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Department of Physics
School of Science
The University of Tokyo

# Annual Report

2021

# 令和３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

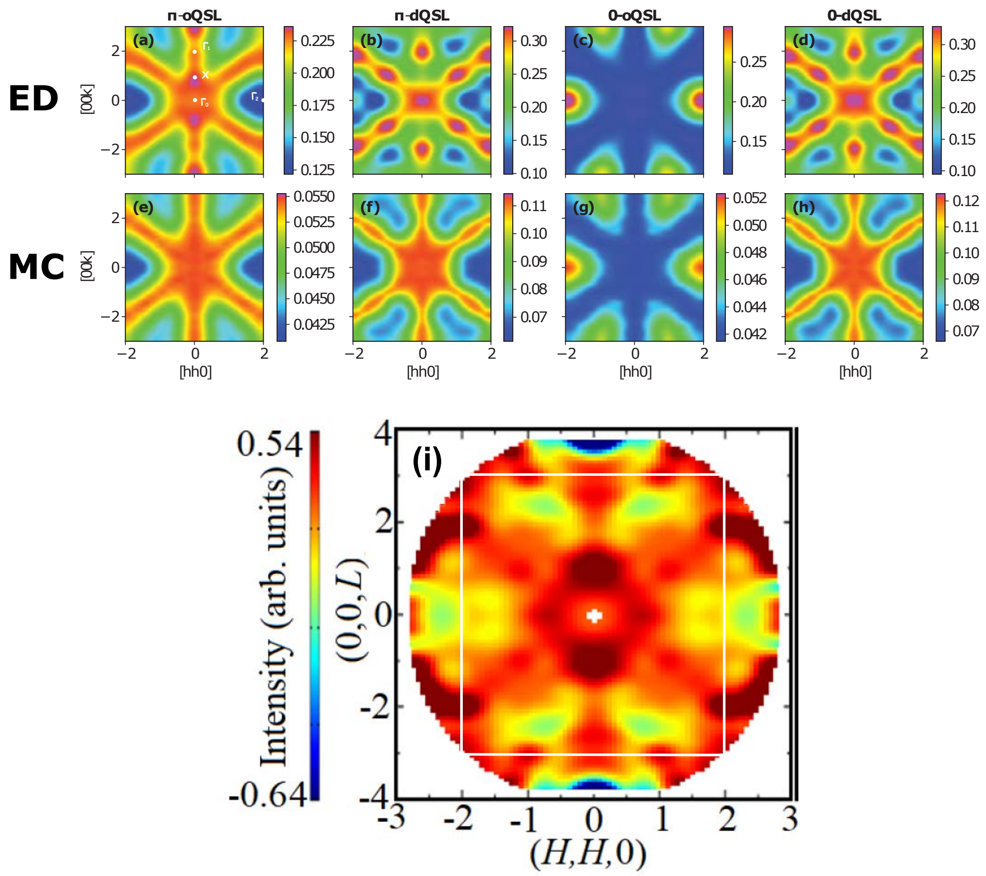


図 1:　希土類パイロクロア化合物 $Ce_2Zr_2O_7$ は、フラストレーションを持つスピン系の代表例の 1 つである。フラストレーションがある場合、スピンは強磁性や反強磁性などの秩序を持たず、あたかも液体のように振舞うという「スピン液体」状態が期待される。この物質のモデルハミルトニアンを調べると、理論的に実現可能なスピン液体相は 4 種類あることが分かった。その内のどれが実現しているかを検証するために、4 種のスピン液体相における中性子散乱強度分布を理論的に予測した。図 (a)–(d) は厳密対角化の手法による結果、(e)–(h) は古典モンテカルロ・シミュレーションの結果である。図 (i) は、比較すべき実験結果である (E. M. Smith *et al.*, arXiv:2108.01217 (2021) /CC-BY 4.0 から転載)。これらの比較から、$\pi$-flux 八極子スピン液体という、新奇のスピン液体状態が実現している可能性が高いことが分かった。(小形研究室の細井將史さんの論文、M. Hosoi *et al.*, arXiv:2201.00828 (2022) から細井さんの許諾を得て転載)。

Rare-earth pyrochlore compound, $Ce_2Zr_2O_7$ is one of the typical frustrated spin systems. In the presence of geometrical frustration, the spin system does not have a long-range order of ferromagnetism or anti-ferromagnetism. Instead, it behaves as a liquid, which is called ‘spin liquid state’. It is shown theoretically that the model Hamiltonian of this compound can have four kinds of spin liquid states. To clarify which state is realized, the intensity distribution of neutron scattering experiment is calculated theoretically for each spin liquid state. Figures (a)–(d) are the results by the method of exact diagonalization and (e)–(h) are the results by the classical Monte Carlo simulation. Figure (i) is the experimental result ( E. M. Smith *et al.*, arXiv:2108.01217 (2021) /CC-BY 4.0 ) to be compared with the theoretical predictions. The comparison between the theory and experiment indicates that the novel type of the spin liquid state called $\pi$-flux octupole spin liquid will be realized in this compound. (Adopted from the article, M. Hosoi *et al.*, arXiv:2201.00828 (2022) with permission by Dr. M. Hosoi. He is from the Ogata group.).

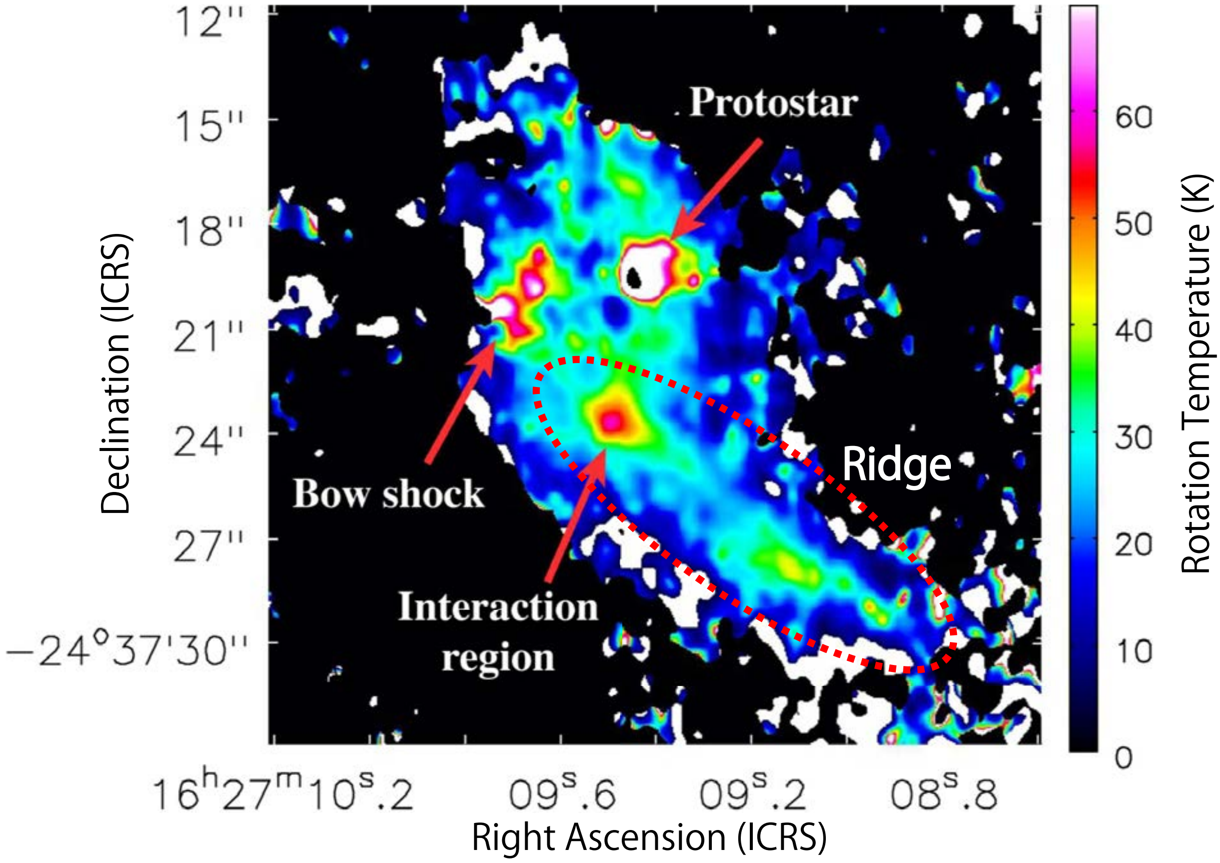


図 2: ALMA による観測によって、へびつかい座にある進化した原始星 Elias 29 で 2 本の一酸化硫黄分子（SO）の回転スペクトル線（$J_N = 6_6 - 5_5$ and $J_N = 6_5 - 5_4$）が捉えられた。それらの強度比を利用して、この原始星周りの 1000 天文単位スケールでの温度分布が明らかになった。原始星以外に 2 か所（bow shock、interaction region）で局所的高温領域が見出された。このことは比較的進化した原始星であってもジェットやアウトフローによって母体となる分子雲コアに大きな影響を与えて続けていることがわかった。（山本研究室）

ALMA observed the evolved protostar Elias 29 in the Ophiuchus molecular cloud in the two rotational transitions of sulfur monoxide (SO), $J_N = 6_6 - 5_5$ and $J_N = 6_5 - 5_4$. The temperature structure around the protostar on a 1000 au scale is first revealed by using their intensity ratio. Two local hot regions (bow shock and interaction region) are identified in addition to the protostar position, indicating that even the relatively evolved protostar still continues to give a substantial impact on a parent core by jets/outflows. (Yamamoto Group)

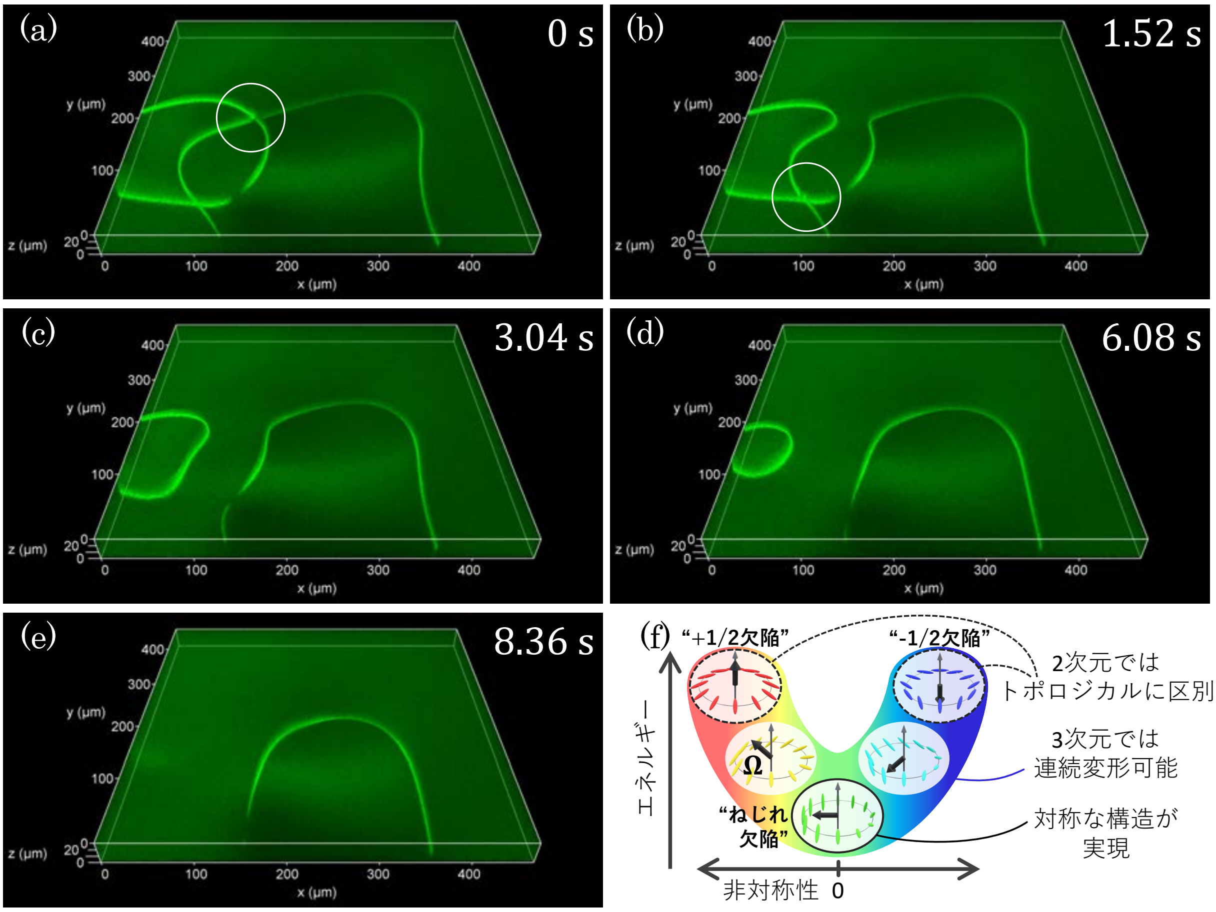


図 3: 液晶には分子の向きを揃える配向秩序があるが、配向の不整合な箇所が点状あるいは線状のトポロジカル欠陥として現れ、互いに相互作用する。(a)-(e) 生じた線欠陥が次第に消えていく様子を、欠陥への蛍光色素の吸着を利用して共焦点顕微鏡で 3 次元的に撮影した。ひも状の線欠陥が繋ぎ替わりながら（(a),(b) の白丸に注目）消えていく様子がわかる。(f) 2 次元では 2 つの点欠陥同士が近づくとき、その運動は非対称であることが知られているが、3 次元における線欠陥同士は対称に近づくことを我々は明らかにした。欠陥のトポロジーとエネルギーを議論することで、3 次元での対称性の回復を理解することができる。(竹内研究室)

Liquid crystals have an orientation order that aligns molecules, but locations of local mismatch of the order also exist. They appear as point-like or line-shape topological defects and interact with each other. (a)-(e) Three-dimensional motion of line defects was observed by confocal microscopy, using fluorescent dye localization on the defects. The string-like defects are reconnected (see the white circles in (a) and (b)) and shrink to disappear. (f) When two point defects in two dimensions approach each other, their motion is known to be asymmetric. In contrast, in three dimensions, we found that line defects approach symmetrically. By discussing the topology and energy of defects, we describe why the symmetry is restored in three dimensions. (Takeuchi group)

# II

# Summary of group activities in 2021

# 1 Fukushima Group

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

**Member:** Kenji Fukushima and Arata Yamamoto

In Theoretical Hadron Physics group, many-body problems of quarks and gluons are studied theoretically on the basis of the quantum chromodynamics (QCD). The subjects studied include quark-gluon plasma in relativistic heavy-ion collisions, particle production mechanism, lattice gauge simulations, matter under extreme conditions, neutron stars, etc.

Highlights in research activities of this year are listed below:

1. Extreme matter in electromagnetic fields and rotation
2. Non-Abelian vortex in lattice gauge theory
3. Limitation of the functional RG method for the $\theta$ vacuum
4. Skyme crystal for dense matter under strong magnetic fields
5. Extensive analysis for the neutron star EoS from calculations and observations

# 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. In particular, 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 the comparisons with cold-atom experiments.

Highlights in research activities of this year include:

1. Charge symmetry breaking force in nuclear DFT
2. Cluster structure of atomic nuclei
3. Functional renormalization group approach to DFT
4. Inverse method to derive nuclear EDF
5. Quartet correlations in nuclear matter
6. Three-body counterpart of BCS-BEC crossover
7. Polaron properties in ultracold atoms and their applications to nuclear systems
8. Topological unitary $p$-wave Fermi gas and spin transport in one dimension
9. Resonant pair scattering in two-band superconductors
10. Sphericity of atoms
11. Lipkin model with quantum computation

# 3 High Energy Physics Theory Group

**Research Subjects:** Particle Physics and Cosmology

**Member:** Takeo Moroi, Koichi Hamaguchi, Yutaka Matsuo

We are working on various topics in particle physics and cosmology, such as physics beyond the Standard Model, dark matter, baryogenesis, inflation, phenomenology of supersymmetric models, grand unified theories, string theory, supersymmetric field theories, conformal field theories, holography, entanglement entropy, and so on. Specific subjects studied in this academic year are summarized below:

1. Phenomenology
   - 1.1. Inflation models [1]
   - 1.2. New physics search at the ILC beam dump [2]
   - 1.3. Axion phenomenology [3]
   - 1.4. Anomalous magnetic moment of muon [4, 5, 6, 7]
   - 1.5. Supersymmetric grand unified theory [8]
   - 1.6. Supersymmetric phenomenology [9, 10]
   - 1.7. MiniBooNE anomalous excess [11]
   - 1.8. Supernova axion detection [12]
2. Superstring theory and formal aspects of quantum field theories
   - 2.1. $q$-Deformation of Corner Vertex Operator Algebras by Miura Transformation [13]
   - 2.2. Quiver Quantum Toroidal Algebra [14, 15]
   - 2.3. Blackhole and capacity of entanglement [16, 17]
   - 2.4. Supersymmetric gauge theory [18]
   - 2.5. Generalized symmetries [19, 20]
   - 2.6. Lorentz-invariant wave packets [21]

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# 4 Sakurai Group

## **Research Subjects:** Structure and dynamics of exotic nuclei and exotic atoms

## **Member:** Hiroyoshi Sakurai and Megumi Niikura

Our group investigates the structure and dynamics of exotic nuclei and exotic atoms. Our experimental programs utilize the accelerator facilities at RI Beam Factory (RIBF) in RIKEN, Research Center for Nuclear Physics (RCNP) in Osaka University, and Heavy Ion Medical Accelerator in Chiba (HIMAC). Some of our research subjects are the following.

**Nuclear charge distribution and radius measurements using muonic X ray**

The nuclear charge distribution and radius are the most fundamental values of atomic nuclei. The muonic X-ray measurement is one of the most common methods to determine the charge radius. We have developed an analysis procedure using higher transitions of the muonic atom in addition to the lowest $K_\alpha$ transitions and reduced the model dependency. Furthermore, we proposed a new method to measure the charge distribution using muonic X rays and evaluated its systematic uncertainty.

**High current beamline for transmutation accelerator**

A high-current beam accelerator for the transmutation of waste fuels from the nuclear power plant is under development. The difficulty of a high beam current transportation is a larger beam diameter than the conventional system, so the accuracy of the paraxial approximation adopted in the conventional beam optical calculation method deteriorates. In addition, a beam halo is generated by the multipole electromagnetic field excited by the beam and the solenoid magnet. We are developing methods to estimate a beam halo considering the effects of multipole electromagnetic fields and to cancel out the multipole electromagnetic field caused by the space charge effect by an appropriate placement and excitation of the solenoid coil.

**HiCARI project at RIBF**

HiCARI (High-Resolution Cluster Array at RIBF) aims at measuring high-level density odd nuclei and the lifetimes of the excited states of unstable nuclei. This array consists of 12 germanium detectors gathered from all over the world. A series of experiments were held at RIBF in 2020 with the world's highest beam intensity of unstable nuclei. In December 2020, our proposed experiment to investigate the neutron shell evolution of titanium isotopes has been conducted and the data analysis is now on going.

**Study of pion production**

We investigate the cluster structure in atomic nuclei by sub-threshold pion production. An experiment to measure the cross-section of pion production was performed at RIBF. $\pi^0$ was produced by $^{52}$Ca beam impinged on a carbon target. Two gamma rays emitted from gamma rays from the decay of $\pi^0$ were detected by CATANA array. To establish the way to distinguish signals from gamma rays from signals from charged particle, reactions of gamma rays and protons in CATANA were simulated by using Geant4. As a result, 80% of signals from protons regarded as those from protons, and 90% of signals from gamma rays regarded as those from gamma rays.

**Performance study of the photon detection system for muonic X-ray spectroscopy**

The photon detection system using Ge detectors and Compton suppressors is under development for muonic X-ray spectroscopy. The energy of muonic X-rays of low and high atomic number elements are dozens of keV and about 6 MeV, respectively. In order to test the performance in such a wide dynamic range, a test experiment was held using the resonance reaction of a proton and Al as shown in Fig. 2.1.1.

**Study of the equation of state of high-density neutron matter by heavy-ion collision**

To study the equation of state of high-density neutron matter experimentally, measurements of the collective flow of protons and neutrons in heavy-ion collisions are promising. We have performed the heavy-ion collision experiment (400-AMeV $^{132}$Xe beam + CsI) conducted at HIMAC and confirmed the collective flow of protons and neutrons at the target rapidity for the first time. We are planning a new experiment with a detector with improved resolution of the reaction plane.

**Decay spectroscopy of neutron-rich isotopes in BRIKEN project at RIBF**

The BRIKEN project targets to measure decay properties of nuclei, such as half-lives, $\beta$-delayed neutron emission probabilities and isomeric transitions. These properties are essential for understanding the $r$-process. In April 2021, an experiment for $N \geq 126$ isotopes was performed. The setup included WAS3ABi array, two HPGe clover detectors and 140 $^3$He counters. Half-lives of at least 28 isotopes from Ir to Po were deduced. Among them, half-lives of 10 isotopes were measured for the first time.

**Precision nuclear mass measurement by MRTOF-MS at RIBF**

Multi-reflection time-of-flight mass spectrograph (MRTOF-MS) at ZeroDegree spectrometer in RIBF is developed to measure nuclear masses of exotic isotopes. It is capable to achieve mass resolving power of greater than 1000000 with measurement time of 25 ms. In December 2021, masses of $^{74}$Ni and $^{75}$Ni were measured for the first time. The study can evaluate neutron separation energy $S_n$ of neutron-rich isotopes which help constrain the $r$-process calculation.

# 5 Yokoyama(M)-Nakajima Group

## Research Subjects: Experimental Particle Physics and Particle Astrophysics

## Member: Masashi Yokoyama, Yasuhiro Nakajima, and Kota Nakagiri

The main focus of our groups is the study of neutrino properties and research using neutrino as a probe. We are leading experiments using Super-Kamiokande and Hyper-Kamiokande detectors and the J-PARC accelerator.

**T2K long-baseline neutrino oscillation experiment**

We have been studying neutrino oscillations with the T2K long-baseline neutrino experiment. In T2K, intense neutrino and anti-neutrino beams produced using the J-PARC accelerator complex are measured with the SK detector, 295 km away. Our current major research goal is the search for a new source of CP symmetry violation in neutrino oscillations. We have been leading the program to upgrade near neutrino detectors for the reduction of uncertainties associated with understanding of neutrino interactions.

**Super-Kamiokande experiment**

Super-Kamiokande is the world's largest underground detector for neutrino physics and nucleon decay. In the summer of 2020, we added 13 tons of $Gd_2(SO_4)_3$ to 50,000 tons of ultrapure water and started new observations as SK-Gd. The addition of gadolinium improves the detection efficiency of neutrons. Utilizing this new capability, we aim for the world's first observation of supernova relic neutrinos.

Using the data collected with the Super-Kamiokande detector, we set the most stringent lower limits to the partial lifetimes of proton decay, $p \to e^+\eta$ and $p \to \mu^+\eta$.

**Hyper-Kamiokande**

In order to significantly extend the reach in the neutrino physics and the proton decay search beyond T2K and SK, the next-generation water Cherenkov detector, Hyper-Kamiokande is under construction. The Hyper-Kamiokande will be a large water Cherenkov detector with a cylindrical tank 68 meters in diameter and 71 meters deep, filled with 260,000 tons of ultrapure water. Our group is leading the design and construction of the Hyper-Kamiokande detector system. We are also testing the performance of the photomultiplier tubes and developing calibration methods.

**R&D of particle detectors for future experiments**

We have been developing novel particle detectors for future experiments. One example is a Time Projection Chamber (TPC) using an organic liquid as a medium for precise measurement of reactor neutrinos and supernova neutrinos. Another is the search for neutrinoless double-beta decay with $^{160}$Gd, utilizing ultra-high purity Gd technology developed for the SK-Gd project.

# 6 Asai group

**Research Subjects:** (1) Particle Physics with the energy frontier accelerators (LHC) (2) Physics analysis in the ATLAS experiment at the LHC: (Higgs, SUSY and Extra-dimension) (3) Particles Physics without accelerator using high intensity of Photon (4) Positronium and QED (5) Quantum Technology and Artificial Intelligence (AI)

**Member:** S.Asai, A.Ishida

- (1) LHC (Large Hadron Collider) has the excellent physics potential. Our group is contributing to the ATLAS group in the Physics analyses: focusing especially on three major topics, the Higgs boson, Supersymmetry, and new diboson resonances(WW and $\gamma\gamma$).
  - Higgs: After the discovery of Higgs Boson, We are measuring the Yukawa coupling precisely.
  - SUSY: We have excluded the light SUSY particles (gluino and squark) whose masses are lighter than 1.4 and 1.5TeV, respectively.
- (2) Small tabletop experiments have the good physics potential to discover the physics beyond the standard model, if the accuracy of the measurement or the sensitivity of the research is high enough. We perform the following tabletop experiments:
  - Dark matter indirect search with multi-wavelength photons.
  - Search for Photon-Photon scattering with XFEL.
  - Search for WISPs in various wavelengths with high-power light sources.
  - Basic study for Bose-Einstein condensation of positronium.
  - Search for vacuum birefringence.

- Search for vacuum diffraction with an XFEL and high power laser beams.
- Precision measurement of the energy spectrum in the orthopositronium decay.
- Measurement of Positronium Hyper-fine splitting.
- Search for weakly coupling neutral particles with ortho-positronium.
- Search for CP violation with ortho-positronium.
- Search for the invisible decay of ortho-positronium.
- Lifetime measurement of ortho-positronium.
- Search for solar axions with Fe-57 resonant absorption.

• (3) Quantum Technology and Artificial Intelligence (AI) for application to fundamental physics.

- Optimization problems (database search and gradient estimation).
- Performance evaluation and improvement of quantum machine learning model with repetitive structure.

# 7 Ogata Group

**Research Subjects:** Condensed Matter Theory

**Member:** Masao Ogata, Hiroyasu Matsuura

We are studying condensed matter physics and many body problems, such as strongly correlated electron systems, high-$T_c$ superconductivity, Mott metal-insulator transition, topological materials, Dirac electron systems in solids, thermoelectric materials with large response, organic conductors, and magnetic systems with frustration and/or spin-orbit interactions. The followings are the current topics in our group.

• Dirac electron systems in solids [1,2]
• Thermal transport phenomena [3-6]
• Theories on topological materials [7,8], and on superconductivity [9]
• Orbital magnetic effects [10]
• Organic conductors [11-14]
• Spin systems and spin-orbit interaction [15,16]


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# 8 Tsuneyuki Group

**Research Subjects:** Theoretical Condensed-Matter Physics

**Member:** Shinji Tsuneyuki and Ryosuke Akashi

Computer simulations from first principles enable us to investigate the properties and behavior of materials beyond the limits of experiments, or rather to 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 calculation based on the density functional theory (DFT). We are also developing new methods that go beyond the limitation of classical MD and DFT to study the electronic, structural, and dynamical properties of materials. One of such new methods is a structure prediction method with data assimilation, where X-ray powder diffraction data insufficient for experimental structure determination is used to support theoretical structure search.

Major research topics in FY 2021 are as follows.

- Application of the data assimilation method for crystal structure exploration containing hydrogen atoms which are hard to observe by X-ray diffraction
- Superconductivity of oxyhydrides with Wannier-interpolation of phonon dynamical matrix
- Eliashberg theory in the electron-gas limit
- Application of density functional theory to nuclei
- Construction of energy density functional using functional renormalization group
- Deformability of atoms
- Correlated wavefunction theory: Transcorrelated method

# 9 Todo Group

**Research Subjects:** Development of simulation algorithms for strongly-correlated systems; Application of machine learning technique to materials science; Fundamental theory of quantum computer; Novel state and critical phenomena in strongly correlated systems; Thermalization and non-equilibrium dynamic of quantum many-body systems; Development of open-source software for next-generation parallel simulations

**Member:** Synge Todo, Tsuyoshi Okubo, and Hidemaro Suwa

We are exploring novel computational physics methods based on sampling methods such as the Monte Carlo algorithm, path integrals to represent quantum fluctuations, information compression using the singular value decomposition and the tensor networks, and statistical machine learning, etc. By making full use of these powerful numerical methods, we aim to elucidate various exotic states, phase transitions, and dynamics in various quantum many-body systems, from quantum spin systems to actual materials. Also, we are studying the basic theory of quantum computers and quantum machine learning algorithms and working on the development and release of open-source software for next-generation large-scale simulations.


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# 10 Katsura Group

## Research Subjects: Condensed Matter Theory and Statistical Physics

## Member: Hosho Katsura and Yutaka Akagi

In our group, we study various aspects of condensed matter and statistical physics. In particular, our research focuses on strongly correlated many-body systems in and out of equilibrium, which would give rise to a variety of novel phases. We study theoretically such systems, with the aim of predicting intriguing quantum phenomena that have no counterpart in weakly-interacting systems and cannot be understood within standard approaches. Our work involves a combination of analytical and numerical methods. We are currently interested in (i) low-dimensional correlated systems, (ii) off-diagonal long-range order in Hubbard-like models, (iii) symmetry-protected topological phases, (iv) topological magnon systems, and (v) frustration-free spin models. In addition, we are also interested in the mathematical aspects of the above-mentioned fields. Our research projects conducted in FY 2021 are the following:

- Strongly correlated systems
  - Exact analysis of nonlinear Drude weights for quantum spin chains [1, 2]
  - Phase diagram of an extended parafermion chain [3]
  - Bose-Einstein condensation in an interacting boson model with flat bands [4]
  - $SU(N)$ generalization of $\eta$-pairing states and off-diagonal long-range order [5]
- Topological phases of matter
  - Symmetry-protected topological phases in spinor Bose-Hubbard models [6]
  - Dirac surface states in magnonic analogs of topological crystalline insulators [7]
  - Nonlinear magnon spin Nernst effect in antiferromagnets and strain-tunable spin current [8]
  - Fractional Skyrmion molecules in a $CP^{N-1}$ nonlinear sigma model [9]
- Mathematical and statistical physics
  - Interrelations among frustration-free models via Witten's conjugation [10]
  - Multiple magnetization plateaus in an extended $S = 1$ Gelfand ladder [11]
  - Exact solutions of few-magnon problems in the spin-$S$ periodic XXZ chain [12]
  - Performance comparison of typical binary-integer encodings in an Ising machine [13]

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# 11 Kabashima Group

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

**Member:** Yoshiyuki Kabashima and 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 2021:

1. Performance analysis of $\ell_1$-reguralized linear regression for Ising model selection
2. Solution analysis of SCAD minimization problem under linear constraints
3. Matrix factorization using Gaussian-based belief propagation and its application to matrix completion
4. Assessment of transfer entropy from biochemical data
5. Statistical mechanics analysis of unbounded knapsack problems
6. Analysis of eigenvalue distribution of sample covariance matrix
7. Performance analysis of iterative self-training with linear classifier
8. Analysis of general objective index

# 12 Tsuji Group

**Research Subjects:** Condensed matter theory, nonequilibrium quantum many-body systems

**Member:** Naoto Tsuji, Huanyu Zhang

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 2021, we worked on the following projects:

- Dynamics of superconductors
  — Higgs mode in superconductors [9]
  — Higher-oder nonlinear optical response and self-interaction of Higgs mode [5, 6]
  — Leggett mode in multiband superconductors [1]
  — $\eta$ pairing superconductivity and coupling to electromagnetic fields
- Dissipative quantum many-body systems [3]
  — Collective modes and phase transitions in dissipative superfluids [2, 4]
  — Superfluidity induced by spontaneous light emission [8]
- Fluctuation, nonlinear response, and chaos [7]

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[7] Naoto Tsuji, “Fluctuations, nonlinear response, and chaos”, Quantum, heat, information mini workshop, online, December 2021.

[8] Naoto Tsuji, “Nonequilibrium superconductivity toward a realization at high temperature”, Condensed matter theory seminar, Osaka University, online, July 2021.

[9] Naoto Tsuji, “Recent developments of’ nonequilibrium physics in quantum many-body systems”, Department of Physics, Osaka University, International Physics Course (IPC), Topical Seminar II, online, July 2021.


# 13 Ashida Group

## Research Subjects: Condensed matter theory, theoretical quantum optics

## Member: Yuto Ashida

This group focuses on theoretical studies at the intersection of quantum many-body physics and quantum optics. We have been studying physics of open and out-of-equilibrium systems, where quantum systems interact with 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 as well as their potential applications. We have also been doing studies related to machine learning methods, such as Bayesian inference and reinforcement learning. We list research/review papers published in the academic year of 2021 below.

- Non-Hermitian physics, open quantum systems [1]
- Strongly interacting quantum light-matter systems [2]
- Statistical physics [3]


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# 14 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 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. Main results in this year are as follows.

**(1) Surface transport and magnetism**:
- soft-magnetic skyrmions at interfaces/heterostructures at ferromagnetic topological insulators
- 2D superconductivity at Ca-intercalated graphene, FeSe atomic layers, and $\alpha$-Sn layers
- non-reciprocal photocurrent at a Rashba surface induced by irradiation of circularly polarized light
- Weak anti-localization and linear magnetoresistance effect at $Cu_2Se$ thin films
- Ferromagnetic states at intercalated graphene and Mn-doped transition-metal dichalcogenide

**(2) Surface phases and atomic-layer materials**:
- Epitaxial growth of ultra-flat SnTe films on $SrTiO_3(001)$

**(3) New methods**:
- Fabrication of a four-point probe UHV system with tunneling-spectroscopy capability
- Fabrication of a UHV-MBE system with polarization-controlled mid-infrared irradiation
- Lateral-ToF system with pulsed laser for carrier mobility measurements


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[3] T. Machida, Y. Yoshimura, T. Nakamura, Y. Kohsaka, T. Hanaguri, C.-R. Hsing, C.-M. Wei, Y. Hasegawa, S. Hasegawa, and A. Takayama: *Superconductivity near the saddle point in the two-dimensional Rashba system Si(111)-*$\sqrt{3} \times \sqrt{3}$*-(Tl,Pb)*, Physical Review B **105**, 064507 (9pp) (Feb, 2022).

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# 15 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 $H_{\parallel}$ on superconductivity of monolayer Pb films on GaAs(110). Superconductivity was found to occur even for $H_{\parallel} = 14$ T, which is much higher than the Pauli paramagnetic limiting field $H_P$. The observed weak $H_{\parallel}$ 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.

   We have studied nonreciprocal charge transport in superconducting ultrathin films. For ultrathin Pb and Al films grown on the cleaved surface of GaAs (110), the antisymmetrized second harmonic magnetoresistance was observed, which suggests that rectification effect occurs in superconducting ultrathin films. Moreover, to clarify the origin of the rectification effect, we made the observation of the cleaved GaAs surface using a scanning electron microscope. We found that an asymmetric edge structure occurs the rectification effect, which is called vortex ratchet.

3. Formation of Dirac cones in ultrathin Bi films
Magnetotransport measurements have been performed on ultrathin Bi films grown on GaAs(110). While large positive magnetoresistance is observed at low temperatures, the Hall resistance is found to be extremely small. This is explained by the cancellation of contributions of electrons and holes, which are estimated to have close density and mobility values. By analogy with graphene near the charge neutral point, magnetotransport properties are discussed in relation to the formation of Dirac cones.

# 16 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 FY2021 are as follows.

1. **Nonequilibrium dynamics of superconductors:** We have investigated the photoexcited nonequilibrium dynamics of high-$T_c$ cuprate superconductors and iron-based superconductors, by using collective modes, namely the Higgs mode and nonlinear Josephson current response as a ultrafast probe for the superconducting order parameter.

2. **Nonequilibrium dynamics of charge density wave system:** We have investigated the photoinduced phase transition phenomena(PIPT) in a thin film of transition metal dichalcogenide (TMD) 3R-$Ta_{1+x}Se_2$ which shows a charge density wave(CDW) order at low temperatures. As a new route

toward the PIPT, we investigated the direct modulation of the order parameter itself by exciting the amplitude mode. Melting dynamics of the CDW order induced by the large amplitude driving of the CDW amplitude mode was studied by terahertz pump and optical probe experiments.

3. **Floquet engineering of Dirac electron systems:** We have aimed at realizing Floquet states in Dirac electron system in thin films of Bi and $Co_3Sn_2S_2$. 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. The results are accounted for by the emergence of light-induced Berry curvature and the induced Hall conductivity is interpreted by the effect of chiral gauge field implemented by the circularly polarized light into the Dirac electron system.

**References**


[1] Hiroaki Niwa, Naotaka Yoshikawa, Masashi Kawaguchi, Masamitsu Hayashi, and Ryo Shimano: Switchable generation of azimuthally- and radially-polarized terahertz beams from a spintronic terahertz emitter, Optics Express **29**, 13331 (2021). Editors' pick

[2] Naotaka Yoshikawa, Hiroki Suganuma, Hideki Matsuoka, Yuki Tanaka, Pierre Hemme, Maximilien Cazayous, Yann Gallais, Masaki Nakano, Yoshihiro Iwasa and Ryo Shimano: Ultrafast switching to an insulating-like metastable state by amplitudon excitation of a charge density wave, Nature Physics **17**, 909 (2021).

[3] Kazuki Isoyama, Naotaka Yoshikawa, Kota Katsumi, Jeremy Wong, Naoki Shikama, Yuki Sakishita, Fuyuki Nabeshima, Atsutaka Maeda, and Ryo Shimano: Light-induced enhancement of superconductivity in iron-based superconductor $FeSe_{0.5}Te_{0.5}$, Communications Physics **4**, 160 (2021).

[4] Romain Grasset, Kota Katsumi, Pierre Massat, Hai-Hu Wen, Xian-Huin Chen, Yann Gallais, and Ryo Shimano: Terahertz pulse-driven collective mode in the nematic superconducting state of $Ba_{1-x}K_xFe_2As_2$, npj Quantum Materials **7**, 4 (2022).


# 17 Takagi-Kitagawa Group

## **Research Subjects:** Physics of Correlated Electron Systems

## **Member:** Hidenori Takagi, Kentaro Kitagawa, Naoka Hiraoka

We are exploring new compounds with transition metal elements in which novel, exotic and/or functional electronic phases are realized. Our main targets in FY2021 included, $4f$ lanthanoide honeycomb-lattice compounds with interplay of electron correlations and strong spin orbit coupling, spin liquids, bosonic Bose-Einstein condensation, excitonic ground states, and instrumental development of ultrahigh-pressure magnetometry device.

Realization of spin liquid, where quantum spins fluctuates at absolute zero, should be a milestone in the field of quantum spin physics. After a theoretical achievement of the exactly solvable spin liquid state on a honeycomb lattice, by Alexei Kitaev, a materialization of this Kitaev Honeycomb Model (KHM) has been intensively pursuit. One dimensional spin liquid has been commonly accepted, while in two or three dimensions, typical known frustrated quantum spin liquid materials, like triangular compounds, is not based on an exactly solvable lattice model. We have been focussed on a two-dimensional honeycomb iridate, $H_3LiIr_2O_6$, and discovered that $H_3LiIr_2O_6$ is indeed spin liquid, as the first material of such a liquid, down to 50 mK by specific heat, magnetic susceptibility, and nuclear magnetic resonance experiments. This key result was published in 2018–2021.

The key ingredient to realize KHM is bond-dependent anisotropic Ising-like interactions, and it was suggested that material engineering for spin-orbit coupled $J_{\mathrm{eff}} = 1/2$ quantum pseudo spins of Ir on (hyper-)honeycomb lattice would be a main route. Two kinds of Majorana fermions represent KHM and they are particles on the exactly solved ground state. Since our discovery is an only spin liquid on Kitaev system, and no report was given to proof two Majorana particles. We will pursuit realization of "true" Kitaev material. For this purpose, we are exploring a new route to Kitaev physics, by making Lanthanoid honeycomb materials. For example, $Na_2PrO_3$ is a newly suggested candidate for a platform of an anti-ferromagnetic Kitaev-type interaction. We have clarified $Na_2PrO_3$ exhibits metamagnetic behavior which has been theoretically expected for the antiferromagnetic Kitaev spin liquid and its proximate. We further explore other $4f$ Lanthanoid honeycomb materials as a new field for quantum magnetism in combination with Material Informatics and traditional crystal growth techniques.

To further accelerate quantum magnetism research in different ways, we apply ultrahigh pressure on such candidate materials to modify the ground state. However, it has been difficult to evaluate magnetic samples above a few giga pascals. This year, we developed a highly sensitive technique to conduct magnetometry under very high pressures up to 7 GPa using an opposed-anvil type cell, which can detect a weak volume susceptibility as small as $\sim 10^{-4}$. The high-pressure cell has an optimized geometry to yield a reduced background in the magnetic response, one order of magnitude smaller than those for previously reported high-pressure cells in a commercial SQUID magnetometer. Using this unique technique, we will explore novel magnetism under pressure.

# 18 Hayashi Group

## Research Subjects: Quantum spintronics/optics

## Member: Masamitsu Hayashi, Masashi Kawaguchi

We work in the field of quantum spintronics and optics. Currently we put a particular focus on the strong coupling of spins, photons, magnons and phonons, mediated by the spin orbit interaction of the system, and look for the physics that can be applied to quantum physics.

- Spin current generation
  - Spin currents in Pt-Bi alloy[2]
  We have studied the spin torque efficiency of $Pt_{1-x}Bi_x$ alloy. The spin Hall angle increases with Bi concentration and exceeds 0.3 when x is close to 0.9. As the magnetic easy axis of a 0.6 nm thick Co layer deposited on the alloy points along the film normal, the system serves as an ideal system for spin − orbit torque magnetization switching devices.

- Polarized THz pulses from a spintronic THz emitter
  - Terahertz wave radiation from via spin current[4]
  Two fundamental terahertz cylindrical vector beams (CVBs), azimuthally- and radially-polarized THz pulses, are generated from a spintronic THz emitter. A metallic bilayer, consisting of a ferromagnetic layer and heavy metal layer, is irradiated with a femtosecond laser pulse. By applying appropriate magnetic fields and using a triangular Si prism, THz CVBs are observed from the emitter. The approach facilitates access of CVBs and paves the way toward polarization control in the THz regime.

  - Helicity dependent photocurrent in metal/semimetal bilayers[3]
  We have studied helicity dependent photocurrent (HDP) in metal/semimetal (Bi) bilayers. Compared to Bi single layer films, we find the HDP is enhanced in metal/Bi bilayers. For the bilayers, the sign of HDP under back illumination reverses from that of front illumination. Using spin transport calculations, we show that the HDP sign reversal under back illumination is caused by spin absorption and spin to charge conversion at the metal/Bi interface. These results show that the HDP can be used to assess interface states with strong spin orbit coupling.

- Chiral magnetism
  - Magnetic compensation in rare-earth baed ferrimagnetic alloy thin films[1]
  We have studied the magnetic properties of Tb-based rare-earth (RE) - transition metal (TM) ferrimagnetic $Tb_x(FeCo)_{1-x}$ thin films. We find that the Tb concentration at which the magnetic moments of the RE- and TM-sublattices compensate increases with decreasing film thickness when the films are grown on Pt underlayers. For the thinnest TbFeCo films (1.5 nm-thick), the magnetic compensation is not observed at room temperature, suggesting that the Tb atoms do not contribute to the magnetization. The Tb concentration at which magnetic compensation occurs decreases when the underlayer is changed from Pt to Ta. These findings contribute to developing the understanding of magnetism in ferrimagnetic alloy based thin film heterostructures.

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# 19 Kobayashi Group

**Research Subjects:** mesoscopic physics, quantum sensing, diamond NV center, noise & fluctuations, nonequilibrium phenomena

**Member:** Kensuke Kobayashi and Kento Sasaki

The nano-fabrication technique allows us to investigate fascinating behaviors of "mesoscopic systems", namely, electronic devices that work in the quantum regime. They have been serving as ideal test-beds to demonstrate various quantum effects in a controllable and thus transparent way since the 1980s, as we can precisely tune and probe the electron transport through a single quantum site. Significantly, the Landauer-Büttiker formalism embodies this advantage of mesoscopic physics, and it has successfully applied to many nano-fabricated conductors (e.g. Aharonov-Bohm ring, quantum dot, etc.), through which mesoscopic physics has been established.

We are interested in various phenomena in mesoscopic systems, especially quantum many-body effects, non-equilibrium phenomena, and spin/thermal transport. High-precision measurement of conductance and current fluctuations enables us to understand quantitatively quantum transport, which has been difficult. We now primarily focus on quantum sensing using diamond NV centers (nitrogen-vacancy centers). We are developing a single quantum spin microscope to apply the high-precision measurement of physical properties, especially in mesoscopic systems.

In FY2021, we addressed the following research topics:

- Vector magnetometry using perfectly aligned nitrogen-vacancy center ensemble in diamond.
- Accurate magnetic field imaging using nanodiamond quantum sensors promoted by machine learning.
- Lock-in thermography using diamond quantum sensors.
- Spin wave detection using NV centers.
- Demonstration of Floquet engineering using pulse driving in a diamond two-level system under a large-amplitude modulation.
- Three-body correlations in nonlinear response of correlated quantum liquid.
- Negative correlation between the linear and the nonlinear conductance in magnetic tunnel junctions.
- Thickness-induced crossover from strong to weak collective pinning in exfoliated $FeTe_{0.6}Se_{0.4}$ thin films.
- Charge density wave transitions in mechanically-exfoliated $NbSe_3$ devices.

Published papers:

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[2] K. Fujiwara *et al., Jpn. J. Appl. Phys.* **60,** 070904 (2021) [Rapid Comm.].

[3] S. Iwakiri *et al., Phys. Rev.* B **103,** 245427 (2021).

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[5] K. Kobayashi and M. Hashisaka, *J. Phys. Soc. Jpn.* **90,** 102001 (2021) [Invited Review].

[6] R. Nakamura *et al., Phys. Rev.* B **104,** 165412 (2021).

# 20 Nakatsuji-Sakai Group

A new era in quantum materials research arises, featuring discoveries of novel topological phases of matter and interdisciplinary approaches. Our research activities focus on designing and synthesizing new materials with emergent quantum properties that have never been seen before, then exploring the physics and functionalities of such properties with our world-leading measurement facilities. We aim to lead the innovative quest for new quantum materials that bear a far-reaching impact not only on basic science but also on our everyday life in the future.

**Major research themes:**
1. Solid-state analogs of relativistic particles and new quantum phenomena in strongly correlated topological phases and frustrated magnets
2. Room-temperature topological transport in magnetic materials
3. Non-Fermi-liquid behavior and exotic superconductivity in multipolar Kondo materials

**Summary of research subjects in 2021**

1. Large anomalous Nernst effect in an iron-based kagome ferromagnet $Fe_3Sn$
Anomalous Nernst effect (ANE), a transverse thermoelectric effect that occurs in magnetic material, has recently attracted attention for its application in energy-harvesting technology. It can be exploited in developing high-efficiency energy-harvesting devices with a simple lateral structure, high flexibility, and low production cost. In this work, we reported our observation of a high ANE exceeding 3 $\mu$V/K above room temperature in the kagome ferromagnet $Fe_3Sn$ with the Curie temperature of 760 K [1]. First-principles calculation clarifies that a "nodal plane" produces a flat hexagonal frame with strongly enhanced Berry curvature, resulting in the large ANE. Our discovery suggests that the flat degenerate electronic states provide a useful guide to design magnetic materials with a large ANE.

2. Enhanced Anomalous Hall signal by electrical manipulation in antiferromagnetic Weyl metal $Mn_3Sn$
The topological band structure of antiferromagnetic $Mn_3Sn$ yields surprisingly large anomalous transport, holding promises for next-generation ultrafast magnetic memory devices. Our recent study reports electric-current control of the anomalous Hall signal in $Mn_3Sn$/heavy metal heterostructures[Nature ('20)]. This work further optimizes the multilayer structure and deposition process and realizes a three-time enhancement of the readout signal (Hall resistance). This improved performance is achieved by (i) aligning the $Mn_3Sn$ crystal grains parallel to the direction of the Hall signal and (ii) improving the interfacial condition between $Mn_3Sn$ and the W layer. This finding may bring memory devices based on topological antiferromagnet closer to real-world applications [2].

3. Ferrimagnetic compensation and its thickness dependence in TbFeCo alloy thin films
Rare earth (RE)-transition metal (TM) ferrimagnetic materials feature reduced net magnetization and bulk perpendicular magnetic anisotropy (PMA), leading to compelling advantages in realizing efficient magnetic application devices. This work focuses on the magnetic properties of Tb-based RE – TM ferrimagnetic $[Tb_x(FeCo)_{1-x}]$ thin films [3]. In films grown on Pt underlayers, a decrease of film thickness leads to increased Tb concentration at which the magnetic moments of the RE- and TM-sublattices compensate. Such magnetic compensation does not occur at room temperature for the thinnest (1.5 nm-thick) TbFeCo films. In these films, inserting a thin Co layer enhances the PMA, while a thin Tb layer insertion reduces the PMA to zero. Such contrasting behavior reveals that the PMA originates from the Pt/Co interface. The Tb concentration at which magnetic compensation occurs decreases when changing the underlayer from Pt to Ta. We infer that Tb becomes magnetically inactive due to intermixing with the Pt underlayer, causing the reduction in PMA.

4. Anomalous scaling behavior of transverse thermoelectric conductivity in ferromagnet CoMnSb
Transverse thermoelectric conductivity $\alpha_{yx}$ is a sensitive measure of momentum-space Berry curvature near the Fermi energy. Recently, critical behavior $\alpha_{yx} \sim T \log T$ arising from a Weyl semimetal state tuned toward a quantum Lifshitz critical point was reported in ferromagnet $Co_2MnGa$ [Nature Physics ('18)]. This study reports the same logarithmic critical behavior in another ferromagnet CoMnSb hosting Weyl semimetal state [4]. Thus, the novel temperature dependence of $\alpha_{yx}$ provides a practical guide to search for new magnetic topological materials.

5. The role of phonons in quantum pyrochlores $Pr_2X_2O_7$ ($X$ = Zr, Ir)

The Pr-based quantum pyrochlores $Pr_2X_2O_7$ ($X$ = Zr, Ir) exhibit exotic liquid states that defy long-range magnetic order. The non-Kramers $Pr^{3+}$ renders strong spin-lattice coupling, and it is essential to understand the role of phonons in shaping their magnetic and electronic properties. We investigate the phonon spectra of single-crystal $Pr_2Zr_2O_7$ and $Pr_2Ir_2O_7$ via Raman spectroscopy [5]. In $Pr_2Zr_2O_7$, lattice dynamics induces a doublet crystal-field excitation splitting at around 55 meV, creating a vibronic state. The phonon spectra of $Pr_2Ir_2O_7$ are similar to that of $Pr_2Zr_2O_7$ but with broadened peaks, attributed to phonon-electron scattering.

6. Record high antiferromagnetic transition in Yb-based heavy fermion proximate to a Kondo insulator
The magnetic transition temperature in Yb-based heavy-fermion systems is typically at least one order of magnitude lower than those observed in Ce-based counterparts despite their similar physical properties. Here, we report that Mn-doping at the Al site in $\alpha$-$YbAlB_4$ brings its heavy-fermion liquid state close to a Kondo insulator, leading to a record high antiferromagnetic transition reaching 20 K [6].


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# 21 Theoretical Astrophysics Group

**Research Subjects:** Observational Cosmology, Extrasolar Planets, Star Formation, high-energy astrophysics, and Artificial Intelligence

**Member:** Yasushi Suto, Naoki Yoshida, Kazumi Kashiyama , Masamune Oguri & Tilman Hartwig

The Theoretical Astrophysics Group conducts a wide range of research programmes. Observational cosmology is our primary research area, but we also pursue other forefront topics such as extrasolar planets, star formation, high-energy astrophysics, and artificial intelligence.

"Observational Cosmology" attempts to understand the evolution of the universe on the basis of the observational data in various wavebands. The proper interpretation of recent and future data provided by Planck, Hubble Space Telescope, ALMA, and wide-field galaxy surveys such as Subaru Hyper-Suprime-Cam survey are very 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, formation and evolution of proto-galaxies and proto-clusters, X-ray luminosity and temperature functions of clusters of galaxies, hydrodynamical simulations of galaxies and the origin of the Hubble sequence, thermal history of the universe and reionization, prediction of anisotropies in the cosmic microwave background radiation, statistical description of the evolution of mass functions of gravitationally bound objects, statistics of gravitationally lensed quasars, and the chemical formation history of the Milky Way.

Astronomical observations utilizing large ground-based telescopes discovered distant galaxies and quasars that were in place 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 were born, which illuminated the universe once again and terminate the cosmic Dark Ages. We study the formation of the first stars and blackholes in the universe. The first stars are thought to be the first sources of light, and also the first sources of heavy elements that enable the formation of ordinary stellar populations, planets, and ultimately, the emergence of life. We perform simulations of structure formation in the early universe on supercomputers. Direct and indirect observational signatures are explored considering future radio and infrared telescopes. We study the formation and mixing of the first heavy elements in the universe. Comparing the predictions of our simulations to observations allows us to better understand the nature of the underlying physical processes.

Can we discover a second earth somewhere in the universe? This puzzling question used to be very popular only in science fictions, but is now regarded as a decent scientific goal in the modern astronomy. Since the first discovery of a gas giant planet around a Sun-like star in 1995, more than 4000 exoplanets have been reported as of March 2021. Though most of the confirmed planets turned out to be gas giants, the number of rocky planet candidates was steadily increasing, which therefore should give the affirmative answer to the above question. Our approaches towards that exciting new field of exoplanet researches include the spin-orbit misalignment statistics of the Rossiter-MacLaughlin effect, simulations of planet-planet scattering, simulations of tidal evolution of the angular momentum of the planetary system, photometric and spectroscopic mapping of a surface of a second earth and detection of possible biomarker of habitable planets.

To maximise the information gain from astrophysical observations and numerical simulations, we also apply and develop state-of-the-art machine learning techniques. We use supervised machine learning algorithms to classify observations of metal-poor stars, quasars, and satellite galaxies of the Milky Way. We improve existing deep learning methods with a new class of activation functions that allow users to improve the extrapolation properties of their neural networks. Artificial intelligence (AI) is a rapidly evolving field with many promising applications. To better understand the social impact of AI research, we also collaborate with social scientists to better understand the impact and public attitudes towards AI research.

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

2021

- Study on the effect of supernova fallback on the neutron star diversity
- Gravitational hierarchical three-body systems with an invisible inner binary: application to binary black-hole search and their dynamical stability
- Analysis of the Large-Scale Structure of the Universe Using Cosmological Simulations and Machine Learning
- Planetary systems predicted from the ALMA disks: planet-disk evolution and long-term orbital stability of multi-planets
- Structure Formation of the Universe with Fuzzy Dark Matter
- Dispersal mechanism of proto-planetary disks

2020

- Observational signatures from tidal disruption events of white dwarfs
- Multiwavelength Signals From Pulsar-Driven Supernovae
- Measuring stellar rotation periods and stellar inclinations of kepler solar-type stars

2019

- Observational characterization of protoplanetary disks, exo-rings, and Earth-twins in exoplanetary systems

- Non-sphericities and alignments of clusters and central galaxies from cosmological hydrodynamical simulation: theoretical predictions and observational comparison
- Probing Cosmic Star-Formation History with Blind Millimetre Searches for Galaxy Emission Lines
- Photoevaporation process of giant planets
- Dilution of heavy elements in galaxies and its implications

2018

- Stellar Inclinations from Asteroseismology and their Implications for Spin-Orbit Angles in Exoplanetary Systems
- Numerical Investigations on Explosion Mechanisms of Core-collapse Supernovae
- Cosmology and Cluster Astrophysics with Weak Gravitational Lensing and the Sunyaev-Zel′dovich Effect
- Photoevaporation of Protoplanetary Disks and Molecular Cloud Cores in Star-Forming Regions
- Numerical Algorithms for Astrophysical Fluid Dynamics
- Radial velocity modulation of an outer star orbiting an unseen inner binary: analytic perturbation formulae in a three-body problem to search for wide-separation black-hole binaries
- The distribution and physical properties of emission line galaxies in the early universe
- Diversities out of the observed proto-planetary disks: migration due to planet-disk interaction and architecture of multi-planetary systems

2017

- Formation of supermassive stars and black holes via direct gravitational collapse of primordial gas clouds
- Formation and growth of massive black holes in the early universe
- Measuring Dynamical Masses of Galaxy Clusters with Stacked Phase Space
- GCM simulation of Earth-like planets for photometric lightcurve analysis
- Tidal disruption events of white dwarfs caused by black holes
- Radio, Submillimetre, and Infrared Signals from Embryonic Supernova Remnants

# 22 Murao Group

## **Research Subjects:** Quantum Information Theory

## **Member:** Mio Murao and Akihito Soeda

Quantum mechanics allows a new type of information represented by quantum states which may be in a superposition of 0 and 1 state. Quantum information processing seeks to perform tasks that are impossible or not effective with the use of conventional classical information, by manipulating quantum states to the limits of quantum theory. Examples are quantum computation, quantum cryptography, and quantum communication.

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. Recently, we are analyzing non-locality, causal structures, parallelizability, and anonymity of quantum information processing and quantum programming by investigating higher-order quantum operations and distributed quantum computation. We also investigate controls for quantum dynamics and quantum resource theory.

This year, our group consisted of two faculty members, Mio Murao (Professor), Akihito Soeda (Assistant Professor), a postdoctoral researcher, Bartosz Regula (JSPS foreign postdoctoral fellow since July), and 4 graduate students, Wataru Yokojima (D2), Atsushi Okamoto (M2), Yutaka Hashimoto (Ms), Kosuke Matsui (M2) and Satoshi Yoshida (M1), and two research students, Yu Tanaka and Timothy Forrer (since October). Our projects engaged in the academic year of 2021 were the following:

- Higher-order quantum operations
  - Probabilistic implementation of inverse map from unknown isometry operations by S. Yoshida, A. Soeda, and M. Murao
  - Storage and retrieval of higher-order quantum operations by W. Yokojima, A. Soeda, and M. Murao
  - Comparison of unknown unitary channels by Y. Hashimoto, A. Soeda, and M. Murao
  - Unitary channel discrimination beyond group structures: Advantages of sequential and indefinite-causal-order strategies, by M. Murao collaborated in collaboration with M.T. Quintino and J. Bavaresco at IQOQI Vienna in Austria
  - Application of Higher-order quantum operations to quantum machine learning by Y. Tanaka, A. Soeda, and M. Murao
- Controls for quantum dynamics
  - Robust control of quantum dynamics for a spin system with unknown parameters by A. Okamoto, A. Soeda, and M. Murao
- Distributed quantum information processing
  - Entanglement-efficient implementation protocols for distributed quantum computation with two quantum computers by K. Matsui, A. Soeda, and M. Murao in collaboration with Cambridge Quantum Computing Ltd. in UK, and Jun-yi Wu, at Tamkang University in Taiwan
  - Entanglement cost of distributed implementations of Clifford operations in two quantum computers by T. Forrer, A. Soeda, and M. Murao
- Quantum resource theory
  - Probabilistic transformations of quantum resources by B. Regula
  - One-shot yield–cost relations in general quantum resource theories by B. Regula in collaboration with R. Takagi from Nanyang Technological University in Singapore and M. Wilde from Louisiana State University in US

# 23 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, quantum Hall effect and vortex lattices in synthetic gauge fields, 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 and the formulations of state reduction dynamics and Hamiltonian estimation 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 FY2021 below.

- Quantum many-body phenomena in ultracold atoms, nonequilibrium open systems
  - Topological field theory of non-Hermitian systems [1]
  - Novel relation between the Liouvillian gap and relaxation time in open quantum systems with skin effects [2]
  - Extension of the BCS theory to open quantum many-body systems [3]
- Unification of quantum physics, statistical mechanics, information theory, and machine learning
  - Convergent and efficient deep Q network algorithm [4]
  - Fundamental theory for training deep neural networks [5, 6, 7, 8]


[1] K. Kawabata, K. Shiozaki, and S. Ryu, Phys. Rev. Lett. **126**, 216405 (2021) [selected for Editors' Suggestion].

[2] T. Haga, M. Nakagawa, R. Hamazaki, and M. Ueda, Phys. Rev. Lett. **127**, 070402 (2021).

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[4] Z. T. Wang and M. Ueda, The International Conference on Learning Representations 2022 (ICLR 2022).

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[6] Liu Ziyin*, K. Liu*, T. Mori, and M. Ueda (*equal contribution), The International Conference on Learning Representations 2022 (ICLR 2022) [Spotlight].

[7] Zhang Zhiyi and Liu Ziyin, 37th Conference on Uncertainty in Artificial Intelligence (UAI 2021).

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# 24 Yokoyama (J) Group

## Research Subjects: Theoretical Cosmology and Gravitation

## Member: Jun'ichi Yokoyama and Kohei Kamada

This group being a part of Research Center for the Early Universe (RESCEU) participates in research and education of Department of Physics in close association with Theoretical Astrophysics Group of Department of Physics. We are studying various topics on cosmology of the early universe, observational cosmology, and gravitation on the basis of theories of fundamental physics such as quantum field theory, particle physics, and general relativity. We have also been working on gravitational wave data analysis to prepare for completion of KAGRA. Below is the list of topics studied during the academic year 2021.

### Cosmology: Geometrical structure of the spacetime

- Superstring theory and $\alpha$-attractors
- Breaking of the Lorentz invariance and supersymmetry breaking
- One-loop correction on the primordial curvature perturbation from single-field inflation
- Vacuum decay in the Lorentzian path integral
- Cosmological implications of pulsar timing array observation

### Cosmology: Creation and evolution of the material contents

- Reheating in the mixed Higgs-$R^2$ inflation
- Gravitational particle production as Stokes phenomenon
- Reconsideration of preheating
- Wash-In Leptogenesis
- Baryon isocurvature perturbation from primordial magnetic fields
- Chiral Gravitational Effect in dynamical chiral plasma
- Time evolution of primordial magnetic fields
- Uncertainties in the formalism of the abundance of the primordial blackholes
- Evaluation of the abundance of the primordial blackholes with conditional probability
- Gravitational microlensing by axion stars

### Gravitational wave analysis

- Offline noise removal method with environmental monitors
- Ultralight dark matter search

### Time-domain astronomy

- Multi-band fast imaging with TriCCS camera

# 25 Ejiri 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

In Ejiri Group, we study magnetic confinement of a torus plasma to realize nuclear fusion energy. We perform basic tokamak plasma physics studies on the TST-2 device located at the university of Tokyo. We also collaborate with JT-60SA at QST, LHD at NIFS, LATE at Kyoto University, and QUEST at Kyushu University. TST-2 is a spherical tokamak with a major radius of 0.36 m and a minor radius of 0.23 m. The plasma current is $<$120 kA for inductive operation and $<$27 kA for RF driven operation. Spherical tokamaks are attractive since they can sustain plasmas with high $\beta$ (kinetic pressure over magnetic pressure). However, plasma current startup and sustainment is a challenge due to limited space for the central solenoid normally used for current drive. Our present focus on TST-2 is current drive through generation of fast electrons by lower-hybrid waves (LHW). The RF current drive experiments are performed using LH waves at 200 MHz. The LH waves are excited using two capacitively coupled combline antennas located at the outer midplane and the top of the plasma. Since LHW drive current by generating fast electrons, measurements of x-ray radiations by those fast electrons are important.

On FY2021, the fast electron transport model was improved and it was found that LHW affects particle balance in addition to driving currents. Off-midplane launch LHW antenna was newly developed for current drive at mid-radius. Metal target was inserted to the outer scrape-off-layer (SOL). Existence of fast electrons were confirmed from the x-ray measurements. It was also found that substantial fraction of counter-current electrons exist in the SOL. Parametric decay instabilities of LHW have been observed with magnetic probes. This year, a new three-wave coupling was observed during LHW injection. Diagnostics to identify the new mode is being developed. The ion doppler spectroscopy was performed to study the ion temperature response to LH power modulation. It was found that the ion temperature response time was 1 ms in the edge and 4 ms near the axis.

Orbit-averaged Fokker-Planck simulation was developed to model the electron cyclotron (EC) wave breakdown of a tokamak plasma. The simulation was applied to breakdown in the TST-2 trapped particle configuration. The predicted breakdown threshold dependence on the vertical field, neutral gas pressure and EC heating power was consistent with the experimental observations.

Several diagnostic developments were performed in FY2021. A double-pass Thomson scattering configuration was tested to measure electron temperature anisotropy. A new magnetic probe was developed to measure the current profile of the LHW driven plasma. A microwave polarimeter was developed to measure the internal current profile of the LHW driven plasma.

As a collaboration, Thomson scattering diagnostic on QUEST is being developed. Density was measured for the CHI plasma, which reached $6\times10^{19}$ m$^{-3}$. As a collaboration with ENN, we are developing a “finline” antenna which is a corrugated metal surface. In FY2021, a new top-launch finline antenna was fabricated which had improved feeder design. The bench measurement showed that the electric field pattern generated in front of the antenna was consistent with the design.

## 26 Yamamoto Group

**Research Subjects:** Millimeter- and submillimeter-wave Astronomy, Star and Planet Formation, Chemical Evolution of Interstellar Molecular Clouds

**Member:** Satoshi Yamamoto and Yoko Oya

Molecular clouds are birthplaces of new stars and planetary systems, which are being studied extensively as an important target of astronomy and astrophysics. Although the main constituent of molecular clouds is a hydrogen molecule, various atoms and molecules also exist as minor components. The chemical composition of these minor species reflects formation and evolution of molecular clouds as well as star formation processes. It therefore tells us how each star has been formed. We are studying star formation processes from such an astrochemical viewpoint.

Since the temperature of a molecular cloud is $10 - 100$ K, an only way to explore its physical structure and chemical composition is to observe the radio wave emitted from atoms, molecules, and dust particles. Particularly, there exist many atomic and molecular lines in the millimeter/submillimeter wave region, and we are observing them toward formation sites of Solar-type protostars mainly with ALMA (Atacama Large Millimeter/submillimeter Array).

So far, it has well been recognized that an envelope/disk system of a Solar-type protostar shows a significant chemical diversity. One distinct case is so called Warm Carbon Chain Chemistry (WCCC), which is characterized by rich existence of various unsaturated carbon-chain molecules such as $C_2H$, $C_4H$, and $HC_5N$. A prototypical source is L1527 in Taurus. Another distinct case is so called hot corino chemistry, which is characterized by rich existence of various saturated organic molecules such as $CH_3OH$, $HCOOCH_3$, and $C_2H_5CN$. A prototypical source is IRAS 16293–2422 in Ophiuchus. Recently, sources having the both characteristics have also be found. Such chemical diversity would reflect the star formation history of each source, more specifically, a duration time of the starless core phase.

We are now studying how such chemical diversity is brought into protoplanetary disks by using ALMA. For the WCCC source L1527, we have found that carbon-chain molecules only exist in an infalling-rotating envelope outside its centrifugal barrier ($r = 100$ AU), while SO preferentially exists around the centrifugal barrier. For the hot corino source IRAS 16293–2422, OCS traces an infalling-rotating envelope, while saturated organic molecules such as $CH_3OH$ and $HCOOCH_3$ trace the centrifugal barrier. Hence, chemical compositions drastically change across the centrifugal barrier of the infalling gas. Since a protostellar disk is formed inward of the centrifugal barrier, the chemical diversity at an envelope scale ($\sim$ 1000 au) is indeed inherited in the disk forming region ($\sim$ 100 au). Then, what is the initial chemical condition of the Solar System? Is it a common occurrence in our Galaxy? To answer these questions, the ALMA large program FAUST (Fifty AU Study of the chemistry in the disk/envelope system of Solar-like protostar) is ongoing. Furthermore, we are now incorporating machine-learning techniques to explore the physical and chemical structures in an unbiased way.

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[2] Oya, Y. and Yamamoto, S. Substructures in the Disk-forming Region of the Class 0 Low-mass Protostellar Source IRAS 16293–2422 Source A on a 10 au Scale, Astrophys. J., **904**, 185 (2020).

[3] Okoda, Y. et al. FAUST II. Discovery of a Secondary Outflow in IRAS 15398–3359: Variability in Outflow Direction during the Earliest Stage of Star Formation?, Astrophys. J., **910**, 11 (2021).

[4] Okoda, Y. et al. Molecular Distributions of the Disk/Envelope System of L483: Principal Component Analysis for the Image Cube Data, Astrophys. J, **923**, 168 (2021).

# 27 Sakai (Hirofumi) Group

### Research Subjects: Experimental studies of atomic, molecular, and optical physics

### Members: Hirofumi Sakai and Shinichirou Minemoto

Our research interests are as follows: (1) Manipulation of neutral molecules based on the interaction between a strong nonresonant laser field and induced dipole moments of the molecules. (2) High-intensity laser physics typified by high-order nonlinear processes (ex. multiphoton ionization and high-order harmonic generation). (3) Ultrafast phenomena in atoms and molecules in the attosecond time scale. (4) Controlling quantum processes in atoms and molecules using shaped ultrafast laser fields. A part of our recent research activities is as follows:

**(1) Stronger orientation of state-selected OCS molecules with relative-delay-adjusted nanosecond two-color laser pulses [1]**

Using the all-optical molecular orientation technique with intense nonresonant two-color laser pulses, stronger molecular orientation $|\langle\cos\theta\rangle| \sim 0.34$ is achieved by employing the following two strategies: (1) carbonyl sulfide molecules lying in the lower rotational states are selected using a home-built molecular deflector and (2) the rising parts of the two wavelengths of the pump pulse are adjusted by introducing a Michelson-type delay line in the optical path. The achieved degree of molecular orientation is higher than that observed in the proof-of-principle experiment [Oda *et al.*, Phys. Rev. Lett. **104**, 213901 (2010)] by about an order of magnitude and the highest ever characterized directly by Coulomb explosion imaging with appropriate probe polarization.

**(2) All-optical control of pendular qubit states with nonresonant two-color laser pulses [2]**

Practical methodologies for quantum qubit controls are established by two prerequisites, i.e., preparation of a well-defined initial quantum state and coherent control of that quantum state. Here we propose a new type of quantum control method, realized by irradiating nonresonant nanosecond two-color ($\omega$ and $2\omega$)

laser pulses to molecules in the pendular (field-dressed) ground state. The two-color field nonadiabatically splits the initial pendular ground state $|\tilde{0},\tilde{0}\rangle$ to a superposition state of $|\tilde{0},\tilde{0}\rangle$ and $|\tilde{1},\tilde{0}\rangle$, whose relative probability amplitudes can be controlled by the peak intensity of one wavelength component ($\omega$) while the peak intensity of the other component ($2\omega$) is fixed. The splitting of the quantum paths is evidenced by observing degrees of orientation of ground-state selected OCS molecules by the velocity map imaging technique. This quantum control method is highly advantageous in that any type of polar molecules can be controlled regardless of the molecular parameters, such as rotational energy, permanent dipole moment, polarizability, hyperpolarizability, and hyperfine energy structures.

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[2] Je Hoi Mun, Shinichirou Minemoto, Dong Eon Kim, and Hirofumi Sakai, "All-optical control of pendular qubit states with nonresonant two-color laser pulses," to appear in Commun. Phys. (8 pages) (2022).

# 28 Gonokami Group

**Research Subjects:** Experimental studies on light-matter interaction in many-body quantum systems, optical phenomena in artificial nanostructures, and development of laser based coherent light sources

**Member:** Makoto Gonokami and Junji Yumoto

We explore new aspects of many-body quantum systems and their exotic quantum optical effects by designing light-matter interactions. Our current target topics consist of a wide variety of matters, including excitons and electron-hole ensembles in semiconductors, and ultra-cold atomic gases. In particular, we have been investigating the phase of Bose-Einstein condensation of excitons, which has not been experimentally proven while considered as the ground state of an electron-hole ensemble. Based on quantitative spectroscopic measurements, the temperature and density of the excitions are determined in a quasi-equilibrium condition where they are trapped in a highly pure crystal kept below 1 K. We are now investigating a stable quantum degenerate state of dark excitons at the low temperature. We also study novel optical and teraherz-wave responses of artificial nanostructures fabricated by advanced technologies. Furthermore, we are now developing novel coherent light sources and spectroscopic methods. We achieved precision measurements of the refractive index of materials in an EUV region using techniques of higher-order harmonics generation. We also developed laser-based angle resolved photoemission spectroscopy using time-of-flight photoelectron analyzer.

The group activities of this year are as follows:

1. The quest for macroscopic quantum phenomena in photo-excited systems:
   1.1. Systematic study of the Bose-Einstein condensation transition of excitons using a dilution refrigerator
   1.2. Preparation of new quantum many-body systems using ultra-cold atomic gases
2. Investigation for non-trivial optical responses and development of applications:
   2.1. Circularly polarized coherent VUV generation by photonics crystal nanomembrane
   2.2. Exploring the mechanism of laser ablation by femtosecond lasers
   2.3. Development of new technology to fabricate micro three-dimensional artificial structures using laser processing and additive manufacturing
3. Development of novel coherent light sources and spectroscopic methods:

3.1. EUV precision spectroscopy using higher-order harmonics
3.2. Laser-based angle resolved photoemission spectroscopy
3.3. Institute for Photon Science Technology

# 29 Ando Group

## Research Subjects: Experimental Relativity, Gravitational Wave, Laser Interferometer

## Member: Masaki Ando and Yuta Michimura

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 200 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
- Development of TOBA (Torsion Bar Antenna)
- Dark Matter Seach
- High-precision experiments on relativity and opto-mechanics

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# 30 Bamba Group

**Research Subjects:** High-energy astrophysics, mainly utilizing X-ray observatories in orbit. Targets are, supernova remnants, black-holes, neutron-stars, magnetars, white dwarfs, active galactic nucleus, and so on.

**Member:** Associate Prof: Aya Bamba, Assistant Prof: Hirokazu Odaka

Our aim is understanding high energy phenomena in the universe, such as supernova explosions and their remnants, compact stars such as neutron stars and blackholes, and active galactic nucleus. Such high energy objects emit X-rays and gamma-rays, thus we observe such high energy photons using balloons and satellites.

This year we studied the shock structure and heating mechanism in supernova remnant (SNR) systems. We have made detailed spatially resolved spectroscopy of young SNRs, Tycho (SN1572) and resolved three-dimentional expansion structure using Doppler broadening of emission lines. We found that the shock is decelerated by the circumsteller medium. This is the first direct discovery of circumsteller material around Tycho, implying the origin of Tycho is not a double-degenerate but a single-degenerate. We have also done similar analysis of Kepler (SN1604) and found asymmetric circumsteller medium [4].

Torus of active galactic nucleus (AGNs) feed supermassive blackholes and important to understand the co-evolution of galaxy and the blackholes. This year we have made systematic analysis of AGNs hidden by their torus with the X-ray emission model we developed ("XClumpy"), and found that around half of AGNs are hidden type. It is found that the covering fluction by their torus is larger than previously expected. Our result implies that there are more undiscovered AGNs hidden by their torus.

We also study on the detector development for the near future missions. For the XRISM, to be launched on the Japanese fiscal year 2022, we fixed the performance verification targets. We also developed the Monte-Carlo based data analysis method for pile-uped data of the X-ray CCD onboard XRISM. For Cipher mission, the first imaging polarimetory cubesat in the hard X-ray band, we completed the readout system and also developed the coded mask pattern with lower noise level. We also started GRAMS mission deverlopment in this year.


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## 31 Kusaka Group

**Research Subjects:** Observational Cosmology, Cosmic Microwave Background (CMB) Observation. (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.

**Member:** A. Kusaka and K. Kiuchi

- Polarbear experiment and its successor, Simons Array, are optimized to measure both inflationary signature and the gravitational lensing effect in CMB polarization. Polarbear experiment has concluded its observation campaign, and Simons Array experiment started the osbervation. Our focus is 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 is under constraction, with the first light expected in two years. We plan to deploy an array of what we call "small aperture telescopes," which are dedicated for the inflationary signal, and a six-meter "large aperture telescope," which enables observation for Neutrinos and the dark content of the universe. We are primarily focusing on the design and development for the small aperture telescope.
- Research and Development for the next generation experiments such as Simons Observatory and CMB-S4 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. We also develop techniques for high-performance computation (HPC) enabling data analysis for new experiments producing order-of-magnitude larger data volume than the current instruments.

## 32 Takeuchi Group

### Research Subjects: Experimental statistical physics for non-equilibrium systems

### Members: Kazumasa A. Takeuchi and Daiki Nishiguchi

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. More specifically, we carried out the following projects among others in the academic year 2021:

**(1) Non-equilibrium phenomena in soft matter systems**
(1-1) Observation of reconnecting topological defect lines in liquid crystal and symmetry restoring [6]
(1-2) Noise-induced synchronization in liquid crystal convection
(1-3) Motion, order and fluctuations of populations of self-propelled colloidal particles [4, 7]

**(2) Non-equilibrium phenomena in living systems**
(2-1) 3D growth of *E. coli* populations and topological defects [5]

(2-2) Bundle structure formation in *E. coli* populations
(2-3) Glass transition in motile *E. coli* populations
(2-4) Swimming of bacteria in quasi-two-dimensional space[8]

**(3) Approaches based on nonlinear science**
(3-1) Algorithm for studying large deviations of non-equilibrium interfaces

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

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# 33 Mio Group

## Research Subjects: Application of lasers

## Member: Norikatsu Mio

Mio Group is conducting research on lasers and their applications. Since the laser was invented in 1960, the laser technology has been widely used in various fields as a fundamental technology that supports modern society, thus is extremely important and indispensable for communication, information technology, material processing and so on. In addition, state-of-the-art photon technology was used in the first observation of a gravitational wave in 2015; photon science and technology work as an important bridge between academia and society.

Our laboratory belongs to Institute for Photon Science and Technology (IPST), where various researches are conducted to deepen science and to promote collaboration with industry. IPST has many members in addition to our laboratory; all of them are working closely together to promote research and education(`http://www.ipst.s.u-tokyo.ac.jp`).

**Physics on laser material processing**

The processes such as cutting, welding, cutting, using lasers are called laser processing. Since advances in laser sources have made it possible to use high-power ultraviolet light and to control pulse widths and wavelengths more freely, the development of new processing has become possible.

However, the actual phenomena are non-equilibrium, open systems, and the interaction between laser light and materials is in a region that cannot be explained by a perturbative approach. The goal of this project is to advance our understanding of this phenomenon and to develop its application.

We are now investigating the non-linear effects on laser beam propagation for laser material processing and the applications of the fine-processing using femto-sesond laser pulses.

**KAGRA project**

More than six years have already passed since gravitational waves were actually detected. The number of events detected to date reaches 90 and observations of gravitational waves become important to build a new picture of the universe.

In Japan, KAGRA is being constructed in the Kamioka Mine in Gifu Prefecture. KAGRA takes advantage of the quiet underground environment and incorporates cryogenic technology. to improve its sensitivity.

Currently, we are cooperating with LIGO in the U.S. and VIRGO in Europe. KAGRA is being improved to join international joint observation called O4 (scheduled to start in mid-December 2022). Our group is involved in developing the laser source of KAGRA. Now, a new solid-state laser that has higher power and stability is being evaluated for replacing the current laser source.

# 34 Nose Group

## Research Subjects: Formation and function of neural networks

## Member: Akinao Nose and Hiroshi Kohsaka

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.Identification of pattern-generating neural circuits that regulate intersegmentally coordinated muscular relaxation.

Typical patterned movements in animals are achieved through combinations of contraction and delayed relaxation of groups of muscles. However, how intersegmentally coordinated patterns of muscular relaxation are regulated by the neural circuits remains poorly understood. Here, we identify Canon, a class of higher-order premotor interneurons, that regulates muscular relaxation during backward locomotion of *Drosophila* larvae. Canon neurons are cholinergic interneurons present in each abdominal neuromere and show wave-like activity during fictive backward locomotion. Optogenetic activation of Canon neurons induces relaxation of body wall muscles, whereas inhibition of these neurons disrupts timely muscle relaxation. Canon neurons provide excitatory outputs to inhibitory premotor interneurons. Canon neurons also connect with each other to form an intersegmental circuit and regulate their own wave-like activities. Thus, our results demonstrate how coordinated muscle relaxation can be realized by an intersegmental circuit that regulates its own patterned activity and sequentially terminates motor activities along the anterior-posterior axis.

### 2.Role of sensory feedback and electrical circuits during the development of nascent motor circuit.

Precocious movements are widely seen in embryos of various animal species. Whether such movements via proprioceptive feedback play instructive roles in motor development or are a mere reflection of activities in immature motor circuits is a long-standing question. Here we image the emerging motor activities in *Drosophila* embryos that lack proprioceptive feedback and show that proprioceptive experience is essential for the development of locomotor central pattern generators (CPGs). Downstream of proprioceptive inputs, we identify a pioneer premotor circuit composed of two pairs of segmental interneurons, whose gap-junctional transmission requires proprioceptive experience and plays a crucial role in CPG formation. The circuit autonomously generates rhythmic plateau potentials via IP3-mediated $Ca^{2+}$ release from internal stores, which contribute to muscle contractions and hence produce proprioceptive feedback. Our findings demonstrate the importance of self-generated movements in instructing motor development and identify the cells, circuit, and physiology at the core of this proprioceptive feedback.

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# 35 Higuchi Group

## Research Subjects:Protein dymamics in vitro,cells and mice

## Member:Hideo Higuchi and Motoshi Kaya

### Reverse stroke by cardiac myosin [1]

To understand how myosin molecules work together in cardiac myofilaments, we measured the force production of cardiac myofilaments using optical tweezers. The measurements revealed that stepwise force generation was associated with a higher frequency of backward steps at lower loads and higher stall forces than those of fast skeletal myofilaments. To understand these unique collective behaviors of cardiac myosin, the dynamic responses of single cardiac and fast skeletal myosin molecules, interacting with actin filaments, were evaluated under load. The cardiac myosin molecules switched among three distinct conformational positions, ranging from pre– to post–power stroke positions, in 1 mM ADP and 0 to 10 mM phosphate solution. In contrast to cardiac myosin, fast skeletal myosin stayed primarily in the post–power stroke position, suggesting that cardiac myosin executes the reverse stroke more frequently than fast skeletal myosin. To elucidate how the reverse stroke affects the force production of myofilaments and possibly heart function, a simulation model was developed that combines the results from the single-molecule and myofilament experiments. The results of this model suggest that the reversal of the cardiac myosin power stroke may be key to characterizing the force output of cardiac myosin ensembles and possibly to facilitating heart contractions.

### Observation of weakened cells by movement of vesicles and GFP diffusion

The cells are weakened and the survival probability is reduced under unfavored environment conditions. State changes such as shrinking are observed in weakened cells., To understand the state change, First, we measured the vesicle movement and diffusion constant of GFP molecule. Those are recoded for long time by automated MATLAB system equipped with shatter, camera control and imaging PC. The automation of the device has made it possible to easily design long-term efficient observation of cell state. By an automated device, we observed changes in the state of weakened cells over time by inhibiting ATP production. As a result, it was found that the diffusion of intracellular vesicles was dramatically reduced in cells in which ATP production was inhibited. When the mean square distance was calculated from the tracking of a single vesicle and the diffusion coefficient was obtained, we found that the diffusion coefficient of the vesicle was several tenths two hours after the start of inhibition of ATP production. The diffusion coefficient of GFP was measured by the fluorescence recovery after photobleaching method. The little time change of the diffusion coefficient was observed. From the results, it has been clarified that the intracellular diffusion is reduced in the weakened cells and size dependent.

### Entropy production in stochastic thermodynamics based on Wasserstein distance[5]

We study a relationship between optimal transport theory and stochastic thermodynamics for the Fokker-Planck equation. We show that the lower bound on the entropy production is the action measured by the path length of the L2-Wasserstein distance. Because the L2-Wasserstein distance is a geometric measure of optimal transport theory, our result implies a geometric interpretation of the entropy production. Based on this interpretation, we obtain a thermodynamic trade-off relation between transition time and the entropy production. This thermodynamic trade-off relation is regarded as a thermodynamic speed limit which gives a tighter bound of the entropy production. We also discuss stochastic thermodynamics for the subsystem and derive a lower bound on the partial entropy production as a generalization of the second law of information thermodynamics. Our formalism also provides a geometric picture of the optimal protocol to minimize the entropy production. We illustrate these results by the optimal stochastic heat engine and show a geometrical bound of the efficiency.

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## 36 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

Our primary goal is to answer the very basic question "What is life". To answer this question , we are trying to fill the gap between the world of molecules and the world of living cells. Direct measurement of molecules in living cells would serve as a basic technology to fill this gap. Thus, we have been working on the development of the technologies for the visualization and non-invasive measurement of the molecular processes in living cells. High-speed, super-resolution live-cell imaging and single-molecule measurement in living cells are the two main technologies we develop.

By using these technologies, we are trying to understand the regulatory mechanisms of motor proteins during axonal transport. Despite the many studies in the past decades by our group and others, it is still unclear how the biophysical properties of motor proteins are related to their biological functions. For example, a point mutation in kinesin-1 can cause hereditary spastic paraplegia, but it is unclear why this mutation selectively affects neurons in the longest tract in the aged patients.

Through these studies and development, we have realized the importance of the cellular states, and our microscope technologies can also be applied to the measurement of the cellular states. Thus, we have proposed a project for the visualization, prediction and control of cellular states. We are now leading this project, and the project members in our lab are working on the development of the technologies to visualize and control cellular states.

This year, we had progress in development of several microscope technologies. Ikezaki developed a new method for single fluorescent molecule localization. The precision of localization is limited by the number of the detected photons from the molecule. With the current method, it has been difficult to achive precision better than 10 nm, because the number of photons emitted from a single fluorescent molecule is limited. Ikezaki introduced a structured illumination optics and suceeded to improve the presicion 10x and achieved precision better than 1 nm.

Kuroda has been working on the development of inverted lightsheet microscope for three-dimensional high-resolution live cell imaging.

Inutsuka developed a single-shot quantitative phase imaging method. polarization-based differential phase constast microscopy, for live imaging of unstained cells. He used his microscope for the imaging of growing HeLa cells, and applied machine-learning techniques for automated segmentation, tracking and prediction of cell cycle states.

Several other students collaborated with Ito-lab of universal biology institute (UBI) and got results with the application of information thermodynamics for the analysis of the biological molecular machines. Ihara is trying to apply the theoretical results of information thermodynamics for the estimation of entropy production from the time-series imaging data. Yoshida extended a theoretical model of secondary active transporters that Muneyuki (Chuo Univ) proposed.

# 37 Furusawa Group

**Research Subjects:** Theoretical Biophysics, Evolutionary Biology, Complex Systems

**Member:** Chikara Furusawa and Yusuke Himeoka

Biological systems have both robustness and plasticity, a property that distinguishes them from artificial systems and is essential for their survival. Biological systems exhibit robustness to various perturbations, including noise in gene/protein expressions and unexpected environmental changes. Simultaneously, they are plastic to the surrounding environment, changing their state through processes such as adaptation, evolution and cell differentiation. Although the coexistence of robustness and plasticity can be understood as a dynamic property of complex and interacting networks consisting of a large number of components, the mechanisms responsible for the coexistence are largely unknown.

Our work extracts the universal features of cellular dynamics responsible for robustness and plasticity in biological systems. We describe the systems using a relatively small number of degrees of freedom with the macroscopic state variables. We expect that such a description will provide novel methods for the prediction and control of complex biological systems.

The current research topics in our group are followings:

1. Laboratory evolution of bacterial cells to analyze dynamics of phenotype-genotype mappings
2. Construction of macroscopic state theory describing adaptation and evolution of biological systems
3. Theoretical analysis of evolutionary process under dynamically changing environments
4. Metabolic simulation for understanding growth and lag-phase
5. Development of a method to characterize animal morphology using machine learning

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