ISSN 0910-0709

Department of Physics
School of Science
The University of Tokyo

Annual Report

2025

令和７年度 年次研究報告

東京大学 大学院　理学系研究科・理学部
物理学教室

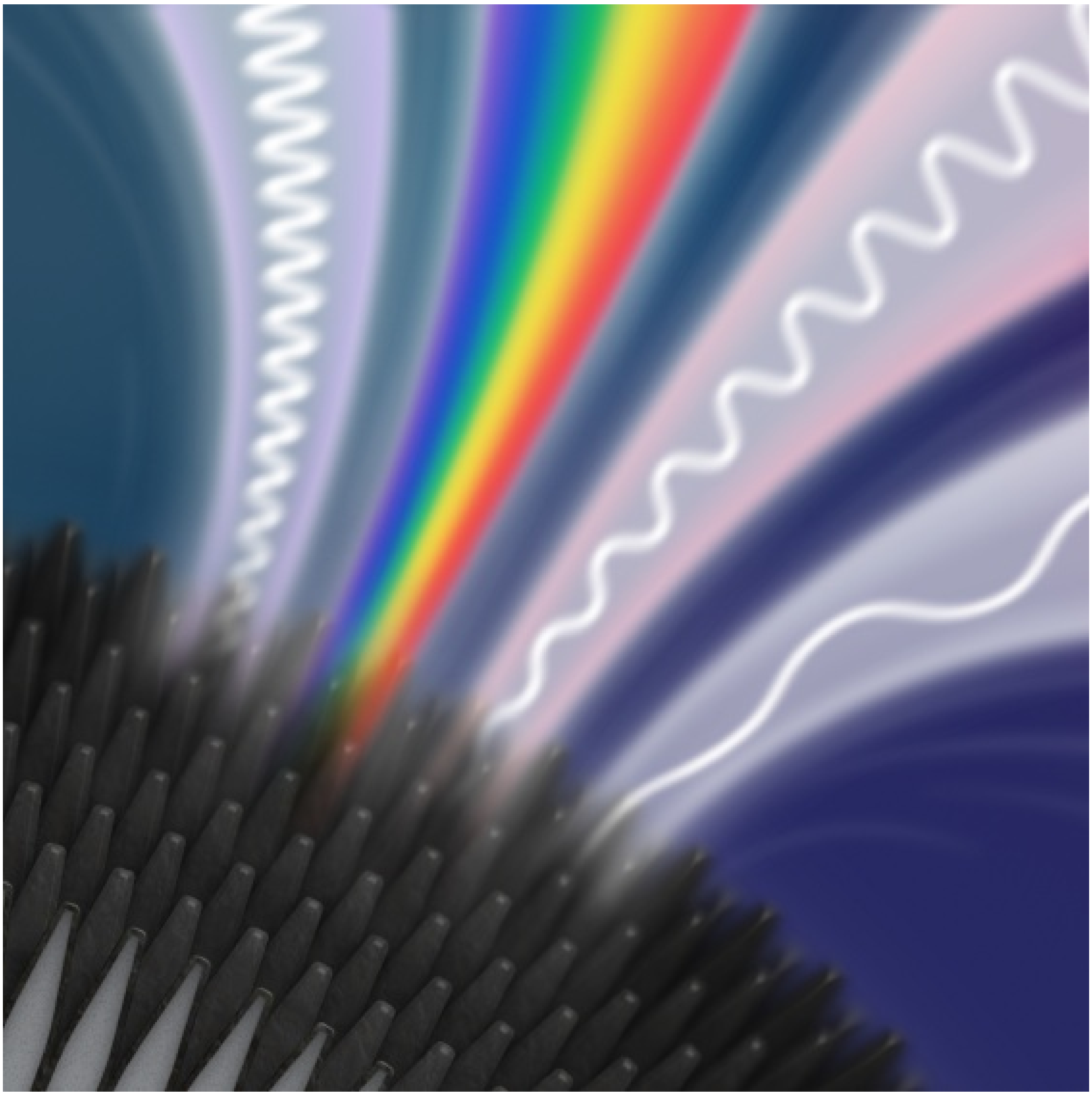

図 1: 広帯域完全吸収モスアイ構造の模式図。下部に示されたモスアイ構造は、シリコンにフェムト秒レーザー加工を施すことにより形成された、数十マイクロメートルオーダーの微細な円錐状突起が周期的に配列した構造であり、その表面は厚さ 100 nm のカーボン膜で覆われている。この構造により、テラヘルツ波から紫外域に至る極めて広い波長範囲において、高効率な光吸収が実現されることが実験的に示された。（小西研究室）

Schematic illustration of a broadband near-perfect absorbing moth-eye structure. The moth-eye structure shown at the bottom consists of a periodic array of fine conical protrusions on the order of several tens of micrometers, formed by femtosecond laser processing of silicon, and its surface is coated with a 100-nm thick carbon film. It was experimentally demonstrated that this structure enables highly efficient light absorption over an extremely broad wavelength range, extending from the terahertz region to the ultraviolet. (Konishi Group)

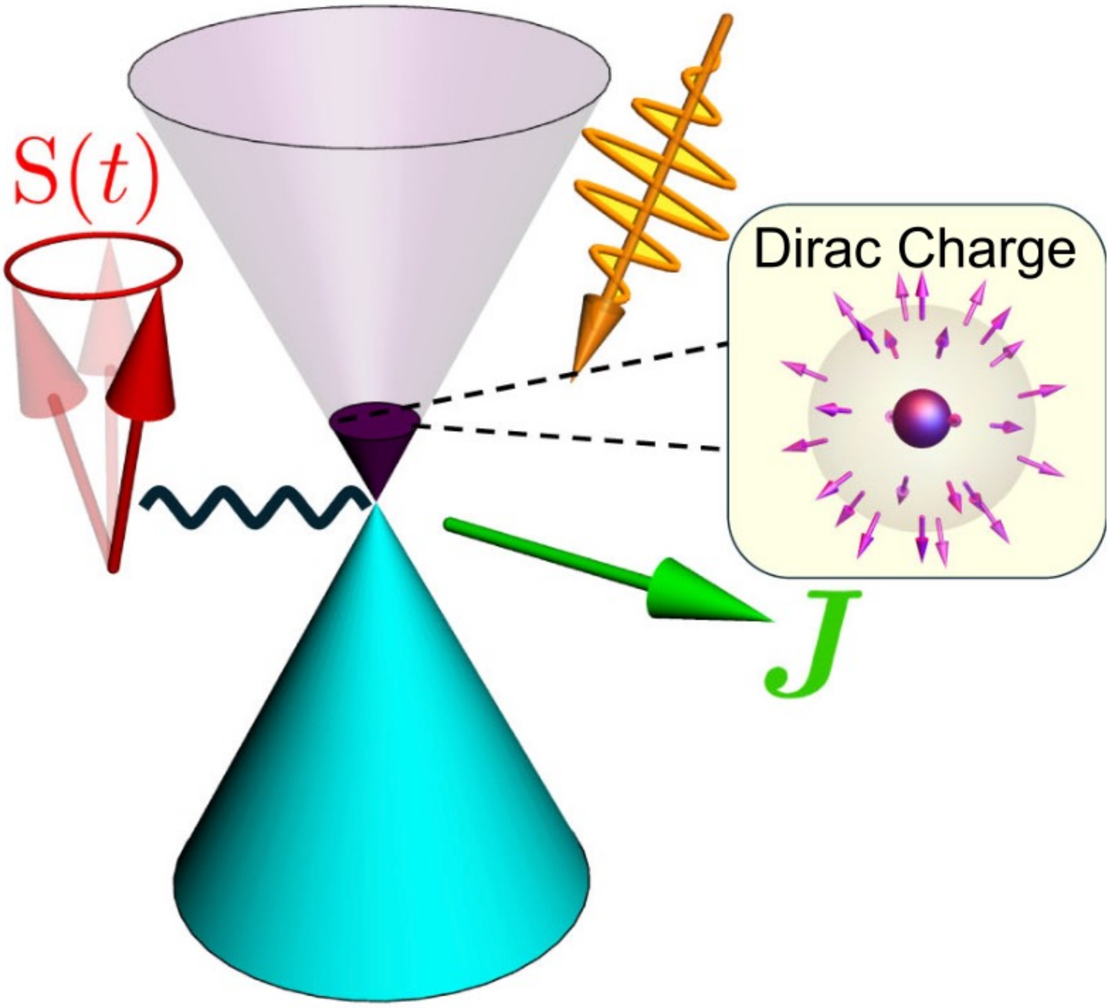

図 2: ディラック半金属における局在スピンダイナミクスに起因する光電流の模式図。電子スピンモーメントと局在スピンモーメントとの交換結合を通じて、時間依存する局在スピンのダイナミクス $S(t)$ が光電流応答 J を生成する。この J の観測からディラック電荷の検出ができる。（有田研究室）

Schematic picture of photocurrent arising from localized spin dynamics in Dirac semimetals. Through the exchange coupling between the electronic spin moment and the localized spin moment, the localized spin dynamics $S(t)$ generates the photocurrent response J. Observation of the resulting photocurrent J provides a way to detect Dirac charges. (Arita Group)

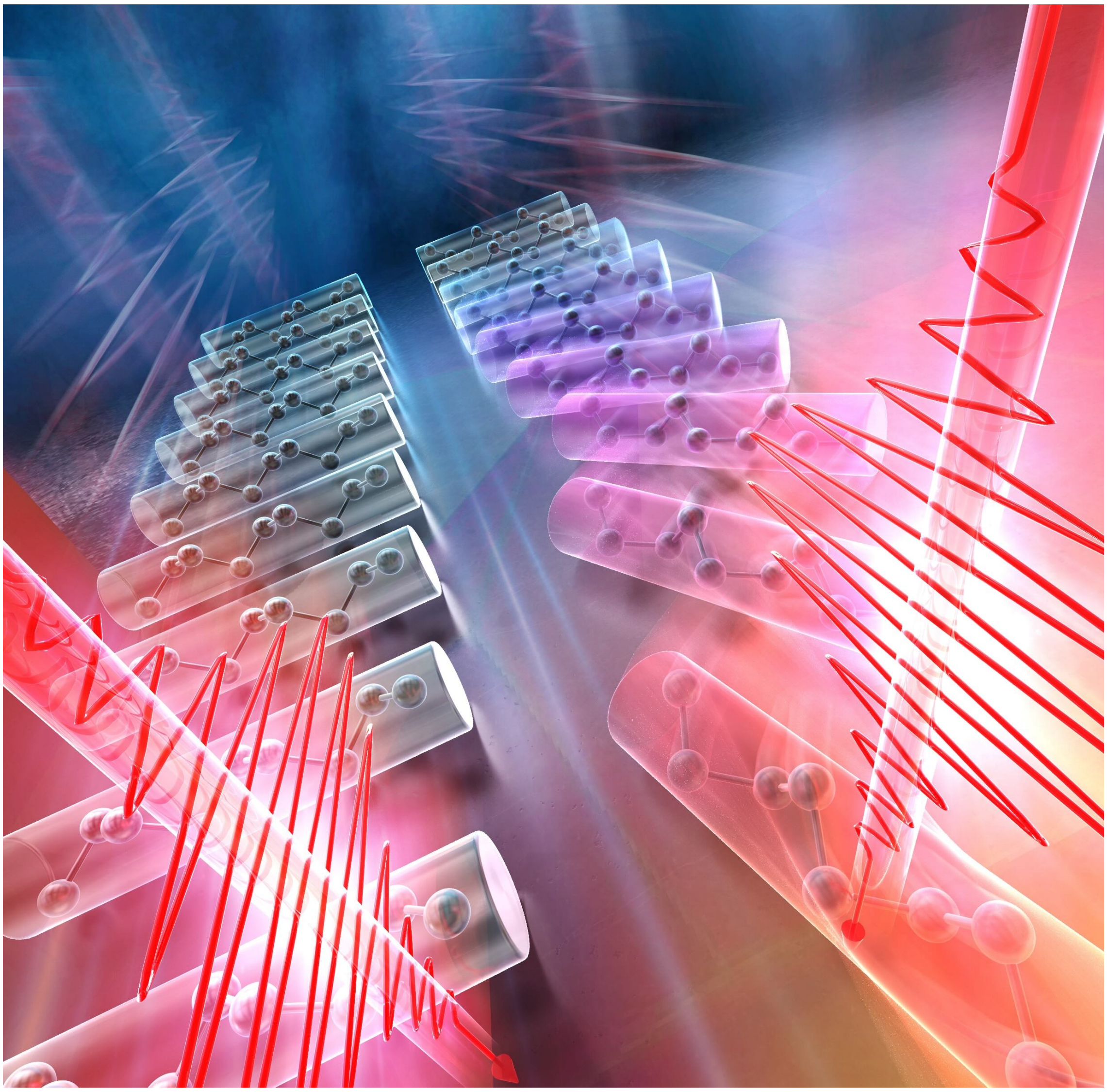

図 3: ピコ秒のパルスレーザーを使って、テルル（Te）結晶の螺旋軸（異方性軸）の向きを制御する模式図。パルスレーザーの偏光と直交する方向に螺旋軸の向きが揃うことが明らかになった。光を使って結晶の異方性を自在に制御できるため、メタレンズ作製などに応用できることが期待される。（林研究室）
A schematic illustration depicting the control of the orientation of the helical axis (anisotropic axis) in a tellurium (Te) crystal using a picosecond pulsed laser. Upon irradiation of the laser pulse, the helical axis aligns in a direction orthogonal to the polarization of the pulsed laser. As this technique enables free control of crystal anisotropy using light, it may find applications in fields such as the fabrication of metalenses. (Hayashi Group)

序

東京大学大学院理学系研究科物理学専攻・理学部物理学科の令和7年度（2025年4月–2026年3月）年次研究報告をお届けします。この小冊子が物理学教室で広く行われている多彩で活発な研究・教育の現状を知っていただく手がかりになれば幸いです。

最初に、新しく入ってこられた教員ですが、教授として、寄田浩平氏（素粒子物理学実験：早稲田大学）杉田有治氏（生物物理学理論：理化学研究所）准教授として、張奕勁氏（物性物理学実験：本学生産技術研究所）助教として加藤 ちなみ氏（吉田研：東京理科大学)、藤田 真奈美氏（中村研：日本原子力研究開発機構)、渡邉 真隆氏（山﨑研：名古屋大学)、北村 徳隆氏（鈴木研：本学理学系研究科原子核科学研究センター)、吉田 博信氏（桂研：理化学研究所)、青木 匠氏（横山研：株式会社キーエンス)、北村 泰晟氏（有田研：理化学研究所)、木村 眞人氏（寄田研：高エネルギー加速器研究機構)、林 優依氏（福嶋研：京都大学)、UGARTE LA TORRE DIEGO RENATO氏（理化学研究所）が着任されました。また、中桐 洸太助教（横山研）が本学宇宙線研究所准教授、渡邊 光助教（有田研）が北海道大学准教授、峰本 紳一郎助教（専攻長預かり）が東北大学助教、高三 和晃助教が本学工学系研究科准教授、大森 寛太郎助教（松尾研）が理化学研究所上級研究員山本 新助教（福嶋研）が理化学研究所上級研究員として転出されました。さらに、長谷川修司教授、松尾泰教授が本年度定年を迎えられました。

本年度も教室関係者の活発な研究・教育活動の結果、多くの方が受賞されています。有田亮太郎教授、中辻知教授がClarivate Highly Cited Researcher 2025を、山﨑雅人教授がBest Paper Prize 2025 (J. Phys. A: Math. Theor.) および令和8年度文部科学大臣表彰科学技術賞を、酒井明人講師が令和7年度丸文研究奨励賞を、青木匠助教（横山・中島研）がATLAS Thesis Award 2025を、高三和晃助教（辻研)、姫岡 優介助教（古澤研)、吉田 博信助教（桂研)、小田部荘達特任助教（相川研）が第20回（2026年）日本物理学会若手奨励賞を受賞されました。また、小林孝嘉名誉教授が台湾国交通大學終身講座教授に任命されました。さらに、吉田智治氏、大賀成朗氏、西村俊亮氏、梅田滉也氏、小川和馬氏、藤本知宏氏が令和7年度理学系研究科研究奨励賞（博士課程）を、影浦優太氏、松浦修大氏、高橋正大氏、愛敬公太氏が令和7年度理学系研究科研究奨励賞（修士課程）を、金田啓氏、山之内達哉氏、髙山光希氏が令和7年度理学部学修奨励賞を受賞しました。

ここ2～3年で、定年を迎えられる教員が多く、教室の陣容が急速に変化してきました。退職・移動される先生方と入れ替わる形で多くの新たな先生方が来られております。実に教室全体の約1/4が入れ替わる形になりました。これにともない、今後新しい変化が様々な形で表れてくると思われます。

令和2年度から始まった物理学教室と産業界との連携はますます発展しています。JSR株式会社との包括連携に基づいた共同研究の基盤活動は、理学部1号館中央棟3階にオープンした協創オフィス「JSR・東京大学協創拠点CURIE」を起点として、教室内の先生との交流を生み、複数の共同研究に繋がっています。この包括連携により、物理学専攻は社会に深く浸透した様々な材料の学理探究を通して普遍的真理と新たな学問領域を見出し、一方JSRはサイエンスに基づく新たな高機能材料の開発を推進していきます。また、物理学専攻の博士課程学生を対象とした給付型フェローシップである、「JSRフェローシップ」もこれまで何名もの学生に給付され、彼らの研究活動を支援しています。JSR社との社会連携は令和7年からさらに3年延長されることが決まりました。これまでの活発な活動が高く評価された形になりました。

また令和3年度からIBM量子コンピューターの実機（ソフトウェア）を用いた量子ネイティブ人材育成を開始していますが、令和4年度からは浅野キャンパスに設置されたIBM量子コンピューターの実機に触れる教育内容に拡充して行っています。

令和4年10月に、サスティナブル量子AI研究拠点が、JST共創の場形成支援プログラム (COI-NEXT) の政策重点分野 (量子技術分野) に採択されました。これは、東京大学・慶應大学・理化学研究所・OIST・シカゴ大学をはじめ川崎市や多数の参画企業が一体となり研究開発を進めるもので、量子機械学習・量子シミュレーション・量子計測デバイスを結合した量子AI技術を創出、量子HPC基盤の構築を目指しています。

令和7年には理物同窓会を発足し、現役世代とOBとのつながりの場を広げてまいりました。また、「理学部物理支援基金」を設置するなど、物理学教室の活動を広く支援していただけるよう努めてまいりました。

物理学教室は、今後も社会における基礎科学の新たな役割を模索しつつ、持続可能な基礎研究・教育の実現に向けて努力してまいります。令和6年度からは東大基金にも参加し、得られた資金をもとに先輩の先生方、卒業生の皆様、ならびに関係各位との交流をさらに深めてまいりたいと考えております。皆様には、引き続きご指導ご鞭撻のほど、よろしくお願い申し上げます。

この年次研究報告は、鈴木大介准教授、酒井明人講師、中村ちか子氏のご尽力によって編集作成されました。この場を借りて感謝いたします。

2026年5月1日
物理学専攻 専攻長・物理学科 学科長
上田 正仁

II

Summary of group activities in 2025

1 Fukushima Group

Research Subjects: QCD phase diagram, Confinement, Lattice simulation, Neutron star, Chiral anomaly

Member: Kenji Fukushima, Yui Hayashi, Syo Kamata, and Arata Yamamoto

In Theoretical Hadron Physics group, many-body quantum problems of quarks and gluons are studied theoretically on the basis of the quantum chromodynamics (QCD). The subjects studied include the quark-gluon plasma in relativistic heavy-ion collisions, lattice gauge simulations with classical and quantum computing, matter under extreme conditions, neutron stars, etc. Highlights in research activities of this year are listed below:

1. Definition of axial charges and anomaly in the Hamiltonian formulation of lattice gauge theory.
2. Nonlocal operators on the lattice for the Higgs-confinement phase transition.
3. Discovery of a new phase window at high temeprature and low baryon density based on the large color number limit of QCD.
4. Analysis of the confined phase and the phase transition in QCD under imaginary rotation.
5. Photon polarization tensor at finite temperature and density in a magnetic field.
6. Novel formulation of relativistic spin hydrodynamics using the anti-symmetric form of the spin tensor and the derivation of the generalized Bargmann-Michel-Telegdi (BMT) equation.
7. Pseudo-gauge dependence of the energy density, pressure, and shear-force distributions inside the nucleon.
8. Reformulation of the in-in formalism incorporating vacuum instability in a constant electric field.
9. Exact-WKB analysis of two-level Floquet systems.

2 Liang Group

Research Subjects: Quantum many-body theories in nuclear and cold-atom physics

Member: Haozhao Liang and Hiroyuki Tajima

In our group, we study the properties of atomic nuclei and neutron stars based on various nuclear many-body theories. In particular, one of the main research themes is nuclear density functional theory (DFT), which aims at understanding both ground-state and excited-state properties of thousands of nuclei in a consistent and predictive way. Our research interests also include the microscopic foundation of nuclear DFT, the interdisciplinary applications in nuclear astrophysics, particle physics, condensed matter physics, etc., and the relevant studies in general quantum many-body problems. To this end, a cold atomic gas can be regarded as an ideal testing ground for many-body theories because of its controllability. In this regard, we are also interested in investigating novel many-body phenomena and developing quantum many-body theories through comparisons with cold atom experiments.

Highlights in research activities of this year include:

1. Quarkyonic matter from an insight based on ultracold atom physics
2. Simulating nuclear force in ultracold atoms
3. Tunneling transport at hadron-quark interface in massive neutron stars
4. Non-Hermitian renormalization group and quantum anomaly

5. Isospin symmetry breaking of nuclear interaction
6. Low-lying excited state of ^{229m}Th
7. Neural network construction of equation of state from relativistic *ab initio* calculations
8. Proton radioactivity in deformed nuclei with microscopic optical potential
9. Collective quantum tunneling with time-dependent generator coordinate method

3 High Energy Particle Theory Group

Research Subjects: Particle Physics and Cosmology

Member: Takeo Moroi, Koichi Hamaguchi, Yutaka Matsuo, Masahito Yamazaki

We are engaged in a broad range of research areas in particle physics and cosmology, including physics beyond the Standard Model, dark matter, baryogenesis, inflation, supersymmetric phenomenology, cosmology, astroparticle physics, neutrino physics, axions, quantum sensing, string theory, supersymmetric field theories, conformal field theories, generalized symmetries, and quantum gravity, among others. The specific topics studied during this academic year are summarized below:

1. Phenomenology
    - 1.1. Quantum-enhanced sensing and detection of dark matter [1, 2, 3]
    - 1.2. Non-thermal production of Higgsino dark matter [4]
    - 1.3. Topological aspects of the early universe [5]
    - 1.4. Quantum parton showers [6]
    - 1.5. Phenomenology of quantum gravity [7]
    - 1.6. Lepton flavor asymmetry [8]
    - 1.7. Sterile neutrino dark matter [9]
    - 1.8. Neutrinos from from the Seyfert galaxy NGC 1068 and dark matter [10]
    - 1.9. Higgsino search with electroweak precision measurements [11, 12]
    - 1.10. Axion emission from neutron stars [13]
    - 1.11. Linear colliders [14]
    - 1.12. Inflation in grand unified theories [15]
    - 1.13. Leptogenesis [16, 17]
2. Superstring theory and formal aspects of quantum field theories
    - 2.1. Construction of two-dimensional conformal field theories [18, 19]
    - 2.2. Fracton quantum field theories [20]
    - 2.3. Anomaly and unitary operators [21]
    - 2.4. Quantum entanglement in strongly-interacting quantum field theories [22]
    - 2.5. Two-dimensional $\mathcal{N} = (0, 1)$ gauge theories [23]
    - 2.6. Four-dimensional Chern-Simons theory [24, 30]
    - 2.7. Quantum lattice models under non-invertible dualities [25, 26]
    - 2.8. BPS counting [27]
    - 2.9. Three-dimensional $\mathcal{N} = 4$ theories and vertex operator algebras [28]
    - 2.10. Ensemble averages in quantum gravity [29]

References

[1] T. Sichanugrist, H. Fukuda, T. Moroi, K. Nakayama, S. Chigusa, N. Mizuochi, M. Hazumi and Y. Matsuzaki, “Entanglement-enhanced ac magnetometry in the presence of Markovian noise,” Phys. Rev. A **111**, no.4, 042605 (2025) [arXiv:2410.21699 [quant-ph]].

[2] H. Fukuda, Y. Matsuzaki and T. Sichanugrist, “Directional Searching for Light Dark Matter with Quantum Sensors,” Phys. Rev. Lett. **135**, no.24, 241802 (2025) [arXiv:2506.19614 [hep-ph]].

[3] S. Chen, H. Fukuda, Y. Iiyama, Y. Mino, T. Moroi, M. Nakahara, T. Nitta and T. Sichanugrist, “Background suppression in quantum sensing of dark matter via collective entangled-state projection,” Phys. Rev. D **113**, no.5, 055014 (2026) [arXiv:2510.01816 [hep-ph]].

[4] H. Fukuda, Q. Li, T. Moroi and A. Niki, “Non-thermal production of Higgsino dark matter by late-decaying scalar fields,” JHEP **06**, 091 (2025) [arXiv:2410.15733 [hep-ph]].

[5] H. Fukuda, Y. Hamada, K. Kamada, K. Mukaida and F. Uchida, “Magnetic helicity, magnetic monopoles, and Higgs winding,” JHEP **03**, 127 (2026) [arXiv:2509.25734 [hep-ph]].

[6] M. Yamazaki, PoS **QCHSC24**, 260 (2025) [arXiv:2502.18059 [hep-ph]].

[7] Y. Gouttenoire, S. F. King, R. Roshan, X. Wang, G. White and M. Yamazaki, Phys. Rev. D **112**, no.7, 7 (2025) [arXiv:2501.16414 [hep-ph]].

[8] K. Akita, K. Hamaguchi and M. Ovchynnikov, ”Affleck-Dine leptoflavorgenesis,” JHEP **12** 142 (2025) [arXiv: 2509.08175 [hep-ph]].

[9] K. Akita, K. Hamaguchi and M. Ovchynnikov, ”Maximal Parameter Space of Sterile Neutrino Dark Matter with Lepton Asymmetries,” Phys. Rev. Lett. **136** 11, 111001 (2026) [arXiv: 2507.20659 [hep-ph]].

[10] K. Akita, A. Ibarra and R. Zimmermann, ”Dark matter explanations for the neutrino emission from the Seyfert galaxy NGC 1068,” [arXiv: 2507.16539 [hep-ph]].

[11] N. Nagata and G. Osaki, “Electroweak precision data as a gateway to light higgsinos,” JHEP **07**, 242 (2025) [arXiv:2503.20602 [hep-ph]].

[12] H. Baer, V. Barger, N. Nagata and D. Sengupta, “Reach of e+e− Higgs factory for light higgsinos via electroweak precision observables and comparison with other future facilities,” Phys. Lett. B **873**, 140203 (2026) [arXiv:2509.18288 [hep-ph]].

[13] K. Hamaguchi, N. Nagata and J. Zheng, “Axion emission from proton Cooper pairs in neutron stars,” JCAP **06**, 038 (2025) [arXiv:2502.18931 [hep-ph]].

[14] H. Abramowicz *et al.* [Linear Collider Vision], “A Linear Collider Vision for the Future of Particle Physics,” Eur. Phys. J. ST (2026) [arXiv:2503.19983 [hep-ex]].

[15] J. Ellis, M. A. G. García, N. Nagata, D. V. Nanopoulos and K. A. Olive, “Deformations of Starobinsky inflation in no-scale SU(5) and SO(10) GUTs,” JCAP **12**, 038 (2025) [arXiv:2508.13279 [hep-ph]].

[16] G. Alessandro, K. Hamaguchi, M.E. Ramirez-Quezada, K. Shimada, J. Wada, and T. Yokoyama, “Insights on the scale of leptogenesis from neutrino masses and neutrinoless double-beta decay,” Eur. Phys. J. C, **85**, 778 (2025) [arXiv:2502.10093 [hep-ph]].

[17] H. Takahashi and J. Wada, “Asymmetric Dark Matter from Low-Scale Spontaneous Leptogenesis,” [arXiv:2601.01849 [hep-ph]].

[18] K. Kawabata and S. Yahagi, SciPost Phys. **18** (2025) no.5, 166.

[19] K. Kawabata, T. Nishioka, T. Okuda and S. Yahagi, JHEP **05** (2025), 105.

[20] K. Ohmori and S. Shimamura, JHEP **09**, 049 (2025) [arXiv:2504.10835 [cond-mat.str-el]].

[21] M. Okada, S. Shimamura, Y. Tachikawa and Y. Zhang, JHEP **11**, 122 (2025) [arXiv:2509.02989 [hep-th]].

[22] M. Watanabe, JHEP **03** (2026), 237 doi:10.1007/JHEP03(2026)237 [arXiv:2506.10072 [hep-th]].

[23] J. Bao, M. Yamazaki and D. Zhou, [arXiv:2508.06865 [hep-th]].

[24] J. i. Sakamoto, R. Tateo and M. Yamazaki, JHEP **01**, 084 (2026) [arXiv:2509.12303 [hep-th]].

[25] W. Cao, M. Yamazaki and L. Li, Phys. Rev. Lett. **136**, no.4, 040402 (2026) [arXiv:2502.20435 [cond-mat.str-el]].

[26] W. Cao, Y. Miao and M. Yamazaki, SciPost Phys. Core **8**, 070 (2025) [arXiv:2501.12514 [cond-mat.str-el]].

[27] J. Bao and M. Yamazaki, SciPost Phys. **18**, no.4, 143 (2025) [arXiv:2501.03365 [hep-th]].

[28] I. Coman, M. Shim, M. Yamazaki and Y. Zhou, Commun. Math. Phys. **406**, no.6, 122 (2025) [arXiv:2312.13363 [hep-th]].

[29] M. Ashwinkumar, A. Kidambi, J. M. Leedom and M. Yamazaki, Adv. Theor. Math. Phys. **29**, no.1, 1-55 (2025) [arXiv:2311.00699 [hep-th]].

[30] M. Ashwinkumar, J. i. Sakamoto and M. Yamazaki, Adv. Theor. Math. Phys. **29**, 1509-1694 (2025) [arXiv:2309.14412 [hep-th]].

4 Nakamura Group

Research Subjects: Spectroscopic study of hypernuclei and related hadron/nuclear physics

Member: Satoshi N. Nakamura, Sho Nagao and Manami Fujita

The Nuclear EXperimental physics group (NEX) consists of two research groups: the Nakamura Group, led by Professor Nakamura and Assistant Professors Nagao and Fujita with two doctor course students and four master's course students, and the Suzuki Group, led by Associate Professor Suzuki and Assistant Professor Noritaka Kitamura. The NEX group is concurrently affiliated with the Quark Nuclear Science Institute (QNSI), established in July 2024, and is leading international collaborative research through the development of the International Quantum Physics Network. This section summarizes the research activities of the Nakamura Group.

We are performing experimental research in modern nuclear physics to understand quantum many-body systems interacting with the strong interaction. To this end, we are conducting experiments of hypernuclei which are composed of nucleons (protons and neutrons) and hyperons (with strange quarks), by making full use of particle accelerators in Japan and abroad.

Quantum many-body systems in which the strong interaction plays an important role include; baryons, which consist of quarks including protons and neutrons; (hyper)nuclei as baryonic many-body systems; and neutron stars, the densest objects in the universe, which are gravitationally bound baryon many-body systems and may be described as "giant nuclei" whose masses are supported by the baryon interaction. Those quantum many-body systems have size scales from 1 fm (10^{-15} m) to 10 km (10^4 m), spanning 19 orders of magnitude. In order to understand these in a unified manner based on the baryon interaction, which extends the nuclear force, we have been conducting experiments at 1) Jefferson Laboratory (JLab) in the United States, 2) Johannes Gutenberg University Mainz, Germany (MAMI), and 3) Research Center for Electron Photon Science, Tohoku University (ELPH). These facilities have high-energy, high-intensity electron accelerators capable of producing strange quarks. In addition to the above, we are leading hypernuclear experiments using the next-generation π meson beams at the High-Intensity High-Resolution beamline (HIHR), which is being prepared as a next-generation flagship project at the hadron experimental facility of J-PARC in Tokai.

Currently, there are four key issues to be solved in hypernuclear research: 1) the hyperton puzzle, 2) the existence or non-existence of atomic number zero hypernuclei (nnΛ), 3) charge symmetry breaking of Lambda hypernuclei, and 4) the hyperon puzzle (why heavy neutron stars exist). We are promoting research to solve these puzzles through the following experiments.

- Spectroscopic study of Λ hypernuclei at Jefferson Lab
  - Search of a neutral hypernuclei, nnΛ
  - Electro-production of hyperons
  - Electro-production of η' mesons
  - High-precision spectroscopy of Λ hypernuclei with the $(e, e'\mathrm{K}^+)$ reaction
  - Design of the next generation experiment of decay π^- spectroscopy
- Decay π^- spectroscopy of electro-produced hypernuclei at MAMI
  - Precise measurement of mass of hypertriton

  - High-precision measurement of electron beam energy using synchrotron radiation interference
  - High precision calibration of magnetic spectrometers

- Study of light hypernuclei at RARiS
  - Lifetime measurement of hypernuclei
  - Study of the Λn interaction by the Final State Interaction measurement

- Study of strangeness nuclear physics at J-PARC
  - Lifetime measurement of light hypernuclei
  - Spectroscopy of Ξ hypernuclei
  - Research and Development for the spectroscopy of Λ hypernuclei with the (π^+, K^+) reaction
  - Study of kaonic nuclei
  - Design of the next generation experiment with the (π, K) reaction at HIHR, J-PARC

5 Suzuki Group

Research Subjects: Experimental nuclear physics: exotic nuclei, nuclear matter and nuclear astrophysics

Member: Daisuke Suzuki and Noritaka Kitamura

Our laboratory specializes in nucleon many-body physics. We are promoting research on nuclei, nuclear matter, and nuclear astrophysics using quantum beams of radioactive isotopes (RI). In particular, focusing on spectroscopic and reaction experiments of asymmetric nuclei with an imbalance of neutrons and protons, we are challenging various problems in modern nuclear physics, from microscopic systems of extremely short-lived nuclei to macroscopic objects such as neutron stars and explosive astrophysical phenomena.

Nuclear physics is a very broad academic field whose main theme is the formation and evolution of hadronic matter in the universe. Nucleon many-body systems, which are our laboratory's area of expertise, i.e., atomic nuclei and nuclear matter, are quantum many-body systems composed of protons and neutrons (collectively called nucleons) that appear in the low-energy limit of quantum chromodynamics (QCD). Although it is a seemingly simple system involving only the *ud* sector, it is known to be a many-body system where direct calculations based on QCD are extremely difficult. In particular, the nuclear force acting between nucleons and many-body correlations in the medium are very complex, with many mysteries remaining and serving as a source of unexpectedly diverse physical phenomena.

While nucleon many-body physics was historically limited to the study of stable nuclei on Earth, technological innovations in heavy-ion RI beam (beams in which the nuclei of heavy ions are replaced with RI) facilities, which emerged in the 1990s, have made it possible to artificially generate extremely short-lived nuclei and nuclear matter that do not exist on Earth using RI beams accelerated to approximately 10% to 70% of the speed of light, and to conduct quantum scattering experiments. Particularly with the successful operation of the RI Beam Factory (RIBF) of RIKEN Nishina Center, the world's first third-generation facility, a global rush to construct RI beam facilities is currently underway.

We are tackling various problems related to three themes: (1) exotic nuclei, (2) nuclear matter, and (3) nuclear astrophysics, through RI beam experiments using electroweak probes (electromagnetic and weak forces) and hadron probes (strong force). Furthermore, we are actively participating in the RIBF Upgrade Project as a medium- to long-term project. This project is an innovative attempt to pioneer the intensity frontier of RI beams by applying beam recycling technology based on a storage ring to RI beam generation for the first time.

Our activities in FY2024 include:

- Investigating shape transition, triaxiality, and octupole deformation using in-beam γ-ray spectroscopy.
- Studying mirror symmetry beyond the proton dripline.
- Addressing the spectroscopic factor quenching problem.

- Researching the nuclear equation of state through heavy ion collision (SπRIT project) and isoscaler giant monopole resonance measurement.
- Exploring the origin of molybdenum elements in the Universe.
- Developing a 3D γ-ray tracking germanium detector (GT-5 project).
- Organizing the international symposium PCM2026 at the University of Aizu to discuss updates and perspectives on nuclear structure studies.
- Organizing the international workshop ADRIB26 for discussions on the RIBF Upgrade Project.

6 Yokoyama(M)-Nakajima Group

Research Subjects: Experimental Particle Physics and Particle Astrophysics

Member: Masashi Yokoyama, Yasuhiro Nakajima, Takumi Aoki, and Seisho Abe

Our group focuses on investigating the properties of neutrinos and utilizing them as probes in particle physics and astroparticle physics. We play leading roles in experiments using the Super-Kamiokande and Hyper-Kamiokande detectors, as well as the J-PARC accelerator.

T2K long-baseline neutrino oscillation experiment

We conduct research on neutrino oscillations through the T2K long-baseline neutrino experiment. In this experiment, intense neutrino and antineutrino beams produced at the J-PARC accelerator complex are detected by the Super-Kamiokande detector located 295 km away. Our primary goal is to identify a new source of CP violation in neutrino oscillations.

We have been leading the upgrade of the near neutrino detectors to reduce uncertainties in neutrino interaction modeling. This year, we have continued data taking with the SuperFGD detector. We are leading its operation, calibration, and data analysis, aiming for precise measurements of electron neutrino interactions and neutrino oscillations.

Super-Kamiokande experiment

Super-Kamiokande (SK) is the largest underground detector in the world for studying neutrino physics and nucleon decay. In the summer of 2022, we added 27 tons of $Gd_2(SO_4)_3{\cdot}8H_2O$ to increase the concentration of gadolinium in Super-Kamiokande from 0.011% achieved in 2020 to 0.033%. By increasing the gadolinium concentration, we have improved the detection efficiency of neutrons.

Our group has been leading the search for the diffuse supernova neutrino background (DSNB) using the enhanced neutron detection capability of Super-Kamiokande, aiming for the world's first observation of these neutrinos. We are also developing a new calibration method based on neutron captures on gadolinium. Furthermore, we are preparing a nuclear physics experiment to improve our understanding of neutrino-nucleus interactions and enhance the sensitivity of DSNB searches.

Hyper-Kamiokande

The next-generation water Cherenkov detector, Hyper-Kamiokande, is currently under construction. It will significantly extend the reach of neutrino physics and the search for proton decay beyond what is possible with T2K and Super-Kamiokande. Hyper-Kamiokande will feature a cylindrical tank measuring 68 meters in diameter and 71 meters in depth, containing 260,000 tons of ultrapure water. Our group has been leading the design and construction of the Hyper-Kamiokande detector, as well as the performance evaluation of photomultiplier tubes, development of calibration techniques, and studies of readout electronics.

R&D of particle detectors for future experiments

We have been developing new particle detectors for future experiments. One of our focus is the search for neutrinoless double-beta decay with ^{160}Gd, utilizing ultra-high purity Gd technology developed for the SK-Gd project.

7 Yorita Group

Research Subjects: High Energy Particle Physics and Astro-particle physics

Member: Kohei Yorita and Masato Kimura

Our group is engaged in high-energy accelerator experiments, in particular participating in international collaborations at the Large Hadron Collider (LHC) at CERN. Our primary research goals are the precise verification of the Standard Model and the search for new physics beyond it. At the LHC, we test the validity of the Standard Model through precision measurements of the Higgs boson and other heavy particles, while simultaneously pursuing searches for signals of unknown particles. In addition, we develop advanced data analysis techniques to improve event reconstruction and particle identification, as well as work on enhancing detector performance for future experiments. Furthermore, in connection with detector development and evaluation for cosmic dark matter searches, we conduct experimental studies using balloon-borne experiments and accelerator-based beam tests, aiming to validate detector performance under realistic conditions and to advance observational techniques. By adopting a complementary approach that integrates results from accelerator experiments with other observational and experimental methods, we aim to address fundamental open questions in particle physics.

- **High Energy Frontier Experiment**
  Our group participates in the ATLAS experiment and carries out a comprehensive research program ranging from detector operation and performance evaluation to physics analyses, as well as development toward the High-Luminosity LHC (HL-LHC) upgrade. During Run 3, we achieved stable data taking and performed long-term operational studies of the tracking detectors, ensuring robust and reliable detector performance under high-luminosity conditions. We also improved sensitivity and updated limits in searches for new physics using combined Run 2 and Run 3 data. In physics analyses, we conduct precision measurements of the Higgs boson and other heavy particles, and actively search for new phenomena such as supersymmetry and other physics beyond the Standard Model. In parallel, we develop and apply advanced analysis techniques, including deep learning, to enhance event reconstruction and particle identification. We also contribute to the design, development, and mass production of next-generation tracking detectors (ITk) for the HL-LHC, playing a key role in ensuring improved performance in future high-rate environments.

- **Cosmic Dark Matter Search**
  This research is based on liquid argon time projection chamber (LArTPC) technology and is being carried out as a Japan–U.S. collaboration to search for dark matter through observations of antimatter in cosmic rays. This approach is characterized by its ability to precisely measure energy loss and track information of particles in the low-energy region, providing excellent capability for antiparticle identification. In particular, antideuterons in cosmic rays are a promising probe for dark matter searches. While antiparticles produced through conventional cosmic-ray interactions (secondary production) rapidly decrease in flux at low energies, antideuterons produced via annihilation or decay of dark matter particles are predicted to exhibit a relatively enhanced flux in this region. Therefore, observations of low-energy antideuterons provide a clean search channel with high discrimination power against background. This research is being conducted in collaboration with the GRAMS experiment, a balloon-borne experiment, aiming for the world's first high-sensitivity observation of low-energy antideuterons. This effort will enable exploration of previously inaccessible regions in cosmic-ray studies and is expected to provide new constraints on the properties of dark matter or important clues to its existence.

- **Detector R&D**
  We conduct detector R&D spanning both fundamental technologies and their applications to particle physics experiments. This includes the development of superconducting detectors and quantum sensors for ultra-sensitive measurements, as well as advanced readout and reconstruction techniques. In addition, we explore technologies relevant to future facilities, including accelerator development for next-generation collider experiments including muon accelerations, aiming to bridge emerging sensor technologies with large-scale experimental systems.

8 Tsuneyuki Group

Research Subjects: Theoretical Condensed-Matter Physics

Member: Shinji Tsuneyuki and Takahiro Ishikawa

Computer simulations from first principles enable us to investigate the properties and behavior of materials beyond the limits of experiments or predict them before experiments. Our main subject is to develop and apply such computational physics techniques to investigate fundamental problems in condensed matter physics. We primarily focus on predicting material properties under extreme conditions, like ultra-high pressure or at surfaces where experimental data are limited. Our principal tools are molecular dynamics (MD) and first-principles electronic structure calculations based on the density functional theory (DFT). We are also developing new methods that go beyond the limitations of classical MD and DFT to study the electronic, structural, and dynamical properties of materials.

This academic year, we applied a data-assimilation crystal structure search method – which uses powder diffraction experimental data to accelerate the search for crystal structures via simulation – to the structural investigation of the high-pressure phase of yttrium and the high-pressure phase of HCl–H_2 compounds. As a result, we discovered several previously unknown new structures.

To verify the hot superconductivity experimentally reported in lanthanum hydride (La-H) under high pressure, we investigated the high-pressure superconducting phases of the La-N-B-H system at 20 GPa, assuming that nitrogen (N) and boron (B) derived from the hydrogen source ammonium borane react with La-H. This investigation was conducted using evolutionary algorithms, machine learning potentials, and first-principles calculations. As a result, we identified the new compound $LaBH_5$ as a thermodynamically stable compound and predicted that it exhibits superconductivity at $T_c = 29.0$K.

We also investigated the superconducting properties of uniformly hole-doped perovskite-type hydride $KMgH_3$ using first-principles calculations, varying doping concentration and the lattice constant to account for pressures. To calculate the dynamic stability of the crystal lattice and the phonon frequencies, we employed the first-principles self-consistent phonon method developed in our laboratory. Furthermore, we employed superconducting density functional theory (SCDFT) to calculate the superconducting transition temperature, accounting for spin fluctuations that had previously been ignored. As a result, we discovered a significant spin fluctuation (SF) effect in hole-doped $KMgH_3$ that counteracts phonon-mediated pairing and lowers T_c. Similar calculations were performed on various hydrides, revealing that an abnormally strong SF effect is observed in hydrides where the hydrogen 1s band is isolated at the Fermi level. This highlights the importance of accounting for spin fluctuations in the search for superconducting hydrides.

We are also working on calculating the dielectric constants of liquids and polymers in the THz band. Using a machine learning model for chemical bond-based dipole moments developed previously, we performed first-principles calculations on the dielectric properties of liquid propylene glycol (PG) and liquid polypropylene glycol (PPG), demonstrating that the frequency and temperature dependencies of the dielectric function can be accurately calculated even at frequencies below the terahertz range. It was found that the model trained using data from propylene glycol dimers can also be applied to PPG with longer chains not included in the training data. This study represents a first step toward developing a general-purpose dipole model.

In addition, we have developed the DFT-1/2 method for predicting physical properties such as band gaps with minimal computational effort, and proposed a theoretical analytical method for spin dynamics in solids under circularly polarized light.

9 Todo Group

Research Subjects: Simulation algorithms for strongly-correlated systems; Novel states and critical phenomena in strongly correlated systems; Quantum computing and quantum algorithms; Machine learning and statistical mechanics

Members: Synge Todo, Hidemaro Suwa, Tsuyoshi Okubo

To understand complex many-body systems across matter, information, and computation, it is essential to reformulate the many-body Schrödinger equation and the partition functions of statistical mechanics into forms that are computationally tractable while preserving their essential features, such as quantum correlations, symmetries, and geometric structures. We address this challenge by combining tensor networks, Monte Carlo methods, variational principles, machine learning, and quantum algorithms to investigate the principles underlying states, phase transitions, dynamics, and information processing that are shared across a wide range of systems, including strongly correlated electron systems, lattice gauge theories, quantum spin systems, open quantum systems, and quantum devices. We advanced new computational methods based on tensor renormalization group techniques and unbiased sampling, foundational technologies for quantum computing, quantum error correction, and quantum tomography, as well as applications extending to materials science, mathematical finance, and machine learning. We are also developing open-source libraries for next-generation parallel computing.

[1] T. Kobori, Y. Suzuki, Y. Ueno, T. Tanimoto, S. Todo, Y. Tokunaga, LSQCA: Resource-Efficient Load/Store Architecture for Limited-Scale Fault-Tolerant Quantum Computing, 2025 IEEE International Symposium on High Performance Computer Architecture (HPCA) (2025).

[2] K. Harada, T. Okubo, N. Kawashima, Tensor tree learns hidden relational structures in data to construct generative models, Mach. Learn.: Sci. Technol. **6**, 025002 (2025).

[3] K. Murota, T. Kobori, Trainable Quantum Neural Network for Multiclass Image Classification with the Power of Pre-trained Tree Tensor Networks, 2025 IEEE International Conference on Quantum Computing and Engineering (QCE) (2025).

[4] S. Mukherjee, V. Suppakitpaisarn, Local Differential Privacy-Preserving Spectral Clustering for General Graphs, Transactions on Machine Learning Research (2025).

[5] K. Kinjo, R. Sakurai, T. Kishimoto, J. Ohkubo, Permutation of Tensor-Train Cores for Computing Moments on Stochastic Differential Equations, J. Phys. Soc. Jpn. **94**, 084001 (2025).

[6] K. Tamai, T. Okubo, T. V. T. Duy, N. Natori, S. Todo, Universal scaling laws of absorbing phase transitions in artificial deep neural networks, Phys. Rev. Research **7**, 033072 (15pp) (2025).

[7] H. Oike, H. Suwa, Y. Takahashi, F. Kagawa, Thermally quenched metastable phase in the Ising model with competing interactions, Phys. Rev. B **112**, 064409 (2025).

[8] K. Sakaue, H. Shinaoka, R. Sakurai, Adaptive sampling-based optimization of quantics tensor trains for noisy functions: Applications to quantum simulations, SciPost Phys. **19**, 038 (2025).

[9] Y. Motoyama, *et al.*, TeNeS-v2: Enhancement for Real-Time and Finite Temperature Simulations of Quantum Many-Body Systems, Comp. Phys. Commun. **315**, 109692 (2025).

[10] R. Kaneko and S. Goto, Seeding neural network quantum states with tensor network states, Phys. Rev. B **112**, 155163 (2025).

[11] H. Kanno, S. Akiyama, K. Murakami, S. Takeda, Grassmann tensor renormalization group for the massive Schwinger model with a θ term using staggered fermions, J. High Energ. Phys. **2025**, 36 (2025).

[12] T. Kobori, S. Todo, Bayesian inference of general noise-model parameters from the syndrome statistics of surface codes, Phys. Rev. A **112**, 052448 (14pp) (2025).

[13] K. O. Akamatsu, K. Harada, T. Okubo, N. Kawashima, Plastic tensor networks for interpretable generative modeling, Mach. Learn.: Sci. Technol. **7**, 015014 (2026).

[14] Y. Sunada, *et al.*, Efficient tomography of microwave photonic cluster states, Phys. Rev. X Quantum **7**, 010323 (2026).

[15] Y. Sugimoto, S. Akiyama, Y. Kuramashi, Phase structure of (3+1)-dimensional dense two-color QCD at $T = 0$ in the strong coupling limit with tensor renormalization group, Phys. Rev. D **113**, 034503 (2026).

[16] M. Gen, *et al.*, Unified Description of Spin-Lattice Coupling and Thermodynamics in the Pyrochlore Heisenberg Antiferromagnet, Phys. Rev. Lett. **136**, 116702 (2026).

[17] S. Akiyama, *et al.*, Tensor renormalization group approach to critical phenomena via symmetry-twisted partition functions, Phys. Rev. D **113**, 074502 (2026).

10 Katsura Group

Research Subjects: Condensed Matter Theory and Statistical Physics

Member: Hosho Katsura and Hironobu Yoshida

In our group, we conduct theoretical research on fundamental problems in condensed matter and statistical physics, with a particular focus on strongly correlated quantum many-body systems, both in and out of equilibrium. Our goal is to understand and predict novel quantum phases and emergent phenomena that arise in these systems. To this end, we use a combination of analytical and numerical methods. We are currently exploring topics such as (i) low-dimensional correlated systems, (ii) spin and heat transport in localized spin systems, (iii) open quantum many-body systems, (iv) non-ergodic dynamics in non-integrable systems, and (v) exactly solvable models. In addition, we are interested in the mathematical aspects of the above-mentioned fields. Our research projects conducted in FY 2025 are the following:

- Low-dimensional correlated systems
  - η-clustering states in an extended attractive SU(3) Hubbard chain [1]
  - Fate of bosonic topological edge modes in the presence of many-body interactions [2]
- Spin and heat transport in localized spin systems
  - Scalar spin chirality Nernst effect in kagome magnets [3]
  - Magnon-induced scalar spin chirality in kagome and honeycomb ferromagnets [4]
  - Spin Nernst and thermal Hall effects of topological triplons in quantum dimer magnets [5]
- Nonequilibrium quantum dynamics
  - Classification of dark states in SU(3) Fermi-Hubbard models with three-body losses [6]
  - Weak ergodicity breaking in non-integrable models [7]
  - Systematic construction of asymptotic quantum many-body scar states [8]
- Mathematical and statistical physics
  - G_2 Affleck-Kennedy-Lieb-Tasaki chain [9]
  - Quantum circuits with free fermions in disguise [10]
  - Integrability of a family of disorder-free SYK models [11]

[1] H. Yoshida, N. Heinsdorf, and H. Katsura, Phys. Rev. A **111**, 063307 (2025).

[2] N. Heinsdorf, D. G. Joshi, H. Katsura, and A. P. Schnyder, Phys. Rev. Lett. **135**, 146702 (2025) [Selected as Editors' Suggestion].

[3] G. Go, D. Prasad Goli, N. Esaki, Y. Tserkovnyak, and S. K. Kim, Phys. Rev. Research **7**, L022066 (2025).

[4] N. Esaki, G. Go, and S. K. Kim, Phys. Rev. B **112**, 104440 (2025) [Selected as Editors' Suggestion].

[5] N. Esaki, Y. Akagi, K. Penc, and H. Katsura, Phys. Rev. B **112**, 134435 (2025).

[6] A. Marché, A. Nardin, H. Katsura, and L. Mazza, Phys. Rev. Research **7**, 043124 (2025).

[7] H. Katsura, C. Matsui, C. Paletta, and B. Pozsgay, Phys. Rev. Research **7**, 023099 (2025).

[8] M. Kunimi, Y. Kato, and H. Katsura, Phys. Rev. Research **7**, 043107 (2025).

[9] H. Katsura and D. Schuricht, SciPost Phys. Core **8**, 052 (2025).

[10] K. Fukai and B. Pozsgay, J. Phys. A: Math. Theor. **58**, 175202 (2025).

[11] K. Fukai and H. Katsura, Phys. Rev. B **113**, 115107 (2026).

11 Kabashima Group

Research Subjects: Statistical mechanics of disordered systems and its application to information science

Member: Yoshiyuki Kabashima, Takashi Takahashi

We are working in a cross-disciplinary field between statistical mechanics and information science. Our research interests include error-correcting codes, cryptography, CDMA multi-user detection, data compression, compressed sensing, sparse modeling, high-dimensional statistics, probabilistic inference, neural networks, random matrix, machine learning, spin glasses, etc.

The followings are highlights in our research activities in AY 2025:

1. Franz-Parisi Potential Analysis of Random Orthogonal Model
2. Dynamical Mean Field Analysis of Associative Memory Models with Non-monotonic Transfer Function
3. Theoretical Analysis of the Hopfield Model Incorporating the Effects of Unlearning
4. Analysis of Modern Hopfield Model with Ising Spins
5. Analysis of Dynamical Properties of Discrete Diffusion Models
6. Analysis of Discrete-Diffusion-Model-Based Two-dimensional Lattice Protein Design
7. Analysis of Task Difficulty in In-Context Learning
8. Analysis of the Impact of Spurious Correlations and Social Biases on Learning
9. Counting Fixed Points in Randomly Coupled Dynamics Using Grassmann Algebra
10. Dynamical Mean Field Analysis of Alternating Descent for Bilinear Regression
11. Statistical Mechanics Analysis of Learning without Solvability
12. Replica Analysis of Mean-Field Spin Glasses with Correlated Disorder

12 Tsuji Group

Research Subjects: Theory of condensed matter physics, nonequilibrium quantum many-body systems

Member: Naoto Tsuji, Kazuaki Takasan, and Shohei Imai

We are interested in nonequilibrium physics of quantum many-body systems and statistical mechanics. The aim is to realize a new order or new physical property by driving quantum systems out of equilibrium. At first sight, it sounds unlikely to happen because energy injected by an external drive would turn into heat, which would destroy all the interesting properties of quantum many-body systems that might emerge at low energies. However, contrary to our intuition, recent studies have found various possibilities such that novel states of matter that can never be realized in equilibrium do emerge out of equilibrium. We are trying to understand their mechanism and explore the frontier of nonequilibrium condensed matter physics.

In the academic year of 2025, we mainly worked on the following projects:

- Dynamics of superconductors
  - Collective modes in layered superconductors [1]
  - Collective modes in multiband superconductors with Lifshitz invariant [4]

  - Current-enabled optical response of collective modes in unconventional superconductors [5]
  - Nonequilibrium phase transition in periodically driven superconductors [7]
- Dynamics of open quantum many-body systems
  - Quantum active matter
  - Strongly correlated electron systems coupled to quantum electromagnetic fields [6]
- Quantum many-body scar states
- Dynamical response of quantum many-body systems
  - Quantum light-driven many-body dynamics [8]
  - Signature of exciton condensation in topological insulator surface states [2]
- Tensor train methods for quantum many-body problems [3]
- Excitons in strongly correlated materials
- Transport phenomena in quantum many-body systems
  - Hall effect in isolated flat-band systems [9]

[1] N. Ziereis, K. Takasan, N. Tsuji, "Light-driven interlayer propagation of collective-mode excitations in layered superconductors", Phys. Rev. B **111**, 134520 (2025).

[2] R. Mori, K. Takasan, P. Ai, S. Ciocys, K. Kawaguchi, T. Kondo, T. Morimoto, A. Lanzara, "Possible evidence of excitonic condensation in a topological insulator", Proc. Natl. Acad. Sci. U.S.A. **122**, e2422667122.

[3] S. Matsuura, H. Shinaoka, P. Werner, N. Tsuji, "Tensor cross interpolation approach for quantum impurity problems based on the weak-coupling expansion", Phys. Rev. B **111**, 155150 (2025).

[4] R. Nagashima, T. Mouilleron, N. Tsuji, "Optically active Higgs and Leggett modes in multiband pair-density-wave superconductors with Lifshitz invariant", Phys. Rev. B **112**, 024503 (2025).

[5] G. Niederhoff, R. Kataoka, K. Takasan, N. Tsuji, "Current-Enabled Optical Conductivity of Collective Modes in Unconventional Superconductors", Phys. Rev. B **112**, 144507 (2025).

[6] T. Nakamoto, K. Takasan, N. Tsuji, "One-dimensional extended Hubbard model coupled with an optical cavity", Phys. Rev. B **112**, 155150 (2025).

[7] H. Zhang, K. Takasan, N. Tsuji, "Nonequilibrium hysteretic phase transitions in periodically light-driven superconductors", Phys. Rev. B **112**, L220503 (2025).

[8] S. Imai, "Macroscopic Schrödinger-cat states of nonequilibrium electrons induced by cat-state optical driving and projective measurements on the light field", Phys. Rev. A **113**, 023702 (2026).

[9] R. Nagashima, M. Ogata, N. Tsuji, "Hall effect in topologically trivial isolated flat-band systems", Phys. Rev. Research **8**, L012041 (2026).

13 Ashida Group

Research Subjects: Condensed matter theory, Theoretical quantum information/optics

Member: Yuto Ashida and Kazuki Yokomizo

This group focuses on theoretical studies at the intersection of quantum many-body physics and quantum information/optics. We have been studying the physics of open and out-of-equilibrium systems, where quantum systems interact with the external world and thus feature nonunitary dynamics. We employ the ideas/methods, including field theory, renormalization group, topology, and variational approach. In addition, we are interested in physical phenomena in the corresponding classical systems and their potential applications. We have also been doing studies related to machine learning and physics. We list research/review papers published in the academic year of 2025 below.

- Open quantum systems [1, 2, 5, 7, 8, 9]
- Non-Hermitian systems [3, 4, 6]

[1] M. Hoshino, M. Oshikawa, and Y. Ashida, Entanglement swapping in critical quantum spin chains, Physical Review B **111**, 155143 (2025).

[2] K. Yokomizo and Y. Ashida, Measurement-induced phase transition in free bosons, Physical Review B **111**, 235419 (2025) [Editors' Suggestion].

[3] Gauge theory for topological waves in continuum fluids with odd viscosity, SciPost Phys. Core **8**, 058 (2025).

[4] T. Yoda, Y. Moritake, K. Takata, K. Yokomizo, S. Murakami, and M. Notomi, Optical non-Hermitian skin effect in uniform media, Physical Review Research **7**, 033214 (2025).

[5] Y. Guo, S. Yang, and X.-J. Yu, Quantum Strong-To-Weak Spontaneous Symmetry Breaking in Decohered One-Dimensional Critical States, PRX Quantum **6**, 040311 (2025).

[6] K. Sone, K. Yokomizo, K. Kawaguchi, and Y. Ashida, Hermitian and non-Hermitian topology in active matter, Reports on Progress in Physics **89**, 016501 (2026).

[7] Y. Guo and Y. Ashida, Tower of Structured Excited States from Measurements, Physical Review Letters **136**, 050604 (2026).

[8] M. Hoshino, M. Oshikawa, and Y. Ashida, Stabilizer Rényi Entropy and Conformal Field Theory, Physical Review X **16**, 011037 (2026).

[9] M. Hoshino and Y. Ashida, Stabilizer Rényi entropy encodes fusion rules of topological defects and boundaries, Physical Review Letters **136**, 080402 (2026).

14 Arita Group

Research Subjects: first-principles calculation, superconductivity, magnetism,
topological phenomena, optoelectronic phenomena

Member: Ryotaro Arita, Taisei Kitamura

Research Overview of Our Laboratory

Our group explores quantum materials through theoretical and first-principles studies. We investigate magnetism, superconductivity, structural transitions, and topological phenomena by combining computational techniques with symmetry and model analysis. Our goal is to understand the microscopic origin of complex material properties and contribute to the discovery of new functional materials.

Studies on Bilayer Nickelate Superconductors: Nickel oxides have emerged as a third class of high-temperature superconductors, alongside cuprates and iron-based systems. In particular, bilayer nickelates show superconductivity near 100 K, motivating studies of their mechanism. We determined the temperature–pressure phase diagram of the crystal structure using a finite-temperature optimization method. We also studied superconductivity using a bilayer Hubbard model with cluster dynamical mean-field theory, revealing pseudogap formation, kinetic-energy-driven pairing, and a short coherence length.

Hidden Spin Textures in Antiferromagnets: We classified collinear antiferromagnets using spin space group theory and discovered hidden alternating spin splittings in systems with time-reversal symmetry. These textures arise from non-trivial symmetry breaking and may induce multiferroic and nonlinear transport responses.

Revealing Hidden Symmetries in Materials via Circularly Polarized Raman Spectroscopy: Material properties are governed by symmetry, yet crucial symmetries are often hidden. By analyzing Raman activity under different polarization configurations, we clarify the relationship between observed signals and hidden symmetry breaking.

Dirac Charge and Its Detection in Antiferromagnetic Topological Semimetals: Topological semimetals host protected band degeneracies, such as Dirac and Weyl points, whose nontrivial topology leads to unique optical phenomena. While Weyl semimetals exhibit quantized injection currents linked to Weyl charges, we reveal a hidden "Dirac charge" in antiferromagnetic Dirac semimetals. Using Berry curvature defined in spin and spin–charge mixed parameter spaces, the Dirac charge is identified as a source or sink in a generalized parameter space. Real-time simulations demonstrate that this emergent charge significantly contributes to photocurrent generation, providing a measurable signature of its existence.

Euler Class and Rotational Symmetry in Three-Dimensional Spinless Systems: We explore the relation between the Euler class and rotational symmetries in spinless systems with $C_{2z}T$ symmetry. We analyze how real Berry curvature transforms under point group operations and derive formulas relating the Euler class and rotation eigenvalues and other symmetry-protected invariants. Extending to 3D, we clarify differences between C_{4z} and C_{6z} cases and incorporate mirror symmetry. Our results predict new topological phases, confirmed by Wilson-loop and surface-state calculations on tight-binding models.

Effective Spin Interactions from First Principles: To construct low-energy effective spin models for complex magnetic materials, we developed a method combining the spin cluster expansion with the disordered local moment approach, enabling systematic evaluation of both conventional and higher-order spin interactions. By alleviating the limitations of basis functions in DFT, we showed that the method can be extended to a wide range of materials.

Our work bridges material-specific predictions with fundamental theory. By developing practical methods and uncovering new physical principles, we aim to support the advancement of electronics, spintronics, and quantum technologies.

15 Hasegawa Group

Research Subject: Experimental Surface/Nano Physics

Members: Shuji HASEGAWA and Ryota AKIYAMA

Surfaces/interfaces of materials and atomic-layer materials are platforms of our research where rich physics is expected due to the low-dimensionality, symmetry breaking, a wide variety of atomic structures, and direct access for measurements. (1) Charge/spin/mass transports including superconductivity and spin current, (2) atomic/electronic structures, (3) phase transitions, (4) spin states and spintronics, and (5) epitaxial growths of coherent atomic/molecular layers/wires on surfaces of metals, semiconductors, topological materials, and nano-scale phases such as surface superstructures, ultra-thin films including atomic-layer materials such as graphene and transition metal dichalcogenides. We use various kinds of ultrahigh-vacuum experimental techniques, such as electron diffraction, scanning electron microscopy(SEM), scanning tunneling microscopy/spectroscopy (STM/S), photoemission spectroscopy(PES), *in-situ* four-point-probe conductivity measurements with four-tip STM and monolithic micro-four-point probes, and surface magneto-optical effects apparatuses. Ex situ measurements of physical Properties are also combined when the surface and thinh films are not degraded by air exposure. Main results in this year are as follows.

(1) Surface transport and magnetism:

- Anomalous Hall effect at sandwich structures consisted of magnetic topological insulators and topological crystalline insulator
- 2D superconductivity at α-Sn layers on a topological crystalline insulator and metal-atoms intercalted graphene
- Non-reciprocal photocurrent at Rashba surfaces induced by irradiation of circularly polarized light
- Ferromagnetism and superconductivity at Yb-intercalated graphene
- Conductivity of highly N-doped surface layer on SiC crystal
- Epitaxial growth of "quasi-crystal" bilayer graphene and its transport property

(2) New methods:

- Fabrication of a four-point probe UHV system with tunneling spectroscopy and quantum Shot noise measurements
- Development of probes for spin injection and spin detection

- Fabrication of a UHV-MBE system with polarization-controlled mid-infrared irradiation

[1] R. Hobara, R. Akiyama, and S. Hasegawa: *Boron-Assisted Epitaxial Growth of Buffer-Layer-Free Graphene on the Si-face of SiC without* 30^{circ} *Rotation*, ACS Applied Electronic Materials **8** (6), 2225-2233 (Mar, 2026).

[2] T. Takashiro, R. Akiyama, R. Minakawa, and S. Hasegawa: *Beyond Superexchange: Emergent Unconventional Ferromagnetism in Thin-Film Sandwich Structures of Intrinsic Magnetic Topological Insulators*, arXiv:2508.14993 (Aug, 2025).

[3] R. Akiyama, S. Sato, Y. Miyai, Y. Hashimoto, J. Jung, R. Hobara, Y. Kumar, A. Kumar, S. Shimizu, R. Minakawa, Y. Yamamoto, H. Tomita, T. Tadamura, T. Moriki, Y. Yamada, S. Ideta, K. Shimada, T. Matsushita, S. Hasegawa: *Superconductivity in graphene induced by atomic intercalation*, Journal of the Ceramic Society of Japan **133** (9), 508-514 (Aug, 2025).

16 Okamoto Group

Research Subjects: Experimental Condensed Matter Physics,

Low temperature electronic properties of two-dimensional systems.

Member: Tohru Okamoto and Ryuichi Masutomi

We study low temperature electronic properties of two-dimensional systems.
The current topics are following:

1. Two dimensional electrons at cleaved semiconductor surfaces:
   At the surfaces of InAs and InSb, conduction electrons can be induced by submonolayer deposition of other materials. Recently, we have performed in-plane magnetotransport measurements on in-situ cleaved surfaces of p-type substrates and observed the quantum Hall effect which demonstrates the perfect two dimensionality of the inversion layers. Research on the hybrid system of 2D electrons and adsorbed atoms has great future potential because of the variety of the adsorbates and the application of scanning probe microscopy techniques.

   To explore exotic physical phenomena related to spin at a semiconductor surface, magnetic-adatom induced two dimensional electron systems are investigated by using low-temperature scanning tunneling microscopy and spectroscopy combined with transport measurements.

2. Superconductivity of monolayer films on cleaved GaAs surfaces:
   Recently, we studied the effect of the parallel magnetic field $H_{\|}$ on superconductivity of monolayer Pb films on GaAs(110). Superconductivity was found to occur even for $H_{\|} = 14$ T, which is much higher than the Pauli paramagnetic limiting field H_P. The observed weak $H_{\|}$ dependence of the superconducting transition temperature T_c is explained in terms of an inhomogeneous superconducting state predicted for 2D metals with a large Rashba spin splitting.

   Low-temperature electrical resistivity measurements have been performed for superconducting ultrathin films on semiconductor surfaces in the presence of an in-plane magnetic field. For ultrathin In films grown on the cleaved surface of GaAs or InAs, the second harmonic magnetoresistance $R^{2\omega}$ exhibited antisymmetric behavior with respect to the direction of the in-plane magnetic field, while $R^{2\omega}$ was almost zero for ultrathin Al films whose the spin-orbit interaction is considered to be negligibly small. These results indicate that nonreciprocal charge transport occurs in the superconducting ultrathin indium films grown on semiconductor surfaces.

17 Shimano Group

Research Subjects: Optical and Terahertz Spectroscopy of Condensed Matter

Member: Ryo Shimano and Naotaka Yoshikawa

We study light-matter interactions and many body quantum correlations in solids, aiming at light-control of many-body quantum phases. In order to investigate the role of electron and/or spin correlations in the excited states as well as in the ground states, we focus on the low energy electromagnetic responses, in particular in the terahertz(THz) (1 THz∼4 meV) frequency range where various quasi-particle excitations and various collective excitations exist. The research topics in FY2025 are as follows.

1. **Nonlinear terahertz spectroscoy in high-T_c cuprate superconductors:** We performed nonlinear terahertz spectroscopy of cuprate superconductors, $La_{1.6-x-y}Nd_ySr_xCuO_4$ to elucidate the interplay between the stripe order and the superconductivity. In particular we applied a two-dimensional terahertz spectroscopy scheme to identify the c-axis Josephson couplings in those La214 compounds. Nonlinear signals origicated from the Josephson current along c-axis were identified in the stripe-ordered superconducting cuprates.

2. **Floquet engineering of Dirac electron systems:** We have aimed at realizing Floquet states in Dirac electron system in thin films of $Co_3Sn_2S_2$. Upon the irradiation of circular polarized mid-infrared light pulses, we observed the light-induced anomalous Hall effect as manifested by the transient Faraday rotation signal in the terahertz frequency range. A cmprehensive frequency dependence masurements revealed that the light-induced optical Hall conductivity is scaled as $1/\omega^3$ against the driving frequency ω, in accordance with the Floquet theory that predicts the light-induced chiral gauge field associated with the Floquet-Weyl state.

3. **Ultrafast time-resolved observation of current-induced magnetization switchng in a non-colinear antiferromagnet Mn_3Sn:** We successfully visualized the current-induced switching dynamics in a non-colinear antiferromagnet Mn_3Sn by ultrafast time-resolved magneto-optical microscope imaging technique. Dependending on the current density and the pulse duration, we have revealed the two distinct switching regimes: a non-thermal process that occurs without the transient melting of antiferromagnetic order, and a thermal-assisted process that accomodates with heating above the magnetic ordering temperature. Our work paves a way to ultrafast magnetic recording using noncolinear antiferromagnets.

References

[1] Naotaka Yoshikawa, Shun Okumura, Yoshua Hirai, Kazuma Ogawa, Kohei Fujiwara, Junya Ikeda, Akihiro Ozawa, Takashi Koretsune, Ryotaro Arita, Aditi Mitra, Atsushi Tsukazaki, Takashi Oka, Ryo Shimano: Light-induced anomalous Hall conductivity in the massive three-dimensional Dirac semimetal $Co_3Sn_2S_2$, Phys. Rev. B **111**, 245104 (2025). (Editors' suggestion)

[2] Kota Katsumi, Yann Gallais, Ryo Shimano: Distinct terahertz nonlinear and Raman responses in cuprate superconductors $Bi_2Sr_2CaCu_2O_{8+x}$, npj Quantum Materials **10**, 91 (2025).

[3] Naotaka Yoshikawa, Kazuma Ogawa, and Ryo Shimano: All-optical switching in ferromagnets and its application to magnetic Weyl semimetals, J. Phys. Soc. Jpn. **94**, 111005 (2025).(invited review article)

[4] Daichi Yoshioka, Fumiya Sekiguchi, Naotaka Yoshikawa, and Ryo Shimano: On-Chip Terahertz Pump–Probe Spectroscopy Revealing Ultrafast Current-Induced Breakdown Dynamics in a Superconducting Nb Microstrip, Nano Letters **25**, 13764 (2025).

[5] Kazuma Ogawa, Hanshen Tsai, Naotaka Yoshikawa, Takumi Matsuo, Yutaro Tsushima, Mihiro Asakura, Hanyi Peng, Takuya Matsuda, Tomoya Higo, Satoru Nakatsuji and Ryo Shimano: Ultrafast time-resolved observation of non-thermal current-induced switching in an antiferromagnetic Weyl semimetal, Nature Materials **25**, 434 (2026).

18 Hayashi Group

Research Subjects: Condensed matter physics

Member: Masamitsu Hayashi, Masashi Kawaguchi

In solids, it is understood that the spin angular momentum of electrons plays an important role in, for example, magnetism, superconductivity, electrical transport and optical properties of solids. In addition to electrons and photons, magnons (magnetic excitation), phonons (lattice vibration), and other excitations in solids possess spin angular momentum. We want to understand the dynamics of particles and waves with spin and how they influence the physical properties of solids.

- Spin transport properties
  - Electron-magnon scattering induced anomalous Hall effect in a layered ferromagnet[2]
  A layered ferromagnet Cr_2Te_3 is attracting growing interest because of its unique electronic and magnetic properties. Studies have shown that it exhibits sizable anomalous Hall effect (AHE) that changes sign with temperature. The origin of the AHE and the sign change, however, remains elusive. We show experimentally that electron-magnon scattering significantly contributes to the AHE in Cr_2Te_3 through magnon induced skew scattering, and that the sign change is caused by the competition with the Berry-curvature or impurity-induced side-jump contribution. The electron-magnon skew scattering is expected to arise from the exchange interaction between the itinerant Te *p*-electrons and the localized Cr *d*-electrons modified by the strong spin-orbit coupling on Te. These results suggest that the magnon-induced skew scattering can dominate the AHE in layered ferromagnets with heavy elements.

- Strong coupling in solids
  - Phonon modes of surface acoustic waves[3]
  Magnon-phonon coupling has garnered increasing interest in condensed matter physics due to its rich physics and potentials for applications in devices with novel functionalities. Surface acoustic waves (SAWs) are widely used to generate coherent acoustic phonons, with magnetoelastic and magnetorotation interactions often mediating the coupling between magnons and phonons. Since these interactions are governed by the strain and rotational fields of the lattice, both of which depend on the material properties and SAW device structure, understanding their behavior is essential. However, conventional SAW devices are built on anisotropic piezoelectric substrates, such as $LiNbO_3$, making experimental analyses and modeling challenging. We present a numerical analysis of SAWs on Y-cut and Y+128°-cut $LiNbO_3$ substrates. Key parameters, including SAW velocity, excitation efficiency, lattice displacement, strain, and rotation, are numerically calculated against the SAW propagation direction relative to the crystal axes and the electrical boundary conditions at the substrate surface. The in-plane shear strain, which contributes to phononic angular momentum, reaches nearly half the amplitude of the longitudinal strain when SAWs propagate at ±45° from the crystal X-axis on Y+128°-cut $LiNbO_3$. The out-of-plane shear strain, relevant to nonreciprocal SAW transmission via magnetoelastic coupling, can be either enhanced or suppressed depending on the surface condition. Additionally, we find that the out-of-plane rotational field, which mediates magnetorotation coupling in systems with perpendicular magnetic anisotropy, can exceed the longitudinal strain by nearly a factor of three. These findings provide useful reference for designing experiments on magnon-phonon coupling and help designing advanced magnonic and phononic devices.

- Non-linear optical properties of solids
  - Laser induced writing of optic axis[1]
  Tellurium (Te), a two-dimensional material with pronounced structural anisotropy, exhibits exceptional electrical and optical properties that are highly sensitive to its crystallographic orientation. However, conventional synthesis offer limited control over the in-plane alignment of Te's crystallographic *c*-axis, hindering large-scale integration. We report a fundamentally different strategy to manipulate the *c*-axis orientation of Te thin films using linearly polarized picosecond laser pulses. We show that the *c*-axis can be omnidirectionally reoriented perpendicular to the laser polarization, even in initially polycrystalline films. The reorientation is reversible, allowing for rewritable and spatially selective control of the *c*-axis orientation post-deposition. This light-driven approach opens path for intereconfigurable optoelectronic and photonic devices, such as active metasurfaces and CMOS-compatible architectures.

[1] Y. Kobayashi, A. Mitsuzuka, H. Kondo, M. Shoshin, J. Uzuhashi, T. Ohkubo, M. Hayashi, M. Kawaguchi, Light-Programmable Reorientation of the Crystallographic c Axis of Tellurium Thin Films. Nano Lett. 26, 104 (2026).

[2] Y. Wang, S. Wang, M. Kawaguchi, J. Uzuhashi, A. K. Patel, K. Nawa, Y. Sakuraba, T. Ohkubo, H. Kohno, M. Hayashi, Significant electron-magnon scattering in layered ferromagnet Cr_2Te_3. Comm. Phys. 8, 262 (2025).

[3] T. Kawada, M. Kawaguchi, H. Matsumoto, M. Hayashi, Model calculations of lattice strains and rotations associated with surface acoustic waves J. Appl. Phys. 138, 053905 (2025).

[4] M. Yunokizaki, Y. Hibino, H. Idzuchi, H. Tsai, M. Ishibashi, S. Miwa, M. Hayashi, S. Nakatsuji, Tunneling magnetoresistance and spin-orbit torque magnetization switching in ferrimagnetic Gd-Fe-Co based magnetic tunnel junction. Jpn. J. Appl. Phys. 64, 010904 (2025).

19 Kobayashi Group

Research Subjects: Quantum sensing and mesoscopic physics

Member: Kensuke Kobayashi and Kento Sasaki

The advancement of nanotechnology since the 1980s has led to the development of mesoscopic physics, which studies the properties of matter using miniature electronic circuits composed of semiconductors, metals, superconductors, and magnetic materials. Progress in this field has opened up new avenues for various quantum technologies. Among them, quantum sensing, a precision measurement technique grounded in the principles of quantum mechanics, has emerged as a promising approach. Our research aims to establish a new framework for precision condensed matter physics based on quantum sensing.

We focus on quantum sensors based on color centers, such as nitrogen vacancy (NV) centers in diamond and boron vacancies in hexagonal boron nitride (hBN). We are developing quantum spin microscopy for various quantum sensing applications. This technique enables quantitative imaging of magnetic field and temperature distributions at submicron scales under a wide range of magnetic field, temperature, and pressure conditions. Such a capability has been challenging to achieve in the field of condensed matter physics. This approach holds promise for exploring various compelling topics, including non-equilibrium transport, spin glasses, and topological edge states.

The primary research topics in FY2025 are as follows.

- Wideband wide-field imaging of spin-wave propagation using diamond quantum sensors [1]
- Systematic investigation of dynamic nuclear polarization with boron vacancy in hexagonal boron nitride [2]
- Investigations of optical aberrations in quantum diamond microscopy toward high spatial resolution and sensitivity [3]
- Observation of chiral domain walls in an octupole-ordered antiferromagnet [4]
- GPa Pressure Imaging Using Nanodiamond Quantum Sensors [5]
- Quantitative imaging of nonlinear spin-wave propagation using diamond quantum sensors [6]

Published papers:

[1] K. Ogawa, M. Tsukamoto, Y. Mori, D. Takafuji, J. Shiogai, K. Ueda, J. Matsuno, K. Sasaki, K. Kobayashi, *Physical Review Applied* **23**, 054001/1–22 (2025).

[2] Y. Nakamura, S. Nishimura, T. Iwasaki, S. Nakaharai, S. Ogawa, Y. Morita, K. Watanabe, T. Taniguchi, K. Sasaki, K. Kobayashi, *Physical Review B* **111**, 195404/1–14 (2025) [Editors' Suggestion].

[3] S. Nishimura, M. Tsukamoto, K. Sasaki, K. Kobayashi, *Review of Scientific Instruments* **96**, 053706/1–17 (2025).

[4] M. Tsukamoto, Z. Xu, T. Higo, K. Kondou, K. Sasaki, M. Asakura, S. Sakamoto, P. Gambardella, S. Miwa, Y. Otani, S. Nakatsuji, C. L. Degen, K. Kobayashi, *Physical Review B* **112**, L020404/1–7 (2025) [Editors' Suggestion].

[5] R. Suda, K. Uriu, K. Yamamoto, M. Sasaki, K. Sasaki, M. Einaga, K. Shimizu, K. Kobayashi, *Journal of the Physical Society of Japan* **94**, 124707/1–9 (2025) [Papers of Editors' Choice].

[6] K. Ogawa, M. Tsukamoto, Y. Mori, D. Takafuji, J. Shiogai, K. Ueda, J. Matsuno, Jun-ichiro Ohe, K. Sasaki, K. Kobayashi, *Physical Review B* **112**, 224411/1–11 (2025).

20 Nakatsuji-Sakai Group

Research Subjects: Condensed Matter Experiment

Member: Satoru Nakatsuji and Akito Sakai

Our research group is advancing a new phase in quantum materials science, where fundamental discoveries are increasingly connected with emerging quantum technologies through interdisciplinary collaboration. We focus on the design, synthesis, and characterization of quantum materials that exhibit novel macroscopic properties. These materials are integrated into thin-film-based devices, enabling us to probe novel quantum functionalities and assess their technological potential. By forging direct links between quantum phenomena and practical applications, our mission is to lead the creation of material platforms that drive both scientific discovery and innovation in computing, sensing, and energy-saving technologies.

Major research themes:
1. Quantum transport in magnetic topological materials
2. Coherent quantum spin transport in antiferromagnetic spintronics
3. Strange metal and exotic superconductivity in strongly correlated electron systems

Summary of research subjects in 2025

1. Isothermal control of exchange bias effect in ferromagnet/Mn_3Sn [1]
The exchange bias effect observed at the interface between a ferromagnet and an antiferromagnet is widely used in spintronics research. However, its manipulation typically requires raising the temperature and field cooling. Its manipulation without any temperature change has been achieved by several methods, including spin–orbit torque switching and electrical control of magnetoelectric antiferromagnets. In this study, we used the Weyl antiferromagnet Mn_3Sn, with broken macroscopic time-reversal symmetry, as the antiferromagnetic layer to improve the controllability of the exchange bias effect [1]. We synthesized a Py($Ni_{80}Fe_{20}$)/Mn_3Sn bilayer and demonstrated that the exchange bias effect can be controlled by isothermal application of a magnetic field, in addition to the conventional field cooling process. The interfacial coupling aligns the magnetization of Py antiparallel to the magnetic octupole order of Mn_3Sn; however, when the Py layer is replaced with Co, the coupling becomes ferroic.

2. Time-resolved observation of ultra-fast current-induced switching in Weyl antiferromagnet Mn_3Sn [2]
Recently, the electrical manipulation of the antiferromagnetic Weyl semimetal Mn_3Sn has attracted significant attention due to its potential for spintronics applications. On the other hand, there is an ongoing debate over whether the current switching of Mn_3Sn is dominated by joule heating, which limits the switching speed to nanosecond timescales, or by non-thermal spin-orbit torque-induced switching with picosecond-scale dynamics. To clarify the exact switching speed and the underlying spin dynamics, we directly observe the switching process using time-resolved magnetic domain imaging. We visualized the micrometer-scale magnetic domain structure of Ta/Mn_3Sn polycrystalline thin films using magneto-optical imaging with a femtosecond-pulsed laser and observed magnetization switching dynamics during sub-ns current-pulse injection. As a result, we demonstrate that the switching speed is comparable to the pulse duration and that a non-thermal switching process occurs, in which the magnetic octupole reverses while the antiferromagnetic order is preserved.

3. Demonstrating two distinct mechanisms behind antiferromagnetic SOT switching [3]
Spin–orbit torque (SOT) switching of antiferromagnetic order is predicted to occur on picosecond timescales, two to three orders of magnitude faster than ferromagnets, due to the terahertz dynamics of antiferromagnets. However, Joule heating during SOT can raise the material above its Néel temperature, triggering a slower, temperature-assisted switching mechanism occurring over tens of nanoseconds. Our study shows a crossover of the SOT switching mechanism in Mn_3Sn, a chiral antiferromagnet, as a function of thickness[1]. Thicker devices exhibit heating-dominated, slow switching. Reducing device thickness suppresses heating, preserves magnetic order, and enables faster, intrinsic SOT-driven switching with shorter current pulses. This study provides design principles for achieving high-speed, energy-efficient antiferromagnetic memory devices.

4. Tuning the transition temperatures and transport properties of antichiral antiferromagnetic Mn_3X thin films via doping [4]

The family of antichiral antiferromagnets Mn_3X (X=Sn, Ge, Ga) exhibits large responses, similar to ferromagnets, such as the anomalous Hall effect, despite their vanishingly small magnetization, which originates from magnetic Weyl points in their band structure. In this study, we investigate the effects of composition in sputtered $Mn_3Sn_{1-x}Ga_x$ thin films and show that the Néel temperature can be tuned between 420 K and 500 K as a function of doping, i.e., the Fermi energy, as well as the anomalous Hall conductivity between 10 S/cm and 75 S/cm at 300 K[2]. We also found that the magnetic phase transition from the antichiral antiferromagnet to a helical phase present in Mn_3Sn can be suppressed by Ga doping. This study provides insights into the optimization of the Mn_3X materials for device applications.

5. Multipole-drive superconductivity in $PrTi_2Al_{20}$ [5]
Since the discovery of unconventional superconductivity in the early 20th century, expanding the landscape and understanding its mechanism have been central themes in quantum materials research worldwide. The ultimate goal of realizing superconductivity at room temperature and under everyday conditions can revolutionize today's technologies, from electrical grids with no loss and new computing techniques to ultra-fast, energy-efficient transportation. Recent research has extensively explored the link between superconductivity and the coexistence of ordered states beyond conventional long-range spin order, generating significant interest. In this study, we focus on $PrTi_2Al_{20}$, which provides a unique and fascinating platform to explore how high-rank multipoles can generate superconductivity in the absence of spin degrees of freedom. We comprehensively characterized the superconducting state through highly challenging thermodynamic experiments, uncovering key insights into the superconducting pairing symmetry. Through La-doping, we identified an intimate link between the multipolar order parameter and superconducting pairing symmetry via chemical tuning, revealing a phase diagram that contrasts sharply with that of the extensively studied spin-fluctuation-driven superconductors. This study is a crucial step in characterizing and showcasing the unique properties of multipole-driven superconductivity.

6. Zero-Field Hall Effect in a Strange Metal State of a Collinear Antiferromagnet $V_{1/3}NbS_2$ [6]
The interplay between strong electronic correlations and nontrivial band topology is opening new frontiers in quantum materials, enabling emergent properties and functionalities in magnetic systems. Transition metal dichalcogenides (TMDs) have emerged as a powerful platform in this direction. In their two-dimensional (2D) form, TMD heterostructures host exotic topological phases and offer exceptional tunability, enabling systematic exploration of key quantum phenomena, such as non-Fermi-liquid behavior and unconventional superconductivity. Intercalating magnetic transition-metal ions into van der Waals TMDs provides an effective means to tune the carrier density and engineer band topology, analogous to electrostatic gating in 2D systems. These magnetically intercalated compounds exhibit a rich interplay between magnetism and correlated electron physics, offering new opportunities for realizing novel quantum functionalities.

In this study, we discovered a striking magnetization-free anomalous Hall effect (AHE) in the collinear antiferromagnet V-intercalated NbS_2, emerging in a non-Fermi-liquid regime where quasiparticles break down. This result reveals an intimate connection between strong correlations and topological electronic structure. The magnetization-free AHE, driven by Berry curvature acting as an effective magnetic field in momentum space, has previously been associated mainly with noncollinear antiferromagnets. Its realization in a collinear system significantly broadens the scope of topological antiferromagnetism and its potential applications.

[1] M. Asakura, T. Higo, T. Matsuo, Y. Tsushima, S. Kurosawa, R. Uesugi, D. Nishio-Hamane, S. Nakatsuji "Magnetic field switching of exchange bias in a metallic FM/AFM heterostructure at room temperature" Nano Lett. **25**, 10294 (2025).

[2] K. Ogawa, H. Tsai, N. Yoshikawa, T. Matsuo, Y. Tsushima, M. Asakura, H. Peng, T. Matsuda, T. Higo, S. Nakatsuji, R. Shimano "Ultrafast time-resolved observation of non-thermal current-induced switching in an antiferromagnetic Weyl semimetal" Nat. Mater. **25**, 434–439 (2026).

[3] T. Matsuo, T. Higo, D. Nishio-Hamane, T. Matsuda, R. Uesugi, H. Tsai, K. Kondou, S. Miwa, Y. Otani, and S. Nakatsuji. "Crossover between intrinsic and temperature-assisted regimes in spin-orbit torque switching of antiferromagnetic order" arXiv:2510.27138v2

[4] M. Raju, T. Matsuo, M. B. Balkew, D. Nishio-Hamane, T. Higo, C. Broholm, S. Nakatsuji "Tunable high Néel temperature and large anomalous Hall response in antiferromagnetic Weyl semimetal Mn_3Sn1-xGax thin films" Commun. Mater. **6**, 205 (2025).

[5] A. Sakai, Y. Matsumoto, M. Fu, T. Isomae, M. Tsujimoto, E. O' Farrell, D. Nishio-Hamane, S. Nakatsuji

"Interplay between multipolar order and multipole-induced superconductivity in $PrTi_2Al_{20}$" Nature Communications **16**, 2114 (2025).

[6] M. K. Ray, M. Fu, *et al.*, "Zero-field Hall effect emerging from a non-Fermi liquid in a collinear antiferromagnet $V_{1/3}NbS_2$" Nat. Commun. **16**, 3532 (2025).

21 Zhang Group

Research Subjects: Condensed mater physics of nanomaterials

Member: Yijin Zhang

We are experimentally studying condensed matter physics using low-dimensional nanomaterials such as graphene and nanotubes, by taking advantage of easy structural controllability of nanomateirals. Our main research progresses in AY2025 are related to bulk photovoltaic effect and one-dimensional moiré superlattice.

The bulk photovoltaic effect (BPVE) is one of the nonlinear optical response, which can convert optical power to electrical power without need of *p*-*n* junction. BPVE has been studied in ferroelectric materials such as $BaTiO_3$ for a long time, but was discovered in WS_2 nanotube in 2019 followed by reports in various nanomaterials. We had adopted nanoscroll structure of Janus TMD. Janus TMD is a unique group of transition metal dichalcogenides (TMDs) in which the transition metal atom is sandwiched by two distinct chalcogen atoms from top and bottom. This structural anisotropy induces a strain that works as a driving force rolling up the two-dimensional sheet to form one-dimensional tubular nanoscroll, resembling nanotubes. We fabricated devices using Janus MoSSe nanoscroll and succeeded in observing BPVE. In addition, we had experimentally confirmed that nanoscroll structure plays an important role in inducing BPVE. Compared to nanotubes, nanoscrolls are superior in the sense that local chirality are identical in all layers. Thanks to this feature, the quantum efficieny in our devices was at best one order of magnitude larger than that of nanotubes reported before.

The second achievement was based on the van der Waals assembly technique. When two-dimensional materials are stacked together with lattice mismatch, a long-rage interference pattern called moiré superlattice emerges. For homobilayers, in which two identical mateirals are stacked together, the moiré superlattice has been investigated in small twist angle region only. This is because the fundamental theoretical understanding of moiré superlattice predicts monotonic decrease of size of moiré superlattice and disappearance around 30°. In stark contrast, we found that moiré superlattice reappear around 60° in twisted bilayer WTe_2. Interestingly, the moiré superlattice becomes stripe patterns around 62 and 58° [6]. We further theoretically verified that the moiré periodicity can be defined only along one direction at these two critical angles, mathematically being one-dimensional. It is found that a mirror symmetry in the constituent materials is important to reduce the dimensionality in moiré superlattice, which largely limits candidate materials to rectangular and centered rectangular lattices. To overcome this ristriction, we proposed racemic van der Waals assembly to stack two flakes with opposite planar-chirality. This method creates mirror symmetry in plane projected homobilayers composed of materials without mirror symmetry. Based on this concept, we succeeded in realizing reducing dimesionality in moiré superlattice made from $ReSe_2$ with oblique lattice [1].

[1] X. Yang, Y. J. Zhang, K. Sato, A. Nishimura, M. Nakashima, L. Chen, K.Aso, M. Onodera, R. Moriya, K. Watanabe, T. Taniguchi, T. Kawakami, N. Nakatsuji, M. Koshino, Y. Yamada-Takamura, Y. Oshima, T. Machida1, "Racemic van der Waals Assembly of Planar-Chiral 2D Materials for Intrinsic One-Dimensional Moiré Superlattices", *ACS Nano*, In press.

[2] A. Nishimura, K. Kinoshita, R. Moriya, Y. Seo, M. Onodera, Y. J. Zhang, K. Watanabe, T. Taniguchi, T. Sasagawa, T. Machida, "Negative differential resistance in $ReSe_2$/*h*-BN/$ReSe_2$ van der Waals tunnel junction", *Appl. Phys. Lett.* **127**, 213101 (2025).

[3] K. Kuruma, M. Onodera, S. Takahashi, I. Takahashi, Y. J. Zhang, T. Machida, Y. Ozeki, "Stimulated Raman Scattering Imaging of Atomically Thin Layers and a Strained Nanotent of Hexagonal Boron Nitride", *Nanoscale* **17**, 26454 (2025).

[4] K. Kinoshita, R. Moriya, M. Onodera, Y. J. Zhang, K. Watanabe, T. Taniguchi, T. Sasagawa, T. Machida, "Resonant Tunneling in WSe_2/*h*-BN/WSe_2/*h*-BN/WSe_2 van der Waals Triple Quantum Well Device" , *ACS Nano* **19**, 35592-35600 (2025).

[5] S. Park, R. Moriya, Y. J. Zhang, K. Watabe, T. Taniguchi, T. Machida, “Emergent photo-thermoelectricity in localized bulk quantum Hall state of graphene”, *Appl. Phys. Lett.* **127**, 103105 (2025).

[6] X. Yang, Y. J. Zhang, L. Chen, K. Aso, W. Yamamori, R. Moriya, K. Watanabe, T. Taniguchi, T. Sasagawa, N. Nakatsuji, M. Koshino, Y. Yamada-Takamura, Y. Oshima, T. Machida, “Intrinsic One-Dimensional Moiré Superlattice in Large-Angle Twisted Bilayer WTe_2”, *ACS Nano* **19**, 13007-13015 (2025).

22 Theoretical Astrophysics Group

Research Subjects: Observational Cosmology, High-Energy Astrophysics and Artificial Intelligence

Member: Naoki Yoshida, Kana Moriwaki, Chinami Kato & Erika Ogata

The Theoretical Astrophysics Group conducts a wide range of research programs. We pursue a variety of topics such as observational cosmology, galaxy formation and evolution, high-energy astrophysics, quantum computing and artificial intelligence.

Observational cosmology attempts to understand the evolution of the universe based on the observational data in various wavebands. The proper interpretation of recent and upcoming observational data provided by JWST, ALMA, Euclid, SPHEREx and Subaru PFS is important both in improving our understanding of the present universe and in determining several basic parameters of the universe, which are crucial in predicting the evolution of the universe. Our current interests include non-linear gravitational evolution of cosmological fluctuations, ionization, thermal history of the universe and reionization.

Astronomical observations discovered distant galaxies and quasars that resided when the Universe was less than one billion years old. We can probe the evolution of the cosmic structure from the present-day to such an early epoch. Shortly after the cosmological recombination epoch when hydrogen atoms were formed, the cosmic background radiation shifted to infrared, and then the universe would have appeared completely dark to human eyes. A long time had to pass until the first generation stars and galaxies were born, which illuminated the universe once again and terminate the cosmic Dark Ages. We explore direct and indirect observational signatures from those objects that can be obtained in future observations. Comparing the predictions of our simulations to observations allows us to better understand the nature of the underlying physical processes.

To maximise the information gain from astrophysical observations and numerical simulations, we also explore several new techniques. We develop supervised machine learning models to analyze noisy observational data. With the aim of utilizing quantum computers in the future for faster computation, we are also working on the development of new computational methods.

Let us summarize this report by presenting recent titles of the PhD and Master’s theses in our group:

2025

- Formation and Evolution of High-Redshift Galaxies Using Cosmological Simulations and Multi-Wavelength Observations
- Development of a Surrogate Model for Neutrino Radiation Transport in Core-Collapse Supernovae
- Redshift Evolution of Halo Occupation Distribution

2024

- The Nature of Dark Matter Probed by Strong Gravitational Lensing
- Long-Term Evolution and Dispersal of Protoplanetary Disks
- Impact of Reionization History on Constraining Primordial Gravitational Waves with Cosmic Microwave Background B-modes
- Probing Cosmic Large Scale Structure with Voids

2023

- Binary Blackhole Mergers Induced by Dynamical Interaction of Hierarchical Triple Systems
- Solving the Boltzmann Equation with Classical and Quantum Computers

23 Murao Group

Research Subjects: Quantum Information (Theory)

Member: Mio Murao

Quantum mechanics allows a new type of information represented by quantum states, which are in a superposition of 0 and 1 states. Quantum information processing seeks to perform tasks that are impossible or ineffective with conventional classical information by manipulating quantum states. Examples are quantum computation, quantum cryptography, quantum communication, and quantum sensing.

We consider that a quantum computer is not just a machine to run computational algorithms but also a machine to perform any operations allowed by quantum mechanics. We analyze what kinds of new properties and effects may appear in quantum systems by using quantum computers to improve our understanding of quantum mechanics from an operational point of view. We also investigate applications of quantum properties and effects such as entanglement for information processing, communication, quantum learning, and quantum manipulations by developing quantum algorithms and quantum protocols.

This year, our group consisted of a faculty member, Mio Murao (Professor), postdoctoral researchers, Zane Marius Rossi (JSPS foreign postdoctoral fellow), Jisho Miyazaki, and graduate students, Timothy Forrer (D3), Satoshi Yoshida (D3), Kosuke Matsui (D2), Natsuto Isogai (D1), Ryotaro Niwa (M2), Manaki Arihara (M1), Ben Yardan Jumoorty (M1). We engaged in active collaborations with colleagues at Ritsumeikan University, Sorbonne Université, Tamkang University, the University of Amsterdam, University of California, Berkeley, University of Manchester, Université Paris-Saclay, Foxconn, Google Quantum AI, and NTT.

Our projects engaged in this academic year were the following:

Quantum Algorithms
– Composition of quantum protocols with knowledge (Forrer, Miyazaki, Murao)
– A Solovay–Kitaev theorem for quantum signal processing (Rossi)
– Quantum advantage in storage and retrieval of isometry channels (Yoshida, Miyazaki, Murao)
– Asymptotically optimal SU(3) estimation (Yoshida, Murao)
– Implementation of quantum combs with group symmetry (Yoshida, Murao)
– Higher-order quantum algorithms with known input states (Yoshida, Murao)
– Randomized dilation superchannels (Yoshida, Niwa, Murao)
– Singular value transformation for unknown quantum channels (Niwa, Rossi, Murao)
– Purification of noisy unitary channels (Niwa, Yoshida, Murao)
– Unitary fingerprint (Jumoorty, Murao)
– Sample query conversion of block encoding (Arihara, Murao)

Distributed Quantum Information Processing
– Improving numerical accuracy of entanglement detection via algebraic geometry (Miyazaki)
– Characterizing quantum measurements realizable with no classical communication (Miyazaki)
– Feasibility of quantum computation with a limited number of qubits (Matsui, Murao)

Quantum Error Correction
– Depth reduction of color code circuits using CXSWAP gates (Yoshida)
– Threshold theorem for the Union-Find decoder (Yoshida)

Quantum Machine Learning and Computational Complexity
– Advantage of quantum machine learning from general computational advantages (Isogai, Murao)
– Derandomization of random advice for relational problems in heuristic complexity (Isogai, Murao)

24 Ueda Group

Research Subjects: Bose–Einstein condensation, fermionic superfluidity, topological phenomena, open quantum systems, information thermodynamics, quantum information, measurement theory, machine learning

Member: Masahito Ueda and Masaya Nakagawa

With recent advances in nanoscience, it has become possible to precisely measure and control atoms, molecules, and photons at the level of a single quantum. We are interested in theoretically studying emergent quantum many-body problems in such highly controllable systems and developing nanoscale thermodynamics and statistical physics that lay the foundations of such problems. Our particular focuses in recent years include many-body physics of ultracold atomic gases and unification of quantum and statistical physics and information theory. Atomic gases which are cooled down to nearly zero temperature by laser cooling techniques offer unique opportunities for studying macroscopic quantum phenomena such as a Bose–Einstein condensation (BEC) in controlled manners. Unprecedented controllability of such gases also enables us to simulate phenomena analogous to condensed matter and astronomical physics, to investigate their universal properties, and to explore unknown quantum many-body physics. In our recent works, we have studied nonunitary dynamics of atomic gases subject to dissipation and/or measurement backaction, classification of phases of matter in nonequilibrium open systems, and thermalization of isolated quantum systems. We are also interested in relating fundamental concepts of quantum and statistical physics with information theory and exploring interdisciplinary fields that unify physics and information. In particular, we have recently worked on generalizations of the second law of thermodynamics and fluctuation theorems in light of information flow under measurements and feedback controls. Furthermore, we have recently tackled an understanding of AI and machine learning from a viewpoint of physics. We list our main research subjects in FY2025 below.

- Quantum many-body phenomena in ultracold atoms, nonequilibrium open systems
  - Quantum master equation for many-body systems based on the Lieb–Robinson bound [1]
  - Superfluidity of dissipative Bose–Einstein condensates [2]
  - Quantum feedback cooling of a trapped nanoparticle by using a low-pass filter [3]
- Unification of quantum physics, statistical mechanics, information theory, and machine learning
  - Proof of nonintegrability of $S = 1$ quantum spin chains [4]
  - Maxwell's demon that rectifies quantum fluctuations [5]

[1] Koki Shiraishi, Masaya Nakagawa, Takashi Mori, and Masahito Ueda, Phys. Rev. B **111**, 184311 (2025) [selected as Editors' Suggestion].

[2] Hongchao Li, Xie-Hang Yu, Masaya Nakagawa, and Masahito Ueda, Phys. Rev. Lett. **135**, 166001 (2025).

[3] Shuma Sugiura and Masahito Ueda, Phys. Rev. A **113**, 023119 (2026).

[4] Akihiro Hokkyo, Mizuki Yamaguchi, and Yuuya Chiba, Phys. Rev. Research **7**, 043297 (2025).

[5] Kangqiao Liu, Masaya Nakagawa, and Masahito Ueda, Phys. Rev. A **113**, 022436 (2026).

25 Jun'ichi Yokoyama Group

Research Subjects: Theoretical Cosmology and Gravitation

Member: Jun'ichi Yokoyama

This group has long been based at the Research Center for the Early Universe (RESCEU), where we have conducted broad research in cosmology, gravitational theory, and gravitational wave physics, grounded in fundamental theoretical physics such as general relativity, quantum field theory, and particle physics. At the same time, we have actively contributed to both education and research within the Department of Physics, Faculty of Science.

Since November 2023, however, Yokoyama has assumed the position of Director of the Kavli Institute for the Physics and Mathematics of the Universe. Accordingly, he continues his duties at the Department of Physics as an adjunct professor to RESCEU. Graduate students are distributed between the Kashiwa and Hongo campuses, residing at either location depending on their preferences.

Cosmology of the early universe and gravitation

- One-loop correction on the primordial curvature perturbation from single-field inflation
- Evolution of primordial magnetic fields and their cosmological constraints
- Einstein-Cartan gravity and cosmology
- No-scale Brans-Dicke gravity and cosmology
- On shell scattering amplitude and quantum effects on black holes
- Enhancement of primordial black hole formation through variable equation of state

Observational cosmology

- Cosmic birefringence as a probe of dark components
- Time domain astronomy using Tomo-e Gozen

Gravitational wave analysis

- LIGO-Virgo-KAGRA collaboration papers

26 Ejiri-Tsujii Group

Research Subjects: high temperature plasma physics experiments, spherical tokamak, wave heating and current drive, nonlinear physics, collective phenomena, fluctuations and transport, advanced plasma diagnostics development

Member: Akira Ejiri, Naoto Tsujii

Our research laboratory focuses on magnetic confinement torus plasmas to realize fusion energy, primarily utilizing the TST-2 spherical tokamak (ST) at the Kashiwa Campus while maintaining extensive domestic and international collaborations. TST-2 is a high-performance ST with a major and minor radius of 0.36 m and 0.23 m, capable of achieving plasma currents up to 120 kA through induction and 27 kA via radio-frequency waves, specifically Lower-Hybrid Waves (LHW). In fiscal year 2025, our efforts were focused on deepening the physical understanding of high-energy electrons generated by LHW through advanced hard X-ray (HXR) and target probe based diagnostics. These studies revealed that high-energy electron orbits significantly dictate energy loss patterns to plasma-facing components. We also made strides in understanding HXR burst mechanisms by analyzing their correlation with magnetic fluctuations and loop voltage, finding that such bursts are detrimental to current drive efficiency as they represent a substantial loss channel for non-inductive current maintenance.

In our pursuit of non-inductive current start-up, we developed an off-midplane LHW launch scenario aimed at driving current closer to the magnetic axis, contrasting with conventional launchers that tend to drive current in the periphery. While numerical simulations using GENRAY and CQL3D predicted a doubling of plasma current through synergistic effects between antennas, experimental results showed only a modest increase of approximately 1 kA. Investigation into this discrepancy considered Parametric Decay Instabilities (PDI) as a possible cause for wave spectral changes, though initial magnetic probe measurements showed no significant difference in PDI activity between single and dual antenna operations, prompting plans for higher-field-side wave analysis. Furthermore, high-energy electron loss was explored through a multi-sightline HXR system equipped with pulse-height reconstruction to mitigate pile-up, which allowed us to distinguish between transiently lost electrons and those contributing to bulk current.

Diagnostic development remained a pillar of our research, highlighted by the creation of a compact, high-performance beam dump and specialized notch filters for the line-integrated Thomson scattering (LITS) system to suppress stray light. This enabled successful temperature and density distribution measurements across five sightlines, which were validated against conventional Thomson Scattering methods. Additionally, we improved microwave inter-polarimetry by identifying wall reflections as a source of Faraday rotation error and proposed a slanted-plate solution to reduce phase errors tenfold. We also successfully measured local toroidal current density distributions using a new bobbinless coil probe, providing qualitative validation of our current density profile modeling in both ohmic and LHW plasmas.

Our computational work utilized the Smilei PIC code to model non-linear wave interactions, successfully observing Ion Bernstein Wave excitation and parametric decay processes in 1D simulations, followed by 2D modeling near the Upper Hybrid Resonance. Collaborative efforts also yielded significant results, including the integration of orbit-averaged Fokker-Planck and extended MHD codes to optimize ECW-assisted start-up for JT-60SA and the development of a remote fiber-scanning mechanism for the QUEST device to enhance measurement resolution during long-pulse discharges. Finally, our laboratory contributed to the conceptual design of the FAST project, performing 0D analyses to clarify the relationships between fusion output, neutron wall loading, and cost, while establishing essential diagnostic requirements for future power demonstration technologies.

27 Aikawa Group

Research Subjects: Levitated optomechanics, ultracold atoms

Member: Kiyotaka Aikawa, Mitsuyoshi Kamba, Soutatsu Otabe, Takumi Ukiya, Yuto Kojima, Jihye Jung, Takuya Kawasaki

We experimentally explore single nanoparticles optically levitated in vacuum. Recently, we realize feedback cooling on all the external degrees of freedom of a single nanoparticle, with one degree of freedom being cooled to the ground state. We have realized time-of-flight free-expansion measurements of the velocity distribution of a levitated nanoparticle and elucidated that cooling the angular motions is crucial to explore the velocity distribution near the ground state. In future, we aim at employing these techniques to explore the quantum behaviors of a nanoparticle as well as its application to sensing beyond current technologies. The main research subjects in FY2025 are as follows:

- Construction of a new apparatus for multi-particle experiments
- Construction of a new apparatus for a hybrid quantum system
- Exploring the application of a nanoparticle to sensing

28 Ando Group

Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

Member: Masaki Ando and Kentaro Komori

Gravitational waves has a potential to open a new window onto the Universe and brings us a new type of information about catastrophic events such as supernovae or coalescing binary neutron stars or binary black holes; these information can not be obtained by other means such as optics, radio-waves or X-ray. Worldwide efforts are being continued in order to construct and improve detectors.

In Japan, we are constructing a large-scale cryogenic gravitational-wave antenna, named KAGRA, at Kamioka underground site. This underground telescope is expected to catch gravitational waves from the coalescence of neutron-star binaries at the distance of 140 Mpc. A space laser interferometer, DECIGO, was proposed through the study of the gravitational wave sources with cosmological origin. DECIGO could detect primordial gravitational waves from the early Universe at the inflation era.

The current research topics in our group are followings:

- KAGRA gravitational wave detector
- Space laser interferometer, DECIGO and precursor missions (B-DECIGO, SILVIA)
- Development of Low-frequency Gravitational-Wave Antenna: TOBA (Torsion Bar Antenna)
- Dark Matter Seach: DANCE
- High-precision experiments on relativity and opto-mechanics

Reference

[1] H. Takidera, *et al.*: Adjusting optical cavity birefringence with wavelength tunable laser for axion searches, Phys. Rev. D 112, 063048 (2025).

[2] K. Suzuki et al.: Observation of an optical spring in a robustly controlled signal-recycled Michelson interferometer, Opt. Express 33, 40026-40039 (2025).

[3] E. Berti, et al.: deci-Hz Gravitational Wave Observations on the Moon and Beyond, arxiv:2602.05923 (2026).

[4] Y. Michimura, et al.: Initial acquisition requirements for optical cavities in the space gravitational wave antennae DECIGO and B-DECIGO, Class. Quantum Grav. 42, 225027 (2025).

[5] T. Ito, et al.: SILVIA: Ultra-precision formation flying demonstration for space-based interferometry, PASJ psaf086 (2025).

[6] Y. Okuma, et al.: Cross-correlated force measurement for thermal noise reduction in torsion pendulum, Phys. Rev. D 111, 082006 (2025).

[7] A. G. Abac et al.: Search for Continuous Gravitational Waves from Known Pulsars in the First Part of the Fourth LIGO-Virgo-KAGRA Observing Run, ApJ 983, 99 (2025).

[8] A. G. Abac et al.: Search for Gravitational Waves Emitted from SN 2023ixf, ApJ 985, 183 (2025).

[9] A. G. Abac et al.: GW250114: Testing Hawking’s Area Law and the Kerr Nature of Black Holes, Phys. Rev. Lett. 135, 111403 (2025).

[10] A. G. Abac et al.: GW241011 and GW241110: Exploring Binary Formation and Fundamental Physics with Asymmetric, High-spin Black Hole Coalescences, ApJL 993, L21 (2025).

[11] A. G. Abac et al.: GW231123: A Binary Black Hole Merger with Total Mass 190-265 Msolar, ApJL 993, L25 (2025).

[12] A. G. Abac et al.: All-sky search for short gravitational-wave bursts in the first part of the fourth LIGO-Virgo-KAGRA observing run, Phys. Rev. D 112, 102005 (2025).

[13] A. G. Abac et al.: GWTC-4.0: An Introduction to Version 4.0 of the Gravitational-Wave Transient Catalog, ApJL 995, L18 (2025).

[14] A. G. Abac et al.: Black Hole Spectroscopy and Tests of General Relativity with GW250114, Phys. Rev. Lett. 136, 041403 (2026).

29 Bamba Group

Research Subjects: High Energy Astrophysics, observations and developments of detectors

Member: Aya Bamba, Kouichi Hagino

This year, we achieved a variety of results, particularly focusing on high-resolution spectroscopy of high-energy astrophysical objects using the XRISM satellite. The most outstanding achievement of this year is our observational results on mass outflows from PDS 456, one of the supermassive black holes ubiquitously found at the centers of galaxies. We discovered multiple absorption lines in the spectrum of PDS 456 originating from iron outflowing at velocities of 0.2–0.3 times the speed of light. The lines are narrow, indicating the presence of multiple velocity components. These results suggest that ultra-fast outflows (UFOs), in which matter is ejected from supermassive black holes at nearly the speed of light, do exist and have a clumpy, multi-component structure. Such clumpy UFOs have been discovered for the first time in the world, attracting significant attention, including publication in Nature and a press conference. In addition, we have achieved many other results on supernova remnants, neutron stars, and related objects.

For future cosmic hard X-ray satellites, we develop semiconductor detectors. We have been fully participating in the space hard X-ray high spatial resolution balloon experiment superHERO, aiming for a balloon launch in FY2028, and have been leading its development as a core institution. In particular, we were responsible for developing the readout system for the focal plane detector, and successfully assembled the system within FY2025. In February 2026, several members stayed at NASA/MSFC for one month, where they successfully conducted beam tests of the focal plane detector. Through these efforts, we are taking a leading role in advancing development toward the balloon launch. In addition, as part of the fundamental development of hard X-ray detectors, the Bamba laboratory is also developing a semiconductor detector called XRPIX. We are aiming for full digitization by integrating an ADC within the XRPIX chip. While energy-related performance targets for space applications, such as energy resolution and gain, have already been achieved, timing-related performance such as photon arrival time resolution and dead time fraction has been measured. We successfully carried out precise measurements of these parameters for the first time and demonstrated that the timing performance also meets the requirements for space applications.

Selected papers:

[1] Aya Bamba, Manan Agarwal, Jacco Vink, Paul Plucinsky, Yukikatsu Terada, Ehud Behar, Satoru Katsuda, Koji Mori, Makoto Sawada, Hironori Matsumoto, Lia Corrales, Adam Foster, Shin-ichiro Fujimoto, Liyi Gu, Kazuhiro Ichikawa, Kai Matsunaga, Tsunefumi Mizuno, Hiroshi Murakami, Hiroshi Nakajima, Toshiki Sato, Haruto Sonoda, Shunsuke Suzuki, Dai Tateishi, Hiroyuki Uchida, Masahiro Ichihashi, Kumiko Nobukawa, Salvatore Orlando, “Measuring the asymmetric expansion of the Fe ejecta of Cassiopeia A with XRISM/Resolve ” , PASJ, 77, S144 (2025)

[2] Tashiro, M., XRISM collaboration, “X-Ray Imaging and Spectroscopy Mission” , PASJ, 77, S1 (2025)

[3] XRISM collaboration, “Structured ionized winds shooting out from a quasar at relativistic speeds” , Nature, 641, 1132 (2025)

[4] H. Uchida, K. Mori, H. Tomida, H. Nakajima, H. Noda, T. Tanaka, H. Murakami, H. Suzuki, S. B. Kobayashi, T. Yoneyama, K. Hagino, K. K. Nobukawa, H. Uchiyama, M. Nobukawa, H. Matsumoto, T. G. Tsuru, M. Yamauchi, I. Hatsukade, H. Odaka, T. Kohmura, K. Yamaoka, T. Yoshida, Y. Kanemaru, D. Ishi, T. Dotani, M. Ozaki, H. Tsunemi, K. Miyazaki, K. Kusunoki, Y. Otsuka, H. Yokosu, W. Yonemaru, K. Ichikawa, H. Nakano, R. Takemoto, T. Matsushima, R. Urase, J. Kurashima, K. Fuchi, K. Hayakawa, M. Fukuda, S. Inoue, Y. Aoki, K. Takayama, T. Sako, M. Yoshimoto, K. Shima, M. Higuchi, K. Ninoyu, D. Aoki, S. Tsunomachi, T. Okajima, M. Ishida, Y. Maeda, T. Hayashi, K. Tamura, R. Boissay-Malaquin, T. Sato, M. Takeo, A. Miyamoto, G. Matsumoto, M. E Eckart, N. Hell, M. A Leutenegger, K. Hayashida, “In-orbit performance of the soft X-ray imaging telescope Xtend aboard XRISM”, Publications of the Astronomical Society of Japan, psaf030, 2025.

30 Kusaka Group

Research Subjects: Observational Cosmology, Cosmic Microwave Background (CMB) Observation, Dark Matter Search. (1) Study of Inflation in the early universe and the evolution of the universe through gravitational lensing using POLARBEAR and Simons Array experiment; (2) Design, Development, and Construction of Simons Observatory aiming to study Inflation, evolution of the universe, Neutrinos, Dark Energy, and Dark Radiation; (3) Research and Development of technologies for Simons Observatory and CMB-S4; (4) Dark matter search using Magnon.

Member: A. Kusaka and S. Takakura

- Polarbear experiment and its successor, Simons Array, are optimized to measure both inflationary signature and the gravitational lensing effect in CMB polarization. Both Polarbear and Simons Array experiments concluded the observations. Our focus has been on data analysis as well as the development and characterization of the continuously-rotating half-wave plate (HWP) enabling accurate measurement of CMB polarization.
- Simons Observatory experiment has been under development since 2016, and we have now started observations. We are deploying an array of what we call "small aperture telescopes," which are dedicated for the inflationary signal, and a six-meter-aperture "large aperture telescope," which enables observation for the large-scale structures and the dark content of the universe. Our current focus is on the analysis of commissioning data of first three telescopes at Chile site and on fabrication of the 4th telescope.
- Research and Development for CMB experiments such as Simons Observatory are crucial component of our research program. We specifically work on superconducting technologies used in the detectors, cryogenic bearing system for HWP, and anti-reflection coating for high-index optical material.
- Dark matter accounts for about 80% of the matters in the Universe. Axion is one of the candidates of the dark matter. In searching for relatively light dark matters such as axion, detectors free from standard quantum limit (SQL), which constrains the sensitivity of conventional methods, play an important role. We are developing magnon qubit hybridized system to overcome SQL aiming at the axion dark matter search.
- Gravitational waves at high frequencies (MHz–GHz) remain largely unexplored, yet they hold rich potential to provide a new view of the early universe. We are launching a new experimental project to explore GHz-frequency gravitational waves by combining a superconducting resonant cavity with microwave quantum-sensing techniques.

31 Takeuchi Group

Research Subjects: Experimental statistical physics for non-equilibrium systems

Members: Kazumasa A. Takeuchi, Yuya Karita

We aim to explore statistical physics of out-of-equilibrium phenomena experimentally. Using soft and living matter, such as liquid crystal, colloids, and granular materials, as well as bacteria, we carry out experiments that we design to capture underlying physical principles, in addition to the understanding of specific phenomena we observe. As a result, we deal with diverse subjects in the group, sometimes enjoying interesting connections in between, through such keywords as active matter, non-equilibrium phase transitions, topology, etc. More specifically, we carried out the following projects among others in the academic year 2025:

(1) Non-equilibrium phenomena in soft matter systems
(1-1) Collective dynamics of magnetic Quincke rollers

(2) Non-equilibrium phenomena in living systems
(2-1) Glass transitions of proliferating bacterial populations
(2-2) Topological edge states in collective motion of bacteria [2]
(2-3) Collective motion of light-driven bacteria
(2-4) Topological defects and extracellular matrix production in early biofilm formation [4]

(2-5) Experimental model soil system for bacteria
(2-6) Collective motion of *Komagataeibacter hansenii* [6]
(2-7) Near-field interaction of *Chlamydomonas reinhardtii* in confined suspension
(2-8) Collective behavior of soldier crabs [5]

(3) Theoretical approaches
(3-1) Large deviations characterizing the Kardar-Parisi-Zhang universality class [7]

More detailed information can be found at the group's website, `https://lab.kaztake.org/`

References

[1] Y. Karita, G. T. Rodríguez-Sánchez, E. Brambilla, J. C. R. Hernandez-Beltran, M. Schwarz, P. B. Rainey, Context-dependent adaptation in structured environments, Proc. R. Soc. B, **293**, 20252004 (2026).

[2] Y. Uchida, D. Nishiguchi, K. A. Takeuchi, Designing topological edge states in bacterial active matter. arXiv:2601.08243.

[3] A. Ochi, K. Shibamoto, Y. Toyotake, D. Fujioka, F. Yokoyama, H. Okanishi, T. Imai, D. Fujita, R. Aono, M. Inoue, M. Takizawa, R. Tobe, Y. Kanai, T. Imai, H. Mihara, Biosynthesis and Export of Membrane-Enveloped Selenium Nanoparticles by *Escherichia Coli*. Environ. Sci. Technol. **60**, 4213 (2026)

[4] F. Yokoyama, K. A. Takeuchi, Biofilm Initiation via Extracellular Matrix Production Regulated by Cell Orientation Patterning in Growing Escherichia coli Populations. bioRxiv, doi: 10.64898/2026.03.26.714369 (2026)

[5] C. Feliciani, H. Murakami, T. Tomaru, Y. Uesugi, S. Tanida, Y. Nishiyama, X. Jia, and T. Maeda, How swarm size affects soldier crab swarming behavior. Artif. Life. Robotics **31**, 69 (2025).

[6] G. Takayama, T. Kondo, Unraveling self-assembly mechanisms in bacterial cellulose hydrogels. bioRxiv, doi: 10.64898/2026.01.21.700946 (2026).

[7] Y. Yanagibashi, K. A. Takeuchi, Population dynamics simulations of large deviations for three subclasses of the Kardar-Parisi-Zhang universality class. arXiv:2602.04357.

32 Konishi Group

Research Subjects: Metasurface, Metamaterials, Nonlinear optics, Laser processing

Member: Kuniaki Konishi and Haruyuki Sakurai

We are investigating new physical phenomena caused by the interaction of light with nano- and micro-scale ultra-fine artificial structures fabricated by state-of-the-art microfabrication techniques, and their application to optical control. Furthermore, based on condensed matter physics, we are exploring the scientific principles of laser processing to understand why light can break things and are developing new methods for fabricating micro three-dimensional structures using state-of-the-art ultrashort pulsed lasers.

As a member of UTokyo Research Institute for Photon Science and Laser Technology, we are also working to create a new system for the rapid transfer of new technologies developed by our group to the real industry.

Exploration of new phenomena and the physics of artificial nanostructures and their application to optical control

Artificial nanostructures that are smaller than the wavelength of light can be used to create new physical phenomena and to control light based on the new concept of manipulating the interaction with light through the "shape" of appropriately designed nanostructures. We are exploring new phenomena in such artificial nanostructures, elucidating their mechanisms, and applying them to light sources. In particular, we are aiming to apply our light source to the vacuum ultraviolet region with wavelengths below 200 nm and terahertz waves with frequencies near 1 THz, which are in need of the development of control methods.

Creation of micro three-dimensional structures by ultrashort pulse laser and their application to electromagnetic wave control

It is a well-known fact that when a material is exposed to intense laser light, the material is dRecent advances in laser technology have made it possible to generate intense and stable ultrashort pulsed lasers that can not only drill and cut objects, but also fabricate micron-order fine three-dimensional (3D) structures that are difficult to fabricate by other methods. Since the structures fabricated by such advanced technology are smaller than electromagnetic waves, such as millimeter waves and terahertz waves, they can be utilized as functional materials for new electromagnetic wave control by fabricating appropriate structures. In this research, we are developing such laser-based 3D structure fabrication technology and at the same time, developing new functional materials using such technology, and we recommend its application to various fields such as astrophysics and next-generation wireless technology (Beyond 5G and 6G).

Elucidating the Principles of Laser Processing

It is a well-known fact that when a material is exposed to intense laser light, the material is destroyed, and in fact, laser processing is an important fundamental technology that supports the current industry. On the other hand, the mechanism by which ultrashort laser pulses, in particular, cause material destruction remains unclear. When intense pulsed light that causes material destruction is incident on a material, what kind of process is used to transfer the energy of the light to the material? How does this energy propagate through the electron and lattice systems inside the material, and what triggers the dramatic and irreversible phenomenon of destruction? To find answers to these questions, we have developed state-of-the-art optical control techniques and various measurement methods, and are conducting research by making full use of these techniques. Through this research, we aim not only to elucidate the mechanism of laser-induced material destruction but also to use this knowledge to advance laser processing technology further.

33 Nose Group

Research Subjects: Formation and function of neural networks

Member: Akinao Nose and Teruyuki Matsunaga

The aim of our laboratory is to elucidate the mechanisms underlying the formation and function of neural networks, by using as a model, the simple nervous system of the fruitfly, *Drosophila.* A part of our recent research activity is summarized below.

1. Segment-specific axon guidance by Wnt/Fz signaling diversifies motor commands in *Drosophila* larvae

Functional diversification of homologous neuronal microcircuits is a widespread feature observed across brain regions as well as across species, while its molecular and developmental mechanisms remain largely unknown. We address this question in *Drosophila* larvae by focusing on segmentally homologous Wave command-like neurons, which diversify their wiring and function in a segment-specific manner. Anterior Wave (a-Wave) neurons extend axons anteriorly and connect to circuits inducing backward locomotion, whereas posterior Wave (p-Wave) neurons extend axons posteriorly and trigger forward locomotion. Here, we show that Frizzled receptors DFz2 and DFz4, together with the DWnt4 ligand, regulate the segment-specific Wave axon projection. DFz2 knock-down (KD) not only reroutes Wave axons to posterior neuromeres but also biases its motor command to induce forward instead of backward locomotion as tactile response. Thus, segment-specific axon guidance diversifies the function of homologous command neurons in behavioral regulation. Since control of anterior-posterior (A-P) axon guidance by Wnt/Fz-signaling is evolutionarily conserved, our results reveal a potentially universal molecular principle for formation and diversification of the command system in the nerve cord. Furthermore, this work indicates that sensorimotor transduction can be rerouted by manipulating a single gene in a single class of neurons, potentially facilitating the evolutionary flexibility in action selection.

2. Synchronous multi-segmental activity between metachronal waves controls locomotion speed in *Drosophila* larvae

The ability to adjust the speed of locomotion is essential for survival. In limbed animals, the frequency of locomotion is modulated primarily by changing the duration of the stance phase. The underlying neural mechanisms of this selective modulation remain an open question. Here, we report a neural circuit controlling a similarly selective adjustment of locomotion frequency in *Drosophila* larvae. *Drosophila* larvae crawl using peristaltic waves of muscle contractions. We find that larvae adjust the frequency of locomotion mostly by varying the time between consecutive contraction waves, reminiscent of limbed locomotion. A specific set of muscles, the lateral transverse (LT) muscles, co-contract in all segments during this phase, the duration of which sets the duration of the interwave phase. We identify two types of GABAergic interneurons in the LT neural network, premotor neuron A26f and its presynaptic partner A31c, which exhibit segmentally synchronized activity and control locomotor frequency by setting the amplitude and duration of LT muscle contractions. Altogether, our results reveal an inhibitory central circuit that sets the frequency of locomotion by controlling the duration of the period in between peristaltic waves. Further analysis of the descending inputs onto this circuit will help understand the higher control of this selective modulation.

References

[1] S. Takagi, S. Takano, Y. Hashimoto, S. Morise, X. Zeng, A. Nose. Segment-specific axon guidance by Wnt/Fz signaling diversifies motor commands in *Drosophila* larvae. eLife (2024)

[2] Y. Liu, E. Hasegawa, A. Nose, FM. Zwart, H. Kohsaka. Synchronous multi-segmental activity between metachronal waves controls locomotion speed in *Drosophila* larvae. eLife **12**:e83328 (2023)

34 Okada Group

Research Subjects: Biophysics, cell biology, super-resolution microscopy, live cell imaging and single molecule imaging.

Member: Yasushi Okada, Sawako Enoki and Keigo Ikezaki

At the heart of our research lies the fundamental question, ‘What is life?’. We develop technologies for visualization and non-invasive measurement of molecular processes in living cells to bridge the gap between molecules and life.

A major breakthrough this year was EverGreen, a photobleaching-free fluorescent labeling system developed with the Kikuchi laboratory at Osaka University ([8]). Conventional fluorescent probes are destroyed by photobleaching, limiting single-molecule tracking to tens of seconds. EverGreen overcomes this through rapid, reversible exchange of fluorogenic dyes on an odorant-binding protein (OBP) tag. We defined quantitative kinetic criteria for continuous exchange-based tracking and demonstrated uninterrupted single-molecule observation for over 24 hours—extending the observation window from seconds to, in principle, infinity.

We also developed GEM2.0, improved genetically encoded multimeric nanoparticles for cytoplasmic viscoelasticity measurement. The original GEM suffered from background noise due to incomplete assembly, restricting the fluorescent protein to Sapphire. Hirokane resolved this by systematic scaffold–fluorescent protein screening, achieving multicolor variants (cyan to near-infrared) and two particle sizes (50 nm and 25 nm). Since the cytoplasm is a complex fluid whose viscoelasticity is scale-dependent, simultaneous tracking of different-sized particles enables more precise physical characterization.

In nonequilibrium biophysics, two complementary approaches were developed for molecular motor energetics. Fukuzawa developed electromagnetic tweezers ([5]) whose force calibration, unlike optical tweezers, is refractive-index-independent and thus transferable to intracellular environments. He validated the platform by reproducing kinesin’s energy conversion efficiency (20%) via the Harada-Sasa equality. Ihara took a perturbation-free approach, applying the short-time thermodynamic uncertainty relation with machine learning to estimate entropy production rates from F1-ATPase trajectories.

Finally, we analyzed two membrane proteins whose associated phenomena were recognized by Nobel Prizes. For SID-1 (systemic RNAi, 2006 Prize), cryo-EM by the Nureki laboratory revealed no channel-like pore, and our single-molecule imaging uncovered a novel mechanism: dsRNA-dependent SID-1 multimerization triggers membrane deformation and endocytosis. For Piezo1 (mechanosensation, 2021 Prize), Mukai exploited its homotrimeric structure by incorporating small fluorescent dyes via unnatural amino acids and detecting conformational changes through homo-FRET anisotropy, establishing a general approach for homomultimeric membrane proteins.

[1] Kubo S, Okada Y. The ATPase asymmetry: Novel computational insight into coupling diverse FO motors with tripartite F1. Biophys J. **124**, 891-900 (2025).

[2] Katoh TA, *et al.*, BMP4 regulates asymmetric Pkd2 distribution in mouse nodal immotile cilia and ciliary mechanosensing required for left–right determination. Dev Dyn. (2025).

[3] Sano FK, *et al.*, Insights into G-protein coupling preference from cryo-EM structures of Gq-bound PTH1R. Nat. Chem. Biol. (2025).

[4] Chen Y, *et al.*, Circumferential actomyosin bundles anchored by CCM1 drive endothelial cell contraction and vessel constriction. Nat. Commun. (2025).

[5] Fukuzawa H, *et al.*, Development of electromagnetic tweezers for single-molecule energetics of kinesin. Biophys. Physicobiol. (2025).

[6] Hasegawa K, *et al.*, Age-related decline in nuclear envelope LINC complex drives neuronal aging via axon initial segment dysfunction. EMBO Rep. (2025, accepted).

[7] Kambara T, *et al.*, Enhanced axonal transport in large vertebrates: KIF5A adaptations in giraffes and pythons. bioRxiv. 2025.05.04.652084 (2025).

[8] Awazu T, *et al.*, Kinetic design of reversible probe exchange enables continuous single-molecule tracking beyond the photobleaching limit. bioRxiv. 10.64898/2026.03.13.711506 (2026).

35 Furusawa Group

Research Subjects: Theoretical Biophysics, Evolutionary Biology, Complex Systems

Members: Chikara Furusawa and Yusuke Himeoka

Biological systems possess both robustness and plasticity, properties that distinguish them from artificial systems and are essential for their survival. They exhibit robustness against various perturbations, including noise in gene/protein expression and unexpected environmental changes. At the same time, they are plastic in response to their surroundings, changing their states through processes such as adaptation, evolution, and cell differentiation. Although the coexistence of robustness and plasticity can be understood as a dynamical property of complex interacting networks consisting of a large number of components, the mechanisms underlying this coexistence remain largely unknown.

Our work aims to extract the universal features of cellular dynamics that give rise to robustness and plasticity in biological systems. We describe these systems using a relatively small number of degrees of freedom and macroscopic state variables. We expect that such a description will provide novel methods for predicting and controlling complex biological systems.

The current research topics in our group are as follows:

1. Laboratory evolution of bacterial cells to analyze the dynamics of phenotype–genotype mapping
2. Construction of a macroscopic state theory describing adaptation and evolution in biological systems
3. Theoretical analysis of evolutionary processes under dynamically changing environments
4. Metabolic simulations for understanding growth, lag phase, and death

References

[1] T. Seike, N. Sakata, H. Kotani, C. Furusawa, Context-dependent activation and evolutionary buffering of a mating pheromone in fission yeast. Commun. Biol., in press.

[2] R. Ono, N. Konno, Y. Nishimura, C. Furusawa, Host range and antibiotic resistance dissemination are shaped by distinct survival strategies of conjugative plasmids. Nucleic Acids Res. **54**, gkaf1479 (2026).

[3] A. Hishida, Y. Himeoka, C. Furusawa, Analysis of metabolic stability under environmental perturbations using a kinetic model. Biophys. Physicobiol. **23**, e230001 (2026).

[4] K. Fujiwara, W. Aoki, C. Furusawa, A. Hasegawa, G. Hayashi, D. Kiga, K. Mikami, S. Takada, Y. Shimizu, Mirror life at the crossroads: Report on the symposia in Japan for discussion toward mirror life synthesis. Biophys. Physicobiol. **23**, e230008 (2026).

[5] N. Konno, K. Miyake, S. Nishino, K. Omae, H. Yanagisawa, S. Tsuru, Y. Nishimura, M. Kikkawa, C. Furusawa, W. Iwasaki, Repeatability of protein structural evolution following convergent gene fusions. Nature Commun. **16**, 8278 (2025).

[6] C. Furusawa, Rethinking life through digital evolution. Nature Rev. Genet. **26**, 740–740 (2025).

[7] Y. Kanai, A. Shibai, N. Yokoi, S. Tsuru, C. Furusawa, Laboratory evolution of the bacterial genome structure through insertion sequence activation. Nucleic Acids Res. **53**, gkaf331 (2025).

[8] H. Ono, S. Tsuru, C. Furusawa, Carbon source diversity shapes bacterial interspecies interactions. ISME J. **19**, wraf224 (2025).

[9] S. Tsuru, C. Furusawa, Congruence between noise and plasticity in protein expression. Sci. Rep. **15**, 24529 (2025).

[10] R. Kamiura, S. Sato, S. Wang, Y. Takanashi, R. Nishiwaki, A. Shibai, C. Furusawa, Complete genome sequence of a bacterial strain, Kurthia intestinigallinarum. Microbiol. Resour. Announc. **14**, e00008-25 (2025).

[11] A. Shibai, M. Izutsu, H. Kotani, C. Furusawa, Quantitative analysis of relationship between mutation rate and speed of adaptation under antibiotic exposure in Escherichia coli. PLoS Genet. **21**, e1011627 (2025).

[12] Y. Himeoka, C. Furusawa, Perturbation-response analysis of in silico metabolic dynamics in nonlinear regime: Hard-coded responsiveness in the cofactors and network sparsity. eLife **13**, RP98800 (2025).

[13] S. Tsuru, C. Furusawa, Genetic properties underlying transcriptional variability in Escherichia coli. Nature Commun. **16**, 2421 (2025).

36 Kawaguchi Group

Research Subjects: Biophysics, Non-equilibrium Physics

Member: Kyogo Kawaguchi, Shunshi Kohyama, Takahiro Kanazawa, Yoshizuki Fumoto, Kentaro Yamashiro, Sangwon Lee, Masahito Mori, Shoma Inoue

The Kawaguchi group aims to elucidate diverse biological and physical phenomena from a physical perspective, through theory, numerical simulation, data analysis, and experimental collaborations. In FY2025, the lab transitioned to a Chief Scientist Lab at RIKEN, continuing research at the interface of biophysics, non-equilibrium physics, and synthetic biology in coordination with The University of Tokyo.

The main research themes for the current fiscal year are as follows:

- **Histone acetylation directly controls chromatin architecture:** Using gene-scale in vitro reconstitution of long chromatin arrays, we demonstrated that histone acetylation directly increases structural fluctuations and transitions chromatin to a more open state. These modification patterns alone reproduce the structural organization observed in living cells, establishing acetylation as a direct physical regulator of higher-order chromatin structure [3].
- **Universal prediction of chromatin compartment organization from coding sequences:** In collaboration with the Hiratani lab (RIKEN BDR), we showed that coding sequence clustering universally predicts chromatin compartment structure across species from human to *Drosophila*, at both fine and coarse genomic scales, revealing a deep correspondence between primary sequence and 3D nuclear organization [10].

- **Self-organized patterning of tracheal cartilage rings:** In collaboration with the Morimoto lab (RIKEN), we proposed a mathematical model for the periodic patterning of tracheal cartilage rings based on ECM-guided collective cell migration. Model and experiment together show that spatial ECM gradients drive periodic accumulation of cartilage progenitors, generating uniformly spaced cartilage rings [12].
- **Hermitian and non-Hermitian topology in active matter:** We provided a comprehensive review of topological concepts—both Hermitian and non-Hermitian—in active matter systems, establishing a unified framework for understanding how non-equilibrium activity generates novel topological phases in biological and soft matter contexts [2].
- **Hydrodynamic optimality of symmetric swimming strokes:** In collaboration with the Ishimoto lab, we analyzed deformable swimmers in viscous fluids without constraining the stroke symmetry. We discovered a hydrodynamic duality: symmetric and anti-symmetric strokes are dynamically equivalent and proven optimal in speed and efficiency among all possible strokes. Validated by 3D Stokes flow simulations, this shows that the prevalence of symmetric gaits in nature reflects a physical optimality principle, not merely developmental constraints [9].
- **Synthetic cell design and protein function engineering:** Shunshi Kohyama contributed a perspective on the collective construction of synthetic cells and a review on protein design strategies for synthetic cells, outlining principles for engineering life-like functional systems from minimal molecular components [4, 5].

37 Sugita Group

Research Subjects: Computational Biophysics, Molecular Dynamics, Machine Learning

Member: Yuji Sugita and Diego Ugarte La Torre

All living organisms are composed of cells, the fundamental unit of life, and within these cells, a diverse array of biomolecules—such as proteins, nucleic acids, and lipids— exist in high concentrations. Our Laboratory aims to elucidate the relationship between the structural dynamics and functions of biomolecules using computational physics, and further, by predicting the interactions between biomolecules in the crowded intracellular environment, to gain a deep understanding of the molecular mechanisms underlying cellular function. To achieve this, relying solely on the existing methods and software is insufficient; it requires the development of new computational methods and molecular models, as well as molecular dynamics simulations optimized for state-of-the-art computers. Furthermore, it is important to establish new approaches that integrate physical simulations, such as molecular dynamics, with information sciences, including machine learning and Bayesian statistics. Using the molecular dynamics software GENESIS (https://mdgenesis.org) that we have developed as a platform, we are developing highly innovative methods and contributing to the biophysical community by widely releasing the latest version of GENESIS, which includes these methods, as free software. Our Laboratory focuses on theoretical and computational research, but we also conduct close collaborative research with many experimental groups both in Japan and abroad, aiming to understand biological phenomena in crowded intracellular environments at the atomic and molecular level.

References

[1] M. Brosz, J. Buck, F. Grunewald, D. Monego, J. Jung, Y. Sugita, C. Aponte-Santamaria, F. Graeter, "Coarse-grained Martini 3 model for collagen fibrils", Biophys. J. **123**, 456789 (2025).

[2] D. Ugarte La Torre, Y. Sugita, "CGBack: Diffusion Model for Backmapping Large-Scale and Complex Coarse-Grained Molecular Systems", J. Chem. Inf. Model. **65**, 9974-9986 (2025).

[3] D. Matsuoka, Y. Sugita, T. Mori, "An Empirical Biasing Force Constant to Minimize Overfitting in Cryo-EM Flexible Fitting Refinement", J. Chem. Inf. Model. **65**, 9790–9799 (2025).

[4] M. Motohashi, M. Oide, C. Kobayashi, J. Jung, E. Muneyuki, Y. Sugita, "The distortion–push mechanism for the γ subunit rotation in F1-ATPase", Proc. Natl. Acad. Sci. USA **122**, e2502642122 (2025).

[5] D. Monego, M. Brosz, J. Buck, V. Viliuga, P. Greicius, J. Jung, T. Stuehn, M. Schmies, Y. Sugita, F. Gräter, ”ColBuilder: Flexible structure generation of crosslinked collagen fibrils”, Bioinformatics, btaf278 (2025).

[6] S. Gopi, G. B. Brandani, C. Tan, J. Jung, C. Gu, A. Mizutani, H. Ochiai, Y. Sugita, S. Takada, ”In silico nanoscope to study the interplay of genome organization and transcription regulation”, Nucleic Acids Res. **53**, gkaf189 (2025).

[7] A. Mizutani, C. Tan, Y. Sugita, S. Takada, ”Heterogeneous condensates of transcription factors in embryonic stem cells: Molecular simulations”, Biophys. J. **124**, 1587–1598 (2025).

[8] K. Yagi, K. Gunst, T. Shiozaki, Y. Sugita, ”High-performance QM/MM Enhanced Sampling Molecular Dynamics Simulations with GENESIS SPDYN and QSimulate-QM”, J. Chem. Theory Comput. **21**, 4016–4029 (2025).

[9] R. E. Amaro et al., ”The need to implement FAIR principles in biomolecular simulations”, Nat. Methods **22**, 641–645 (2025).

[10] A. Niitsu, A. R. Thomson, A. J. Scott, J. T. Sengel, J. Jung, K. R. Mahendran, M. Sodeoka, H. Bayley, Y. Sugita, D. N. Woolfson, M. I. Wallace, ”Rational Design Principles for De Novo α-Helical Peptide Barrels with Dynamic Conductive Channels”, J. Am. Chem. Soc. **147**, 11741–11753 (2025).

[11] J. Jung, Y. Sugita, ”Langevin integration for isothermal–isobaric condition with a large time step”, J. Chem. Phys. **162**, 104108 (2025).

[12] Y.-K. Lei, K. Yagi, Y. Sugita, ”Efficient Training of Neural Network Potentials for Chemical and Enzymatic Reactions by Continual Learning”, J. Chem. Theory Comput. **21**, 2695–2711 (2025).

年次研究報告　2025年度

2026年 5 月 30 日

東京大学大学院理学系研究科・理学部
物理学教室

発　行　上田正仁
編　集　鈴木大介
酒井明人
中村ちか子