Similarly, we can introduce the K-theoretic small J-function $J(q,Q)$ as a generating function of K-theoretic GW invariants defined by the moduli spaces $M_{0,1}(X, d)$. However, in addition to the variables $Q_1, \ldots, Q_r$ we have to introduce also an extra variable q for the following reason. In the cohomological case, the invariants are defined by integrating $ev_1^*(\phi)\,\psi^k$ where ψ is the 1st Chern class of L_1. The power k is uniquely determined from the degree d because the degree of the cohomology class must be equal to the dimension of the virtual fundmental cycle. In the K-theoretic case however, we have to compute the Euler characteristic of $ev_1^*(\Phi)L_1^k$ and since there is no dimension constraints, the number k could be chosen arbitrary. The variable q is introduced in order to keep track of the powers of L_1. It can be proved (see [2]) that the K-theoretic small J-function $J(q,Q)$ is a solution to a system of q-difference equations. It is a very interesting open question to find an interpretation of $J(q,Q)$ in terms of mirror symmetry. In a joint work with Alexis Roquefeuil [3], under the assumption that $c_1(X) \geq 0$, we proved that if we rescale the variables Q_i and the components of $J(q,Q)$ by appropriate powers of $q - 1$, then the resulting function has a limit $q \longrightarrow 1$ which coincides with the cohomological small J-function of X. Having in mind the interpretation of the cohomological small J-function in terms of period integrals, it is very tempting to conjecture that there is a general method for constructing q-deformations of the period integrals in the theory of deformations of complex structures.

References

[1] A. Givental, On the WDVV equation in quantum *K*-theory. Michigan Math. J. 48(2000), 295–304

[2] A. Givental and V. Tonita, The Hirzebruch-Riemann-Roch theorem in true genus-0 quantum K-theory, In: Symplectic, Poisson, and noncommutative geometry, Math. Sci. Res. Inst. Publ., vol. 62, Cambridge Univ. Press, New York (2014), 43–91

[3] T. Milanov and A. Roquefeuil, Confluence in quantum K-theory of weak Fano manifolds and q-oscillatory integrals for toric manifolds, arXiv:2108.08620

[4] E. Witten, Two-dimensional gravity and intersection theory on moduli space, Surveys in Diff. Geom. 1 (1991), 243–310

5.4 Solving Chiral Gauge Theories

Hitoshi Murayama

For a long time, physicists believed that there is no difference between left and right. If you drop a ball in front of a mirror, what happens in the mirror looks completely normal. Yes, it is true that most of us are right-handed, and our heart is on the left-side of the body. But we can easily imagine that on some other planets, intelligent life forms are left-handed with their heart on the right side of their body. There is no essential difference between left and right. In fact, the laws of gravity, electromagnetism, and the strong nuclear force are all completely indifferent between left and right.

When it was discovered that another force in nature called the weak force fundamentally distinguishes left from right, it came as a huge shock to physicists. The famous experiment conducted by Chien-Shiung Wu, whom we at Kavli IPMU named our recent fellowship for distinguished female scientists after, studied the beta decay of ^{60}Co nuclei. When she fixed the direction of the spin of ^{60}Co by a clever technique and observed which way an electron comes out, it preferred the same direction as the spin. But in the mirror, it would prefer the opposite direction. The world in the mirror is not the same as ours! Later, we learned something even more dramatic. Elusive elementary particles called neutrinos come in only one variety. All of them are left-handed, namely they spin counterclockwise. Right-handed neutrinos have never been observed.*

The Standard Model of particle physics, established experimentally in 2012 by the long-anticipated discovery of the Higgs boson, is built on the principle that left and right are fundamentally different. Such a theory is called "*chiral*", the term that originates in the ancient Greek word for hand χείρ (kheir). Because the Standard Model is based on another principle called gauge theory, it belongs to a general class called "*chiral gauge theory*." The problem is that we never figured out what exactly it does.

Quantum Field Theory, which unifies two pillars of modern physics, special relativity and quantum mechanics, is notoriously difficult to study. Practical calculations produce infinities that do not make sense. Fortunately for many cases, we can define theories on discretized space and time called lattice so that we can avoid the infinities. The theory is then completely well-defined and can be put on a supercomputer to work out its consequences. This approach has been especially successful for the strong nuclear force. But so far this approach has not been possible for chiral gauge theories such as the weak force for many technical reasons.

For most purposes, the weak force is weak enough that we can resort to a technique called perturbation theory. However, in some cases, we would like to know what happens if the weak force were stronger. Also, in many attempts to unify the observed forces into a single force called "grand unified theories," we need to understand what chiral gauge theories do. I've proposed to study this question using supersymmetry as a guide. Nathaniel Seiberg and his collaborators showed how we can work out exact solutions to supersymmetric gauge theories. Yet the results did not appear to be anywhere close to how the real world works. My proposal is to introduce a small breaking of supersymmetry that still allows for exact solutions that do not rely on the weakness of the force. I could obtain many such solutions, and they appear to connect smoothly to what we would expect in the real world without supersymmetry [1].

In addition, I could also explain why the nuclei bind to enable the periodic table of elements. The protons and neutrons bind to form nuclei because there is a bound state called pion that is much lighter than proton and neutron, as originally proposed by Yukawa. It is light because of the spontaneous breakdown of chiral symmetry as pointed out by Nambu. My method showed explicitly that this occurs because of a condensate of meson bound states on a piece of paper, which used to be possible only with supercomputers.

The next step was to study chiral gauge theories. This proved much more difficult technically, but with the help of collaborators, Csaba Csàki and Ofri Telem, we could solve some of the simplest chiral gauge theories [2]. The result turned out to be completely different from what people had conjectured back in 80s. It was suggested that chiral gauge theories lead to an abundance of massless composite fermions, but we found they seem to minimize such composite states as much as they can.

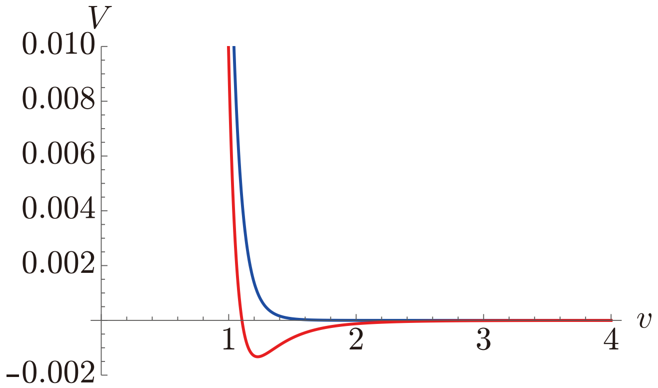


Figure: The potential for the SO(10) theory with 3 matter fields in the 16 representation. When supersymmetry is exact, the potential does not have a minimum and the theory runs away (blue). With a small supersymmetry breaking, it settles to the minimum where the SU(3) global symmetry is broken to its SO(3) subgroup (red). Taken from [4].

Technically, we studied SU(N_c) gauge theories with the matter content in the anti-symmetric tensor and N_c–4 anti-fundamental representations. When N_c is even, the SU(N_c–4) global symmetry is broken to its Sp(N_c–4) subgroup and there is no massless composite fermion. When N_c is odd, the SU(N_c–4) global symmetry is broken to its Sp(N_c–5)×U(1) subgroup and there are N_c–5 massless composite fermions. In both cases, past conjectures suggested that there should be O(N_c^2) of them. Since our results are very concrete, it should be possible to see which conjecture is correct once chiral gauge theories are simulated on supercomputers in the future. We found similar results in theories with a symmetric tensor [3].

Of course, the exact solutions we could obtain are possible only when the size of supersymmetry breaking is small. To reach the real-world situations, the size of supersymmetry breaking needs to be made large. If there is a phase transition between the two limits, we do not gain any new insights by studying the solutions I proposed. There is no proof that two limits are smoothly connected. I am working with my collaborators further to understand this question better.

More recently, I studied arguably the simplest chiral gauge theories based on the SO(10) gauge group with N_f matter fields in the 16-dimensional spinor representation. According to Prof. Yoshio Kikukawa of the University of Tokyo, these theories are likely the first ones to be simulated on supercomputers. Together with a student at Kavli IPMU, Dan Kondo, and an undergraduate student in Berkeley, Cameron Sylber, we came up with clear predictions about what happens to global symmetries [4]. When N_f=1, there is no global symmetry. When N_f=2, the SU(2) global symmetry remains unbroken. When N_f=3, the SU(3) global symmetry breaks to SO(3). In all cases, there are no massless composite fermions.

I do not know whether nature makes use of these fascinating theories. I can only hope she does, perhaps in the dark sector of the Universe ;-)

References

[1] Hitoshi Murayama, "Some Exact Results in QCD-like Theories," *Phys. Rev. Lett.* **126** (2021) 251601.
[2] Csaba Csàki, Hitoshi Murayama, and Ofri Telem, "Some exact results in chiral gauge theories," *Phys. Rev.* **D 104** (2021) 065018.
[3] Csaba Csàki, Hitoshi Murayama, and Ofri Telem, "More exact results on chiral gauge theories: The case of the symmetric tensor," *Phys. Rev.* **D 105** (2022) 045007.
[4] Dan Kondo, Hitoshi Murayama, and Cameron Sylber, "Dynamics of Simplest Chiral Gauge Theories," arXiv:2209.09287.

---

*The plot thickened after our former PI Takaaki Kajita discovered that neutrinos actually have mass. Because massive particle can stop, there cannot be distinction between left and right, raising an important paradox. We do not know yet how these two facts can be reconciled.

5.5 Commissioning of Prime Focus Spectrograph (PFS) on the Subaru Telescope: The Last Spurt of Its Development Has Started

Naoyuki Tamura

We at Kavli IPMU are working on the development of a major astronomical instrument for more than a decade now. It is called PFS (Prime Focus Spectrograph), a next generation facility instrument on the Subaru telescope. The biggest news in FY2021 was clearly the start of engineering observation. Namely, we started receiving photons from the sky on the spectrograph detectors all the way through the Subaru telescope and the PFS hardware!

PFS is a very wide-field, massively multiplexed, and optical & near-infrared spectrograph, and Kavli IPMU is the leading institute in both aspects of the instrument development and the planning of a 360-night observation campaign on the Subaru telescope for cosmology, galaxy & AGN evolution, and Galactic archaeology sciences. Exploiting the Subaru's prime focus, 2394 reconfigurable fibers will be distributed in the 1.3 degree-diameter field of view. The spectrograph system has been designed with 3 arms of blue, red, and near-infrared cameras to simultaneously deliver spectra from 380nm to 1260nm in one exposure. From the Subaru's prime focus, the Hyper Suprime Cam (HSC) has been continuously delivering superb imaging data over a large area of the sky. Conducting spectroscopic follow-up using PFS is crucial to complete a large census of the universe. This is unique not only because it exploits the unique capabilities of the Subaru Telescope such as the light-gathering power of the 8.2m primary mirror and the wide field of view on the prime focus, but also because HSC and PFS enable deep imaging and spectroscopic surveys on the same patches of the sky using the same 8.2m telescope, so one can well understand various systematics in the data which is essential for robust understandings of statistical properties of the universe.

The instrumentation has been carried out by the international collaboration managed by the PFS Project Office hosted by Kavli IPMU, with work packages for subsystem and subcomponent developments assigned to various institutes in the collaboration. During the last few years, we delivered several subsystems from the PFS institutes to the Subaru telescope observatory on the summit of Maunakea, and successfully commissioned them (see Table 1). The recent highlight is obviously Prime Focus Instrument (PFI). It is a very complex subsystem with 2394 reconfigurable fiber positioners "Cobras" which are the key components to deliver fluxes from stars and galaxies to the PFS instrument. Having had Metrology Camera System (MCS), the first spectrograph module (SM1) with visible cameras, and the first on-telescope fiber cable (Cable B1) ready earlier, PFI was being the missing piece for several months to start testing the PFS instrument system on the telescope and start an engineering observation. So its delivery and commissioning was a very important milestone for the project. In fact, to make the best use of the time before the PFI arrival, we devised an additional instrument that enables to take night-sky spectra on SM1 without PFI. It is Subaru Night-Sky Spectrograph (SuNSS) that is a small telescope system with a short fiber cable to deliver photons from the sky to PFS Cable B and then PFS Spectrograph System. It was assembled at LNA in Brazil and then in Princeton University in USA before the delivery to the Subaru summit. We installed SuNSS on the Subaru telescope in February 2021 and started SuNSS+PFS observations right away. Until March 2022, ~500 hours of data were taken and these have been very useful to develop the data reduction pipeline and characterize the stability of Cable B1 and SM1.

Subsystem	Delivered to Hawaii	Fully commissioned at Subaru summit	Origin of the shipment to Hawaii
MCS	April 2018	October 2019	ASIAA (Taiwan)
SM1	October 2019	November 2020	LAM (France)
Cable B1	December 2020	February 2021	LNA (Brazil)
SuNSS	January 2021	February 2021	Princeton Univ. (USA)
PFI	June 2021	September 2021	ASIAA (Taiwan)
Cable B2	October 2021	April 2022	LNA (Brazil)

Table 1: The actual timeline of PFS subsystems deliveries and commissioning. Most of the subsystems were developed by a collaboration of multiple other institutes as well as the one being the origin of the shipment to Hawaii, and the members of Kavli IPMU were involved essentially everywhere from various perspectives of project management, systems engineering, software developments and system integration & test at Subaru summit.

In FY2021, we obtained two opportunities of on-telescope engineering test. The first period was on September 13-26 2021. On Sep 13, PFI was successfully installed on the telescope prime focus, for the first time simultaneously together with MCS and Cable B1 also on the telescope and SM1 in the dedicated clean room in the telescope enclosure building (Figure 1). The installation of PFI is actually a complex process consisting of two stages: Firstly PFI is put into the Prime Focus Unit so-called POpt2 that accommodates either Hyper Suprime Cam (HSC) or PFI and integrates it with the Wide Field Corrector (WFC) lens system. In case HSC resides in POpt2 before PFI installation, HSC has to be removed first and then PFI is installed in it. This is one-day process. And then on a later day, POpt2 with PFI inside is installed on the telescope. Both processes are carried out by a few Subaru daycrews and a couple of PFS team members so far. For the PFI installation into POpt2, we performed a dry run in July 2021 in collaboration with the daycrews, which was an important step for the successful installation at this September run. In addition, MCS has to be installed to the Cassegrain focus beforehand. Needing a specific equipment at two different foci to operate one instrument is a unique requirement of PFS in the Subaru instrument operation, and scheduling all of these in a timely manner for an observation is not trivial at all. But thanks to various considerations and efforts by the divisions and staffs at the observatory, we successfully installed PFI and MCS on the telescope without any major problems for starting the night operation.

Then during the nighttime from Sep 13 to 26 (which were in the period of telescope downtime), various tests were performed using these subsystems. Most of the time we needed to keep the dome closed, but nevertheless we managed to succeed in completing the major planned test items, for example:

- We confirmed the MCS performance such as image quality and centroiding accuracy using the back-illuminated real fibers in PFI under the presence of dome seeing effect.
- We understood the PFI focal plane geometry and coordinate transformation between PFI and MCS, and managed to converge the Cobras/fibers to target positions in ~10um accuracy on PFI coordinate with the telescope pointed to the zenith.
- We took spectral images with SM1 of the forward illumination from the dedicated calibration lamps on PFI as well as the Subaru facility dome flat lamps.

Then finally, during the night of Sep 26 (i.e. the last night of this two-week PFS engineering campaign), thanks to the observatory's permission and the cooperation of the Maunakea's weather, the sky was observed (with no sidereal tracking though) through PFI, Cable B1 and SM1! (Figure 2(a) & 2(b)).

Meanwhile, during the second period of engineering observation on November 17-21, progresses were limited unfortunately due to some troubles on PFI hardware components and software bugs, but nevertheless we made a few important achievements:

- For the first time, we managed to take images of bright stars on the sky with the Acquisition and Guide (AG) cameras in PFI (i.e. AG camera First Light).
- Still some more tests are needed for confirmations, but we got partial but substantial success in the field acquisition and auto guiding processes.
- We continued to test the performance of Cobras converging to their target positions on the PFI focal plane at different telescope elevation angles and obtained good results (Figure 2(c)).

Since these on-telescope tests of PFS instrument system began, the software development is rapidly progressing. The instrument control software is delivered to the Subaru telescope observatory with its hardware subsystem, continuously developed through the tests to commission the subsystems at Subaru, and then integrated with the system-level layer through the on-telescope engineering. To operate multiple subsystems in coordinated manners, the operation database (opDB) is a key component. The development is being carried out primarily by Kavli IPMU, and various parts of the schema are being continually fleshed out as more subsystems are delivered and tested.

Data processing is another area where Kavli IPMU is playing key roles. PFS data are processed in two stages: 2D Data Reduction Pipeline (2D DRP) developed by Princeton University, Kavli IPMU, NAOJ and California Institute of Technology processes spectrograph detector images and delivers fully calibrated one-dimensional (1D) spectra. Then 1D Data Reduction Pipeline (1D DRP) developed by LAM performs various measurements on the 1D spectra delivered from 2D DRP. In both 2D DRP and 1D DRP, updated versions have been released quite regularly at a reasonably short cadence and become deployable automatically. Also, a release of 2D DRP comes with simulated spectra and products after reduction processes. Hence it is worth giving the outputs from 2D DRP to 1D DRP for verifying the entire data processing. Based on this motivation, the infrastructure for such an end-to-end test was set up at Kavli IPMU and the regular data processing has been in operation since 2020. It has been very useful to discover unexpected problems and issues and steer team's efforts to resolutions and improvements.

The team is continuing efforts to deliver more hardware components to the observatory and to perform engineering observations for system-level tests for the next couple of years aimed at starting the scientific operation of the PFS instrument from sometime within 2024.

As the instrument development is progressing, the collaboration is in parallel trying to develop a timely plan of large-sky survey observation to be proposed and conducted in the framework of Subaru Strategic Program (SSP). Having the three main survey components labelled as cosmology, galaxy & AGN evolution, and Galactic archaeology, the team is aiming at addressing key questions in the modern cosmology and astrophysics by multiple approaches over multiple scales of dark matter density structure, which should lead us to comprehensive challenges to the ΛCDM cosmology. Due to COVID-19, opportunities to organize in-person meetings have still been very limited, but the team has been continuously updating and refining the plan in detail through discussions regularly by remote meetings and e-mails.

As we will take more data from future on-sky engineering observations, we should be able to better understand the real characteristics of the PFS instrument such as its on-sky sensitivity including the accuracy of sky subtraction, the speed of fiber reconfiguration, and various stabilities. Accordingly, the team needs to update and re-optimize the PFS SSP survey plan based on the real performances. But this updating process may not be very straightforward because the commissioning of an instrument is unfortunately often a complex process, and it is very likely even more so for PFS because it is a very complicated instrument. Appropriate data sets need to be carefully selected for evaluations of instrument characteristics, and then need to be processed carefully with the pipelines and other tools most of which are still under developments. Under this circumstance, clearly the interplays between the science team and technical team are crucial, but not only that, coordinated interplays are necessary in order to minimize risks of propagating information that is wrong or too preliminary, and subsequently generating confusion across the collaboration. As part of such coordination efforts, occasionally (but more often than before the COVID-19 pandemic) collaboration-wide online meetings such as general collaboration meeting and science meeting are organized, and various topics are actively discussed among ~100-200 participants (Figure 3). The members at Kavli IPMU have been working very hard not only to complete the PFS instrumentation, but also to steer the entire collaboration into efficient team work during the critical periods for the project in the following fiscal years to achieve ultimate scientific and technical successes of PFS.

Figure 1: (a) [Left] PFI being lifted from the test bench on the floor in the telescope area for the installation into POpt2 later. (b) [Middle left] PFI after the installation on the prime focus of the telescope. (c) [Middle right] MCS installed on the telescope at the Cassegrain focus. (d) [Right] SM1 operating in the dedicated temperature-controlled clean room inside the telescope dome building to receive photons from the sky through PFI and Cable B1.

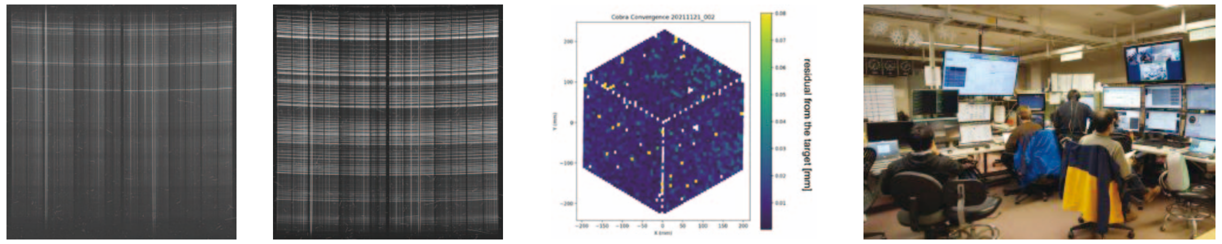


Figure 2: (a) [Left] An image showing ~600 spectra of the sky on the spectrograph detector from a 1000-second exposure during the observation in September 2021. This is from the blue camera that covers the wavelengths of 380—650nm. (b) [Middle left] Same as (a) but this is an image from the red camera for 630—970nm. (c) [Middle right] One of the best results for the convergence of fiber positioners Cobra to target positions during the observation in November 2021. Color-coded are the residual distances in mm to their targets of the fibers moved by the Cobras distributed on the hexagonal PFI focal plane. (d) [Right] One scene of the team at the Subaru summit in the control room during a night of engineering observation. The team in Hilo and some other people at various other places were participating via Zoom in this run to carry out the observation together.

Figure 3: Screenshots of the participants on Zoom in the 13th PFS general collaboration meeting.

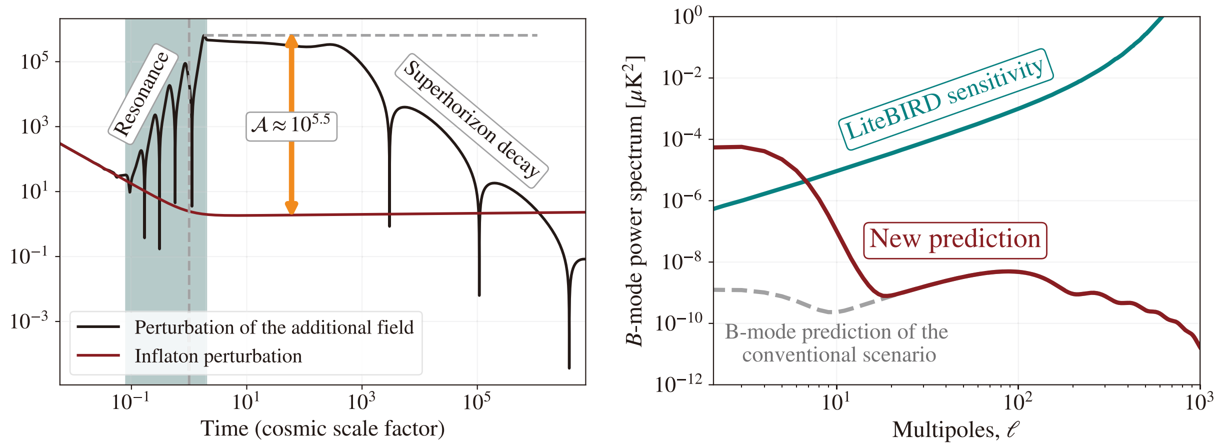
5.6 Identifying the Origin of Primordial Gravitational Waves

Valeri Vardanyan

The existence of gravitational waves (GWs) is one of the pivotal predictions of Einstein's theory of General Relativity. The joint effort of theoretical and experimental researchers led to the groundbreaking direct observation of GWs [1] in 2015 originating from a merger of two black holes in a binary system. This detection by the LIGO Scientific and Virgo collaborations, along with their Japanese counterpart KAGRA, has been revolutionizing the ways we observe the Universe. Besides their important astrophysical implications, they also provide information about the fundamental cosmological scenarios, such as about the potential existence of primordial black holes [2, 3], values of cosmological parameters [4], and can even probe the large-scale distribution of dark matter [5, 6].

GWs do not only originate from the violent mergers of massive astrophysical-scale objects. They can also be produced from quantum vacuum fluctuations of various fields, and the space-time itself. The latter possibility has been long investigated and is one of the major, smoking-gun predictions of the cosmological inflation. Inflationary expansion stretches the quantum fluctuations to astronomical scales, which then could be detected by their specific polarization imprint on cosmic microwave background (B-mode polarization). These primordial GWs generated from vacuum are very weak, and are very difficult to capture directly. However, the Japanese-led LiteBIRD space mission [7] is designed to measure those in the near future. Just as the detection of astrophysical GWs discussed above provide us with a crucial new window to the Universe, the yet-undetected primordial GWs will teach us valuable lessons about the physics in the early Universe. In particular, the detection of these GWs is linked to the energy at which the inflation took place. It is aslo linked to how much the inflaton field, the energy source of inflation, can vary — a celebrated relation commonly referred to as the "Lyth bound". Particularly, inflationary models designed to take place at lower energies are believed to generate negligible amounts of primordial GWs, hence rendering such low-scale scenarios untestable.

I have led a research project [8], which involved Kavli IPMU deputy director Prof. Sasaki and colleagues from USTC (China), where we have challenged this common lore. The idea relies on the fact that while scalar-type perturbations cannot source gravitational waves in a linear theory, they can perfectly do so non-linearly. While more difficult to analyze because of its non-linear nature, this opens up a possibility for generating additional gravitational waves during inflation. The quantum scalar fluctuations during standard inflation should be small in order to agree with the observed amount of clumpiness of large-scale matter distribution in the Universe, and the observed temperature anisotropies of the cosmic microwave background sky. As a result their non-linear contributions to inflationary GWs is also suppressed. An important challenge, therefore, has been to construct a scenario where a copious production of gravitational waves during inflation from enhanced scalar field perdurbations does not require enhanced clumpiness of the structure in the Universe. Such a task has been considered to be very difficult, if not impossible, by the community. An essential ingredianet of our proposal is the presence of a second scalar sector, in addition to the standard inflaton. The scalar perturbation modes of the additional sector are amplified drastically due to resonance effects, which then non-linearly source GWs, without significantly altering the clumpiness of the Universe. The left panel of the figure depicts the time evolution of scalar perturbations of the inflaton field (the dark-red line) which is the source of the large-scale structure we observe in the Universe, and those of the additional scalar field which is resonantly amplified by more than 5 orders of magnitude during inflation, before the scale of the perturbation becomes larger than the inflationary horizon. The right-hand panel shows the imprint of the produced gravitational waves on the B-mode polarization of the cosmic microwave background anisotropies. The dashed gray line, which is the prediction of a conventional inflationary scenario operating at a very low energy scale, remains way below the detectable limit (teal-colored solid line). The prediction of our proposal (dark-red solid line), on the other hand, can clearly be detectable, even though inflation still operates at low energies.



The importance of this study is that we now have a concrete mechanism where the Lyth bound is invalidated – a low-energy-scale inflation can produce detectable amounts of gravitational waves, without altering the other desirable properties of cosmic inflation. Our results highlight once more the importance of primordial gravitational wave searches through B-mode polarization of cosmic microwave background (see e.g. [9] for a review). Our findings were published in Physical Review Letters in 2021, and were featured as an IPMU press release.

References
[1] LIGO Scientific and Virgo Collaborations, Phys. Rev. Lett., 116 (2016) 6, 061102
[2] Sasaki, Suyama, Tanaka, Yokoyama, Phys. Rev. Lett., 117 (2016) 6, 061101
[3] Bird et. al., Phys. Rev. Lett. 116 (2016) 20, 201301
[4] LIGO Scientific and Virgo Collaborations, Nature 551 (2017) 7678, 85-88
[5] Canas-Herrera, Contigiani, **Vardanyan**, 2021, Astrophys. J. 918 (2021) 1, 20
[6] Canas-Herrera, Contigiani, **Vardanyan**, Phys. Rev. D 102 (2020) 4, 043513
[7] https://www.isas.jaxa.jp/en/missions/spacecraft/future/litebird.html
[8] Cai, Jiang, Sasaki, **Vardanyan**, Zhou, Phys. Rev. Lett. 127 (2021) 25, 251301
[9] Komatsu, Nature Rev. Phys. 4 (2022) 7, 452-469

5.7 Could Bizarre Lumps of Q-balls Leave Behind a Hint About How Matter Was Formed?

Graham Albert White

One of the key motivations for believing our understanding of physics is incomplete, is that we have no way of explaining why the Universe is full of matter rather than being a featureless soup of radiation. Everything we know predicts matter and anti-matter will be produced at equal rates in the early Universe, yet at some stage for the production of every ten billion anti-particles, ten billion and one particles were produced. To explain this we need new physics!

An elegant explanation for the origin of matter, is that at the end of inflation many scalar fields were far from the value that minimises the energy. These scalar fields can have non-zero baryon or lepton number and will roll towards the minimum in an elliptical orbit. Therefore, baryon or lepton number conservation is violated right when the universe goes out of equilibrium. If there exists a CP violating operator, the elliptical orbit can be biassed into a clockwise or anti clockwise direction. This fulfils all the conditions needed to explain the asymmetry between baryons and anti-baryons and is known as the Affleck Dine mechanism.

As elegant as the Affleck Dine mechanism is, it is notoriously difficult to test with very limited ideas on how to approach testability in the last three decades. We propose that if we consider various general features of Affleck Dine baryogenesis, it is very likely that Affleck Dine leaves a signature in the gravitational wave background that can be seen today.

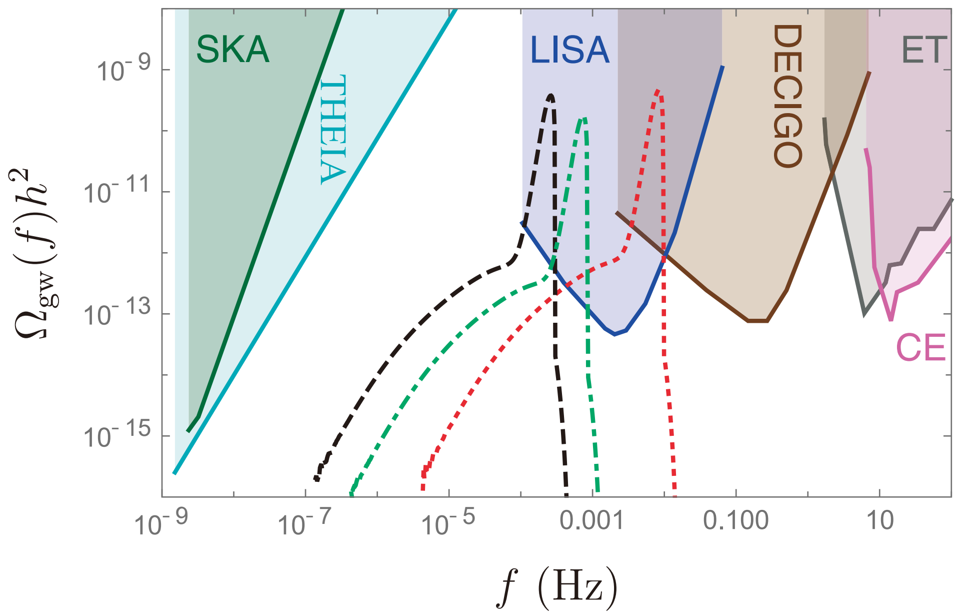
The mechanism is somewhat indirect. We first observe that the scalar fields that violate baryon or lepton number must be flat enough to avoid dominating the energy budget of the Universe during inflation. If a potential is flat enough, there can exist a possibility that the energy of a bunch of quanta with non-zero baryon or lepton number can be lower in extended field configurations known as Q-balls than they would be in the same quanta of free particles. The most well motivated models in Supersymmetric theories indeed have baryon or lepton violating flat directions that allow a Q-ball solution.

Second, we note that any decay channel must be inefficient, or loop corrections would spoil the flatness of the potential. This means that the system prefers to fragment into Q balls rather than decaying into particles. Once these Q-balls form, there is a minimal amount they can contribute to the energy budget of the Universe in order to explain the asymmetry between baryons and anti-baryons. Simulations, however, suggest that the system usually fragments into a large amount of both Q balls and anti Q-balls, such that the total energy in Q-balls is typically much more than the bare minimum. In fact, it can often be within a few orders of magnitude of the total energy in the Universe after reheating.

Once these Q-balls form, they generally decay to fermions. This decay rate is already reasonably slow to preserve the flatness of the potential. However, the decay rate is further slowed down by the fact that the decay can only happen at the surface of the Q-ball. The reason for this is that the large ratio between the energy of a Q ball quanta and vacuum expectation value usually forbids the decay kinematically. However, even if that is not the case, the fermions can quickly fill up the Fermi sea, meaning further decay within the Q ball becomes Pauli blocked.

These Q-balls dilute as slowly as matter does in the expanding Universe, which is slower than how the rest of the radiation dominated Universe dilutes. The inefficient decay process therefore means that, usually, Affleck Dine predicts that these Q balls will dominate the energy budget of the Universe for a period of time. When they do decay, however, the decay accelerates and happens very quickly, as the surface to volume ratio that suppresses the decay rate is rapidly increasing. The collapse of these Q-balls is so fast that the scalar perturbations that were growing during matter domination cannot melt away when the transition to radiation domination occurs. Instead, they form sound waves. These sound waves can constructively interfere with any existing gravitational wave background, including the very small one predicted from inflation. At a particular frequency, there will be a resonant enhancement of this background which is often visible at the next generation of experiments. This mechanism of secondary production is known as the Poltergeist mechanism.

Note that not every scenario that predicts a transition from matter to radiation domination can mimic the signal. The transition has to be faster than the exponential collapse predicted in the standard scenario where a heavy particle decays after a period of dominated the energy of the Universe. So not only is it generally true that Affleck Dine baryogenesis generally leaves a detectable trace in the gravitational wave background, if we do see such a signal, we can narrow it down to a limited number of cosmological scenarios!



Reference

[1] Graham White, Lauren Pearce, Daniel Vagie, Alexander Kusenko, "Detectable Gravitational Wave Signals from Affleck-Dine Baryogenesis", Phys. Rev. Lett. 127 (2021) 18, 18, arXiv:2105.11655 [hep-ph]

5.8 Exporing Theta-Vacua of Yang-Mills Theories

Masahito Yamazaki

While the celebrated Yang-Mills theory is one of the most crucial ingredients in Nature, it is notoriously difficult to solve for the theory in general, even for the textbook-example of the four-dimensional pure SU(N) Yang-Mills theory. Since the theory is intrinsically strongly-coupled at the low energies, one of the most established techniques for extracting quantitative predictions of the theory is to use numerical methods. The basic idea is simple: we discretize the field theory into the lattice (lattice gauge theory), and the infinite-dimensional path integral is replaced by an integral over a large but finite number of variables, which integral is evaluated by Monte-Carlo sampling techniques.

While the lattice gauge theories have been successful over the decades, the situation is rather different when we include the topological θ-term to the theory, which term determines the relative weights of different topological sectors of the gauge fields. In this case, the Euclideanized action contains a pure imaginary term, and the phase of the exponentiated action fluctuates wildly—this leads to significant mutual cancellations in the sampling, making the numerical evalution practically impossible. (This is the notorious sign problem.) It has therefore been a longstanding question to study the dependence of the vacuum free energy f(θ) as a function of the topological parameter θ. We are particularly interested in the special value $\theta = \pi$, where we have classically the CP symmetry; the fate of this CP symmetry is correlated with the question of whether the theory confines or not [1].

In our recent paper published this year [2] in collaboration with researchers from KEK, we have approached this problem by the novel "sub-volume" method (see [3] for a similar method for the two-dimensional $\mathbb{CP}^{N-1}$ model). Instead of turning on θ everywhere on the lattice, we turn on the value of the θ only in a small region (subvolume); this can be regarded as an insertion of an operator inside the subvolume, in which case one expects that the sign problem is ameliorated. Once we measure the free energy for various sizes of the region, we can extrapolate the results to the full volume.

We have applied this technique to the lattice version of the four-dimensional SU(2) pure Yang-Mills theory at temperatures $T = 0$ and $T = 1.2T_c$, where T_c is the critical temperature for the confinement/deconfinement transition. The final results for the free energies f(θ) as a function of θ are shown in Fig. 1. For $T = 1.2c$, the $f(\theta)$ is well described by the 2π-periodic function $\propto 1-\cos\theta$, as one expects from the dilute instanton approximations. For $T = 0$, however, $f(\theta)$ is clearly not a 2π-periodic function of θ, and instead f(θ) keeps growing past $\theta = \pi$. Since the Lagrangian in itself is manifestly 2π-periodic, what this means is that f(θ) is a multi-valued function, and that we have followed one of the branches in our simulations. That we have multiple branches in f(θ) was suggested long ago in the large N limit [4]. Our results shows that $N = 2$ case should be thought of "large N" in this respect, and this furthermore suggests that the theory confines and has a mass gap, as we observed previously in an earlier publication [5].

We can also promote the θ-parameter to a dynamical axion field, and such axions are discussed widely in particle physics and cosmology. I myself have worked on this topic in the context of inflation [6, 7] and dark energy [8], and theoretical considerations of the discussed above have many implications there. It is fascinating to contemplate that the predictions of lattice gauge theories obtained in supercomputers can one day be observed somewhere deep in our Universe.

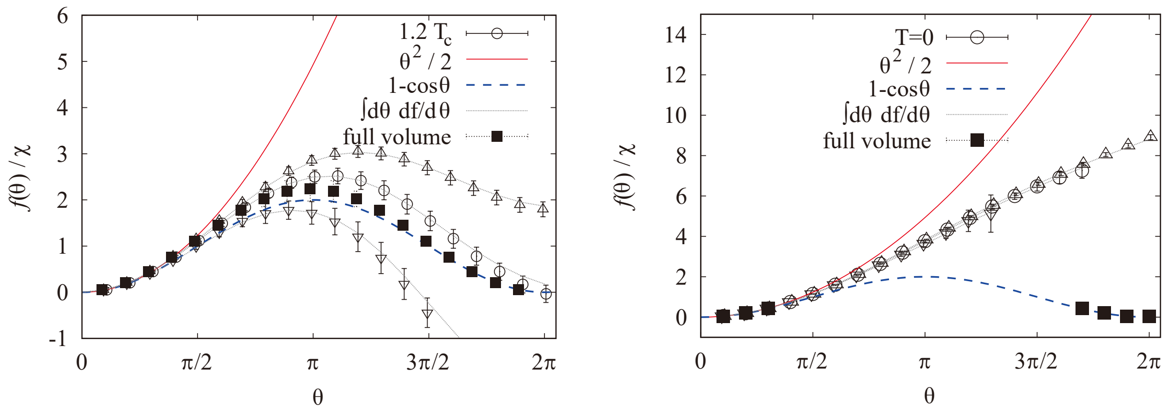


Figure 1: The vacuum free energy as a function of the topological angle θ for $T = 1.2T_c$ (left) and $T = 0$ (right). We obtained these results from lattice gauge theory simulations with lattice size $24^3 \times 8$ (left) and $24^3 \times 48$ (right).
The free energy is normalized by the topological susceptibility χ, which is the theta coefficient of the $\theta^2/2$ term in the Taylor expansion around $\theta = 0$. The uncolored circles and triangles represent results from the sub-volume method, with three different extrapolation methods. For $T = 1.2T_c$ the free energy is consistent with the 2π-periodic cosine function, and this is also reproduced by the full-volume computation. For $T = 0$ the free energy deviates from the cosine function, and is not 2π-periodic. In this case the full-volume computation is plagued by the sign problem and is not applicable for θ away from 0, 2π.

References

[1] D. Gaiotto, A. Kapustin, Z. Komargodski and N. Seiberg, "Theta, Time Reversal, and Temperature," JHEP **05**, 091 (2017) [arXiv:1703.00501 [hepth]].

[2] R. Kitano, R. Matsudo, N. Yamada and M. Yamazaki, "Peeking into the θ vacuum," Phys. Lett. B **822**, 136657 (2021) [arXiv:2102.08784 [hep-lat]].

[3] P. Keith-Hynes and H. B. Thacker, "Fractionally charged Wilson loops as a probe of theta-dependence in CP(N-1) sigma models: Instantons vs. large N," Phys. Rev. D **78**, 025009 (2008) [arXiv:0804.1534 [hep-lat]].

[4] E. Witten, "Large N Chiral Dynamics," Annals Phys. **128**, 363 (1980)

[5] R. Kitano, N. Yamada and M. Yamazaki, "Is $N = 2$ Large?," JHEP **02**, 073 (2021) [arXiv:2010.08810 [hep-lat]].

[6] Y. Nomura, T. Watari and M. Yamazaki, "Pure Natural IInflation," Phys. Lett. B **776**, 227-230 (2018) [arXiv:1706.08522 [hep-ph]].

[7] Y. Nomura and M. Yamazaki, "Tensor Modes in Pure Natural Inflation," Phys. Lett. B **780**, 106-110 (2018) [arXiv:1711.10490 [hep-ph]].

[8] M. Ibe, M. Yamazaki and T. T. Yanagida, "Quintessence Axion Revisited in Light of Swampland Conjectures," Class. Quant. Grav. **36**, no.23, 235020 (2019) [arXiv:1811.04664 [hep-th]].

5.9 AI Ethics Score Research

Hiromi Yokoyama

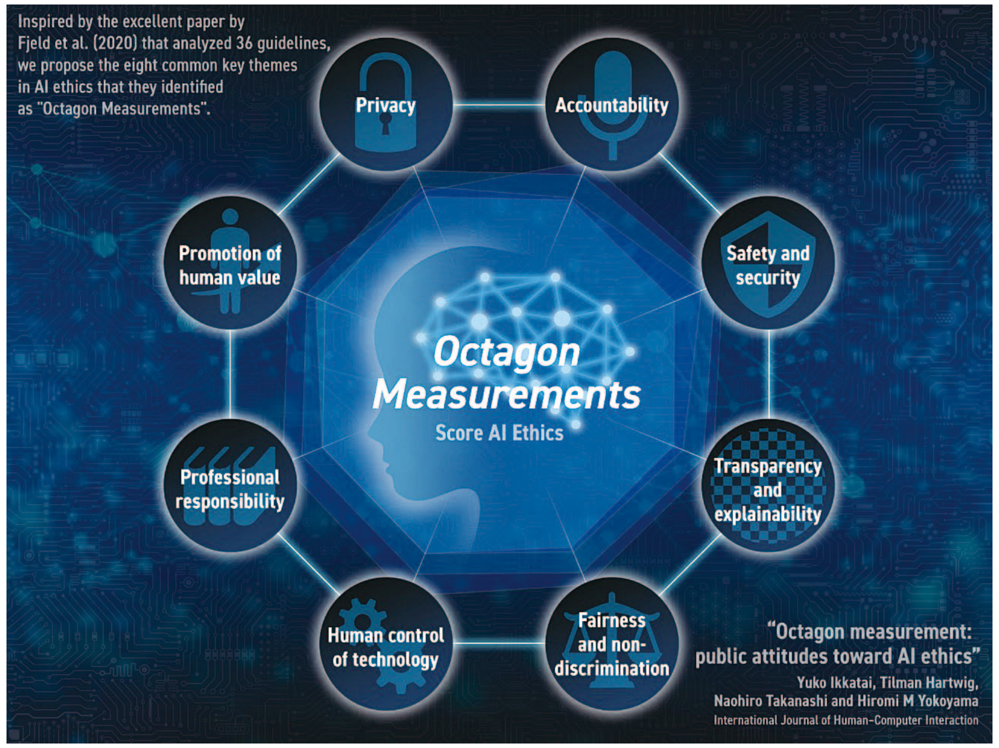
Since 2020, Yokoyama has organized a research group and continues to research AI ethics using AI decision tree analysis. AI has become an essential technology for society, but there are many ethical issues, and there has been no research to visualize the ethical issues of AI in numerical form. The ethical issues of novel science and technology are called ELSI, an acronym for ethical, legal, and social issues. The project was named "Score ELSI" to quantify the level of ethical issues in the AI technologies that are actually in use in society.

Many AI technologies are in use in society, and the project took up four examples that are already being discussed in society. The four examples of AI technology used in the project are Scenario (1) using AI to recreate a deceased singer, Scenario (2) AI-based shopping, Scenario (3) AI weapon, and Scenario (4) AI criminal tracking. We developed a scale that measures the degree of ethical problems with AI using written scenarios of the possible positive and negative aspects of the above four AI applications. These results led to the publication of two papers in FY2021.

Paper [1] Octagon Measurement

To date, there has been no research to quantify the problem of AI ethics. What would be a reasonable measure of ethics? We turned our attention to an analysis of guidelines issued by countries in a worldwide competition; a study analyzing 38 guidelines identified eight common items. These are "privacy," "accountability," "safety and security," "transparency and explainability," "fairness and non-discrimination," "human control of technology," "professional responsibility," and "promotion of human values." The eight items, which are common throughout the world, provide a sufficient basis for quantifying AI ethics.

We therefore used these eight items to measure the ethical level of Scenarios 1 to 4. Specifically, we asked people in Japan to read the four scenarios and check their level of concern about the eight items. The results showed that of the four scenarios, Scenario 3 (AI drone weapons) was the most concerning, and that people of older age were more concerned about the use of AI overall. We proposed this eight-item measure of AI ethics, which we named the "Octagon Measure".



Inspired by the excellent paper by Fjeld et al. (2020) that analyzed 36 guidelines, we propose the eight common key themes in AI ethics that they identified as "Octagon Measurements".

"Octagon measurement: public attitudes toward AI ethics"
Yuko Ikkatai, Tilman Hartwig, Naohiro Takanashi and Hiromi M Yokoyama
International Journal of Human-Computer Interaction

Figure: Octagon measurements for AI ethics.

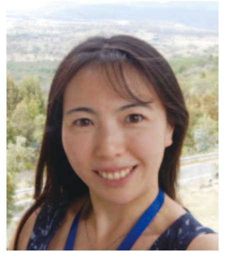
Paper [2] ELSI Score development
We sought a different way to measure AI ethics than the octagonal measure. The octagon measure is suitable for AI ethics, but it is difficult to use for other advanced technologies because it is based on a guideline analysis of AI. Therefore, we devised a more versatile measurement method that could be used for other advanced technologies.

We prepared 12 questions about ELSI and measured them in Japan and the US using four scenarios. Using these data, we performed an AI decision tree analysis and were able to reduce the 12 items to three items—ethics, tradition, and policies—with one item each remaining for ethics, social, and legal issues. We found that, in the future, we can effectively classify the scenarios by asking about these three items when we study them.
In addition, the combined analysis of Japanese and US data showed that the first item to cause divergence was *country*, followed by *age*. Country and age are major branches in judging AI ethics. We were able to show that the ELSI classification is useful for comparing and quantifying AI ethics across countries. We are currently developing this research further.

References
[1] Hartwig, T., Ikkatai, Y., Takanashi, N. & Yokoyama, H.M. (2022). 'Octagon Measurement: Public Attitudes toward AI Ethics,' *International Journal of Human–Computer Interaction*
[2] Hartwig, T., Ikkatai, Y., Takanashi, N. & Yokoyama, H.M. (2022). 'Artificial intelligence ELSI score for science and technology: a comparison between Japan and the US.' *AI & Soc*. https://doi.org/10.1007/s00146-021-01323-9

6

AWARDS & HONORS



Chiaki Kobayashi awarded a Research Fellowship by the Leverhulme Trust

Chiaki Kobayashi, a visiting scientist at the Kavli Institute for the Physics and Mathematics of the Universe, and Associate Professor at the University of Hertfordshire, was awarded a Research Fellowship by the Leverhulme Trust in the United Kingdom.

The Leverhulme Trust was established in the United Kingdom after the death of Lord Leverhulme in 1925. Lord Leverhulme, a committed philanthropist, left a proportion of his company to provide scholarships for research and education. The 2021 Research Fellowship grant supports projects, including Kobayashi's project, in the natural sciences, humanities, and social sciences

Hirosi Ooguri elected Chair of the Board of Trustees of the Aspen Center for Physics

Hirosi Ooguri, Director of Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), was elected the Chair of the Board of Trustees of the Aspen Center for Physics at the general members assembly on July 13, 2021.

The Aspen Center for Physics was established in 1962 to nurture cutting-edge research in physics and related disciplines by providing a unique physical and scientific environment ideally suited for stimulating interactions, collaborations, and innovation. Every year, more than 1,000 physicists from around the world come to the Center, located in Aspen, Colorado, to ponder, argue, and discover the new ideas that underlie advances in science and technology. The Center is an independent non-profit corporation not affiliated with any university and run by scientists and a small number of administrative staff.

Hirosi Ooguri named Benjamin Lee Professor

Hirosi Ooguri, Director of the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), and the Fred Kavli Professor of Theoretical Physics and Mathematics and the Founding Director of the Walter Burke Institute for Theoretical Physics at California Institute of technology, was named Benjamin Lee Professor, it was announced by the Asia Pacific Center for Theoretical Physics (APCTP) in South Korea.

The professorship was created in honor of Korean theoretical physicist Benjamin Lee, who had a distinguished career in particle physics theory, and invites the researcher to stay at APTCP for an extended period to interact with domestic researchers and graduate students.

Young-Kee Kim elected Vice President of the American Physical Society

The American Physical Society (APS) elected Young-Kee Kim, Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU) Principal Investigator and Louis Block Distinguished Service Professor in Physics at The University of Chicago, as its next Vice President, it was announced by the APS Nominating Committee.

The APS was founded in 1899, and is a nonprofit membership organization working to advance and diffuse the knowledge of physics through its research journals, scientific meetings, and education, outreach, advocacy, and international activities. Currently, there are more than 55,000 members in the US and around the world. The APS also operates the Physical Review journals.

Eiichiro Komatsu awarded the Inoue Prize for Science

Max Planck Institute for Astrophysics Director and Kavli Institute for the Physics and Mathematics of the Universe Principal Investigator Eiichiro Komatsu was selected as one of the recipients of this year's Inoue Prize for Science. The Inoue Prize for Science was established in 1984 by the Inoue Foundation for Science, and presents researchers with a gold medal and some research funding assistance. The foundation recognizes researchers under 50 who have made remarkable achievements in natural and fundamental sciences.

Hitoshi Murayama named new AAAS fellow

Hitoshi Murayama, Principal Investigator of the Kavli Institute for the Physics and Mathematics of the Universe and MacAdams Professor of Physics at University of California, Berkeley, was named a new fellow of the American Association for the Advancement of Science (AAAS).

The AAAS was established in 1848, with the goal to "advance science, engineering, and innovation throughout the world for the benefit of all people." This includes enhancing communication among researchers, engineers, and the public. Today, the AAAS hosts the biggest science communication annual meeting every year, and is also the publisher of the scientific journal Science.

7 CONFERENCES

Conference title Date, Place	Attendees (from abroad)
Number Theory, Strings and Quantum Physics 1-4 June 2021, [Online]	287 (209)
Hyper-Kamiokande Collaboration Meeting 7-18 June 2021, [Online]	175 (121)
Quarkonia Meet Dark Matter 15-18 June 2021, [Online]	119 (70)
Focus Week on Quantum Mechanical Systems at Large Quantum Number 30 August - 3 September 2021, [Online]	46 (44)
Particle Acceleration in Solar Flares and the Plasma Universe --Deciphering Its Features Under Magnetic Reconnection-- 15-19 November 2021, [Online]	155 (126)
The World of Mathematical Physics II 21 November 2021, [Online]	84 (4)
Dark Sectors of Astroparticle Physics (AstroDark-2021): Axions, Neutrinos, Black Holes and Gravitational Waves 7-10 December 2021, [Online]	174 (107)
New Observational Windows on the High-Scale Origin of Matter-Antimatter Asymmetry 10-14 January 2022, [Online]	79 (70)
Hyper-Kamiokande Collaboration Meeting 14-25 February 2022, [Online]	145 (84)
Cosmic Cartography 2022: Exploring the Cosmic Web and Large-Scale Structure 7-11 March 2022, [Online]	199 (145)
PFS 13th Collaboration Meeting 22-24 March 2022, [Online]	186 (95)
What Is Dark Matter? - Comprehensive Study of the Huge Discovery Space in Dark Matter - 29-30 March 2022, [Online]	149 (12)

8 CONFERENCE PRESENTATIONS AND SEMINAR TALKS

Invited talks given by the Kavli IPMU researchers (Selected 12 of 179)

Date	Presenter	Presentation title	Conference name
Apr. 14, 2021	Thomas Edward Melia	**Developments in Hilbert series for EFT**	HEFT 2021 Conference
Jun. 5, 2021	Misao Sasaki	**Primordial Black Holes**	Quantum Gravity and Cosmology (Sakharov's centennial)
Jun. 15, 2021	Hirosi Ooguri	**Stringy Resolutions of Null Singularities**	PASCOS 2021
Aug. 2, 2021	Elisa Gouvea Mauricio Ferreira	**Dark Energy Overview**	COSMO 21
Aug. 24, 2021	Meer Ashwinkumar	**4d Chern-Simons Theory as a 3d Toda Theory, and a 3d-2d Correspondence**	The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)
Aug. 28, 2021	Hitoshi Murayama	**Why SUSY is great**	SUSY 2021
Aug. 31, 2021	Hiraku Nakajima	**Intersection cohomology groups of instanton moduli spaces and cotangent bundles of affine flag varieties**	68th Geometry Symposium
Sep. 7, 2021	Takeo Higuchi	**Belle II: Status and Prospects**	The 22nd Edition of Particle and Nuclei International Conference (PANIC 2021)
Oct. 12, 2021	Joshua Armstrong Eby	**Terrestrial Signals from Axion Star Explosions**	GGI Workshop, "New Physics from the Sky"
Oct. 14, 2021	Masahito Yamazaki	**Theta vacua in 4d Yang-Mills Theories**	Strings, Fields and Holograms
Oct. 29, 2021	Shigeki Matsumoto	**Summary talk on BSM particle productions**	ILCX2021
Mar. 30, 2022	Satoshi Shirai	**Progress on the study of QCD axions**	What is dark matter? 2022 - Comprehensive study of the huge discovery space in dark matter

9

OUTREACH AND PUBLIC RELATIONS

EVENT TITLE	DATE	VENUE	number of participants
The 24th ICRR & Kavli IPMU Joint Public Lecture "The Wonders of a Universe Full of Matter"	Apr. 10, 2021	Online	1,173
Film Screening "Secrets of the Surface: The Mathematical Vision of Maryam Mirzakhani"	Apr. 25, 2021	Online	452
Celebration of Women in Mathematics	May 15, 2021	Online	353
Fundamentalz Bazaar	Jun. 6, 2021	Miraikan	431
Science Café 2021 "Universe"	Jun. 20, 2021	Online	48
Go Global Gateway Online Event: Film Screening "Secrets of the Surface: The Mathematical Vision of Maryam Mirzakhani"	Aug. 6, 2021	Online	64
Collaborative Knowledge Creation Practical Learning Course with the University of Tokyo CoREF "Learning and Creating Physics - From High School to the Forefront Research of the Universe"	Aug. 4-5, 7, 2021	Online	77
Science Café 2021 "Universe"	Sept. 19, 2021	Online	51
Kashiwa Campus Open Day, 2021	Oct. 23-24, 2021	Online	8,667*
6th “Actually I Really Love Physics!“–Career Paths of Female Physics Graduates	Nov. 6, 2021	Online	48
Kavli IPMU x ICRR Joint Public Lecture: “A Dream of Modern Mathematics. A Cutting Edge of Physics“	Nov. 28, 2021	Online	394
10th Annual WPI Science Symposium: “To the Future NanoWorld“	Dec. 18, 2021	Online	567
7th Kavli IPMU/ELSI/IRCN Joint Public Lecture: “A Question of Origins“	Jan. 30, 2022	Online	595
Fundamentalz Festival mini: An Exhibition of Work by Artists and Researchers	Mar. 19-25, 2022	JR Ueno Station Platform 13	200

*Total number of participants to all institutes on the Kashiwa campus

Kavli IPMU
Annual Report 2021
April 2021–March 2022

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

5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan TEL: +81-4-7136-4940 FAX: +81-4-7136-4941 http://www.ipmu.jp/

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

ISSN 2187-7386

Printed in Japan