Trends in Theory of Correlated Materials 2016

The Workshop "Trends in Theory of Correlated Materials" (TTCM2016) will take place May 22-25 at the Paul Scherrer Institute. This workshop is a continuation of very successful three-days workshops that have taken place on a yearly basis from 2009 to 2014. It aims at bringing together the Swiss and Japanese community of condensed matter theorists working on correlated materials:

- quantum spin systems, multiferroics, and spintronics;
- topological phases of matter;
- Dirac and Weyl fermions;
- cold atoms;
- many-body localization and out-of-equilibrium correlated matter;
- and computational correlated physics.

This workshop also aims at nurturing scientific exchanges, collaborations, and friendships among young theoreticians between the two countries.

The homepage is to be found at: https://indico.psi.ch/conferenceDisplay.py?confId=4478

CONTENTS

I. TIME TABLE

A. Monday, May 23, 2016, Auditorium PSI-West, WHGA/001, Paul Scherrer Institut

1. 08:30-09:00: Registration and Opening

2. 09:00-10:30: Session I chaired by Markus Mueller

09:00-09:30: "Out-of-equilibrium phenomena and Transport in Cold Atoms,"
by Thierry Giamarchi, University of Geneva

09:30-10:00: "Entanglement Dynamics in Optical Lattice Systems,"
by Isao Maruyama, Fukuoka Institute of Technology

10:00-10:30: "Nonequilibrium dynamics of electron-boson systems,"
by Philipp Werner, Fribourg University

3. 10:30-11:00: coffee break

4. 11:00-12:30: Session II chaired by Frederic Mila

11:00-11:30: "Current-induced Magnetizations in Crystals with Helical Structure,"
by Takehito Yokoyama, Tokyo Institute of Technology

11:30-12:00: "Spin ordering induced by local lattice distortions in Heisenberg antiferromagnets on pyrochlore lattices," by Kazushi Aoyama, Osaka University

12:00-12:30: "Spin-Wave Spin Current in Multiferroics,"
by Shin Miyahara, Fukuoka University

5. 12:30-14:00: lunch

6. 14:00-15:30: Session III chaired by Gianni Blatter

14:00-14:30: "Topological superconductivity from gapless superconductivity,"
by Yoichi Yanase, Kyoto University

14:30-15:00: "Perturbation Theory around the Dynamical Mean-Field Approximation: New Insight into Heavy-Fermion Superconductivities," by Junya Otsuki, Tohoku University

15:00-15:30: "Snake states and their symmetries in graphene,"
by Rakesh P. Tiwari, Basel University

7. 15:30-16:00: coffee break

8. 16:00-18:00: Session IV chaired by Christopher Mudry

16:00-16:30: "Torsional chiral magnetic effect in a Weyl semimetal with a topological defect,"
by Satoshi Fujimoto, Osaka University

16:30-17:00: "Gravitational Chiral Anomaly and Spin Chiral Magnetic Effect,"
by Atsuo Shitade, RIKEN

17:00-17:30: "Roles of edge states in topological pumping,"
by Yasuhiro Hatsugai, University of Tsukuba,

17:30-18:00: "New fermionic excitations is solids,"
by Alexey Soluyanov, ETHZ

B. Tuesday, May 24, 2016, Auditorium PSI-West, WHGA/001, Paul Scherrer Institut

1. 09:00-10:30: Session V chaired by Philipp Werner

09:00-09:30: "Many-body localization and periodically driven systems,"
by Dmitry Abanin, University of Geneva

09:30-10:00: "Topological phase transitions on multi-layer honeycomb lattices induced by circular polarized light," by Nobuo Furukawa, Aoyama Gakuin University

10:00-10:30: "Laser-induced phenomena in quantum spin systems,"
by Shintaro Takayoshi, University of Geneva

2. 10:30-11:00: coffee break

3. 11:00-12:30: Session VI chaired by Hirokazu Tsunetsugu

11:00-11:30: "Magnetic properties of volborthite determined by a coupled-trimer model,"
by Shunsuke Furukawa, University of Tokyo

11:30-12:00: "Topological aspects of symmetry breaking in triangular-lattice Ising antiferromagnets,"
by Andrew James Smerald, EPFL

12:00-12:30: "Spin-orbital entangled exotic insulators in the $(t_{2g})^4$ correlated electron system,"
by Toshihiro Sato, RIKEN

4. 12:30-14:00: lunch

5. 14:00-15:30: Session VII chaired by Yasuhiro Hatsugai

14:00-14:30: "Engineering topological states in 2D systems,"
by Jelena Klinovaja, University of Basel

14:30-15:00: "Self-consistent soliton dynamics in unconventional Fermi superfluids,"
by Daisuke A. Takahashi, RIKEN

15:00-15:30: "Topological Phases of Inhomogeneous Superconductivity,"
by Silas Hoffman, University of Basel

6. 15:30-16:00: coffee break

7. 16:00-18:00: Session VIII chaired by Christoph Bruder

16:00-16:20: "Nodal chain metals,"
by Tomas Bzdusek, ETHZ

16:20-16:40: "Non-Abelian topological spin liquids from arrays of quantum wires or spin chains," by Jyong-Hao Chen, PSI and ETHZ

16:40-17:00: "Scaling theory of topological phase transitions," by Wei Chen, ETHZ

17:00-17:20: "Dimerization transitions in spin-1 chains," by Natalia Chepiga, EPFL

17:20-17:40: "Chiral spin liquid phases of SU(N) fermionic Mott insulators," by Miklos Lajko, EPFL

17:40-18:00: "Quantum-Monte-Carlo study of mass-imbalanced Hubbard models," by Ye-Hua Liu, ETHZ

18:40-18:20: "Incompressible Polaritons in a Flat Band," by Matteo Biondi, ETHZ

8. 18:00-20:00: Posters

9. 20:00-22:00: Banquet

C. Wednesday, May 25, 2016, Auditorium PSI-West, WHGA/001, Paul Scherrer Institut

1. 09:00-10:30: Session IX chaired by Shin Miyahara

09:00-09:30: "$\mathbb{Z}_3$ symmetry breaking and parasitic ferro quadrupole orders in Pr compounds," by Hirokazu Tsunetsugu, University of Tokyo

09:30-10:00: "Classical impurities and boundary Majorana zero modes in quantum chains," by Markus Mueller, PSI

10:00-10:30: "Tensor network study on magnetization process of the kagome lattice Heisenberg antiferromagnets," by Tsuyoshi Okubo, University of Tokyo

2. 10:30-11:00: Coffee break

3. 11:00-12:30: Session X chaired by Shinsei Ryu

11:00-11:30: "Polarization and Large Gauge Invariance," Masaki Oshikawa, University of Tokyo

11:30-12:00: "A mechanical topological insulator," by Sebastian Huber, ETHZ

12:00-12:30: "Reduction of the classification of topological insulators and superconductors by quartic interactions," by Akira Furusaki, RIKEN

4. 12:30-12:45: Closing Remarks

5. 14:00: Visit Large Scale Facilities at PSI

II. TALKS (ALPHABETICAL ORDER BY AUTHORS)

1. **Many-body localization and periodically driven systems,**
Dmitry Abanin, University of Geneva,
present from 22-May-2016 to 25-May-2016

2. **Spin ordering induced by local lattice distortions in Heisenberg antiferromagnets on pyrochlore lattices,**
Kazushi Aoyama, Osaka University,
present from 22-May-2016 to 25-May-2016

3. **Photons in flat bands,**
Matteo Biondi, ETHZ,
present from 23-May-2016 to 25-May-2016

4. **Nodal chain metals,**
Tomas Bzdusek, ETHZ,
present from 22-May-2016 to 25-May-2016

5. **Non-Abelian topological spin liquids from arrays of quantum wires or spin chains,**
Jyong-Hao Chen, PSI and ETHZ,
present from 20-May-2016 to 27-May-2016

6. **Scaling theory of topological phase transitions**
Wei Chen, ETHZ,
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7. **Dimerization transitions in spin-1 chains,**
Natalia Chepiga, EPFL,
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8. **Torsional chiral magnetic effect in a Weyl semimetal with a topological defect**
Satoshi Fujimoto, Osaka University,
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10. **Magnetic properties of volborthite determined by a coupled-trimer model,**
Shunsuke Furukawa, University of Tokyo,
present from 22-May-2016 to 26-May-2016

11. **Reduction of the classification of topological insulators and superconductors by quartic interactions,**
Akira Furusaki, RIKEN,
present from 22-May-2016 to 26-May-2016

12. **Out-of-equilibrium phenomena and Transport in Cold Atoms**
Thierry Giamarchi, University of Geneva,
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14. **Topological Phases of Inhomogeneous Superconductivity,**
Silas Hoffman University of Basel,
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15. **A mechanical topological insulator,**
Sebastian Huber, ETHZ,
present from 21-May-2016 to 27-May-2016

16. **Engineering topological states in 2D systems,**
Jelena Klinovaja, University of Basel,
present from 22-May-2016 to 25-May-2016

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24. **Perturbation Theory around the Dynamical Mean-Field Approximation: New Insight into Heavy-Fermion Superconductivities,**
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25. **Spin-orbital entangled exotic insulators in the $(t_{2g})^4$ correlated electron system,**
Toshihiro Sato, RIKEN,
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Daisuke A. Takahashi, RIKEN,
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Shintaro Takayoshi, Geneva University,
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32. **$\mathbb{Z}_3$ symmetry breaking and parasitic ferro quadrupole orders in Pr compounds,**
Hirokazu Tsunetsugu, University of Tokyo,
present from 22-May-2016 to 25-May-2016

33. **Nonequilibrium dynamics of electron-boson systems,**
Philipp Werner, Fribourg University,
present from 22-May-2016 to 24-May-2016

34. **Topological superconductivity from gapless superconductivity**
Yoichi Yanase, Kyoto University,
present from 22-May-2016 to 25-May-2016

35. **Current-induced Magnetizations in Crystals with Helical Structure,**
Takehito Yokoyama, Tokyo Institute of Technology,
present from 22-May-2016 to 25-May-2016

III. POSTERS

1. **When strong correlations become weak: Consistent merging of GW and DMFT,**
Lewin Boehnke, lewin.boehnke@unifr.ch, University of Fribourg,
present from 23-May-2016 to 25-May-2016

2. **High-Temperature Multiferroic Spin Spiral State by Local Frustration,**
Andrea scaramucci andrea.scaramucci@psi.ch, Paul Scherrer Institut,
present from 22-May-2016 to 26-May-2016

3. **Edge current of chiral p-wave superconductors – revisited,**
Sarah Etter, ETHZ,
present from 23-May-2016 to 25-May-2016

4. **Understanding the unusual spin excitations in the frustrated magnet of MgCr2O4,**
Shang Gao, PSI,
present from 22-May-2016 to 25-May-2016

5. **Vortices in the pair-density wave phase of multilayer superconductors,**
David Moeckli, ETHZ,
present from 22-May-2016 to 25-May-2016

6. **Observable signatures of Floquet-Majorana modes in a spin system,**
Paolo Molignini, ETHZ,
present from 22-May-2016 to 25-May-2016

7. **Amplitude modes in strongly-coupled phonon-mediated superconductors,**
Yuta Murakami, University of Fribourg,
present from 22-May-2016 to 25-May-2016

8. **Numerical methods for Heisenberg SU(N) models,**
Pierre Nataf, EPFL,
present from 22-May-2016 to 25-May-2016

9. **Entanglement in the periodically driven Dicke model,**
Luca Papariello, ETHZ,
present from 23-May-2016 to 25-May-2016

10. **Identifying detrimental effects for multiband superconductivity – Application to Sr2RuO4,**
Aline Ramires, ETHZ,
present from 22-May-2016 to 25-May-2016

11. **Nonsymmorphic Weyl superconductivity in $\mathbf{UPt_3}$,**
Youichi Yanase, Kyoto University,
present from 22-May-2016 to 25-May-2016

IV. PRACTICAL INFORMATIONS FOR JAPANESE PARTICIPANTS

To organize your transfer from the airport to the hotel, go to the web site:

http://www.sbb.ch/en/home.html

Assuming that you are landing in Zurich,

- Enter Zurich Airport as departing point.
- Enter Boettstein, Schloss as destination.
- Enter Search connection.

You will find two options per hour to reach Boettstein, Schloss. In both cases the train takes you to Brugg. You then take a connecting bus.

You can buy your ticket online with a credit card, or you can buy it in the train station of the airport, either with cash or with a credit card. One way ticket costs CHF 13.50

The hotel is 30 minutes away from PSI by foot. You can either walk to PSI or take the bus. Hereto, you use

http://www.sbb.ch/en/home.html

to select your bus.

- Enter Boettstein, Schloss as departing point.
- Enter Villigen, PSI West as destination.
- Enter Search connection.

The trip last 3 minutes at a cost of CHF 3.10 one way. You need to pay cash in the bus.

The welcoming party on Sunday night from 7-8 PM comes with snacks. This might not be sufficient for a dinner. A dinner at the hotel would cost from CHF 30-70. The hotel takes credit cards. The hotel comes with a free breakfast. On Monday you can lunch and dine at the cafeteria of PSI, see

https://www.psi.ch/gastronomie/wochenmenue-oase

The cheapest lunch menu is CHF 10.70. The most expensive one is about CHF 20. Count CHF 20 for a dinner in the cafeteria. You need cash for the cafeteria. The banquet on Tuesday night will be free. As it will finish after the last bus leaves from PSI to the hotel, PSI will provide transit back to the hotel.

PSI is spread accross the two sides of a large river. The auditorium of PSI where the meeting will take place is on the West side of PSI. The building hosting the auditorium is facing the bus stop. It is colored in red. Most importantly, the majestic statue of a pink-red mammoth guards the entry of this building (named WHGA). The auditorium is immediately to the left of this entrance.

WIFI is available in the auditorium. The password for WIFI will be given Monday morning and should be valid for one week. All the information regarding the conference will be made available on line at

https://indico.psi.ch/conferenceDisplay.py?confId=4478

Titles and Abstracts of the Talks

May 19, 2016

Many-body localization and periodically driven systems

Dmitry Abanin
University of Geneva

Abstract: Periodic driving provides an efficient way of quantum control. In particular, in recent experiments driving was used to realize topological Bloch bands in optical lattices. In this talk, I will present several rigorous results regarding periodically driven many-body systems.

First, I will derive strong bounds on the heating rates of generic many-body systems. I will introduce a new approach based on a series of local unitary transformations, and will use it to show that, at times shorter than the (parametrically long) heating time scale, systems dynamics is well described by a time-independent effective Hamiltonian. Our approach can be extended to analyze the effects of coupling to a heat bath and slow turn-on of the drive.

Second, I will show that strong disorder can induce many-body localization (MBL) in periodically driven systems. This phase, realized at high driving frequency, is characterized by the absence of heating and emergence of a complete set of local integrals of motion. I will argue that at low driving frequency delocalization is inevitable. Therefore, there is an MBL-delocalization transition as a function of driving frequency.

I will close by discussing experimental implications.

Spin ordering induced by local lattice distortions in Heisenberg antiferromagnets on pyrochlore lattices

Kazushi Aoyama
Theoretical Condensed Matter Theory Group
Osaka University

Abstract: In frustrated magnets, spins are often coupled to other degrees of freedom in solids. A series of spinel oxides AB_2O_4 provides typical examples of the coupling between the spin and the lattice or orbital degrees of freedom, where the magnetic ion B^{3+} forms a pyrochlore lattice which is a three-dimensional network of corner-sharing tetrahedra. In this study, bearing chromium spinels with spin-3/2 in our mind, we investigate effects of local lattice distortions on long-range spin ordering in the antiferromagnetic classical Heisenberg model on the pyrochlore lattice. The results of our Monte Carlo simulations show that the spin-lattice coupling originating from site phonons induces a first-order transition into two different types of collinear magnetic ordered states, each accompanied by commensurate local lattice distortions. In the presentation, we will compare our results with experimental data on the chromium spinels.

Photons in flat bands,

Matteo Biondi, Institute for Theoretical Physics, ETHZ

Abstract: Geometric frustration is known to enhance perturbations and give rise to exotic phases of matter typically discussed in the context of spin systems and cold atoms. Here, we present theoretical as well as experimental results on geometrically frustrated photonic lattices, which are non-equilibrium systems where a non-trivial steady state cannot follow from energy minimization but originates from the balance between drive and dissipation. In the theory work [1], we make use of frustration to boost interactions and show that photons pumped into the flat band of a photonic circuit QED lattice form an incompressible state of light with non-trivial spatial correlations at the onset of crystallization. Such a system is readily realizable with state-of-the-art circuit QED technology. In the experimental work [2], we show how the interplay of frustration and disorder leads to the fragmentation of an exciton-polaritons condensate in a quasi-1D Lieb lattice of micropillar optical cavities. The spatial coherence of the condensate is analyzed through interferometric as well as spectral techniques and interpreted in terms of Anderson theory of localization.

[1] M. Biondi, E. v. Nieuwenburg, G. Blatter, S. Huber, and S. Schmidt, Incompressible polaritons in a flat band, PRL 115, 143601 (2015).
[2] F. Baboux, L. Ge, T. Jacqmin, M. Biondi, E. Galopin, A. Lemaitre, L. Le Gratiet, I. Sagnes, S. Schmidt, H. E. Treci, A. Amo and J. Bloch, Bosonic Condensation and Disorder-Induced Localization in a Flat Band, PRL 116, 066402 (2016).

Nodal chain metals,

Tomas Bzdusek,
Institute for Theoretical Physics, ETHZ

Abstract: The band theory of solids is arguably the most successful theory of condensed matter physics, providing the description of the electronic energy levels in a variety of materials. Electronic wavefunctions obtained from the band theory allow for a topological characterization of the system and the electronic spectrum may host robust, topologically protected fermionic quasiparticles. Many of these quasiparticles are analogs of the elementary particles of the Standard Model, but others do not have a counterpart in relativistic high-energy theories. A full list of possible quasiparticles in solids is still unknown, even in the non-interacting case.

We report on a new type of fermionic excitation that appears in metals [1]. This excitation forms a nodal chain – a chain of connected loops in momentum space – along which conduction and valence band touch. We discuss the symmetry requirements for the appearance of this novel excitation and predict that it is realized in an existing material IrF_4, as well as in other compounds of this material class. Using IrF_4 as an example, we provide a discussion of the topological surface states associated with the nodal chain. We argue that the presence of the novel quasiparticles results in anomalous magnetotransport properties, distinct from those of the known materials. In the presence of the sublattice symmetry, the nodal chain is enriched by an additional loop and yield a three-dimensional nodal net structure.

[1] Tomas Bzdusek, QuanSheng Wu, Andreas Rueegg, Manfred Sigrist, and Alexey A. Soluyanov, arXiv:1604.03112.

Non-Abelian topological spin liquids from arrays of quantum wires or spin chains,

Jyong-Hao Chen
Condensed Matter Theory Group, PSI
and Institute for Theoretical Physics, ETHZ

Abstract: We construct two-dimensional non-Abelian topologically ordered states by strongly coupling arrays of one-dimensional quantum wires via interactions. In our scheme, all charge degrees of freedom are gapped, so the construction can use either quantum wires or quantum spin chains as building blocks, with the same end result. The construction gaps the degrees of freedom in the bulk, while leaving decoupled states at the edges that are described by conformal field theories (CFT) in (1+1)-dimensional space and time. We consider both the cases where time-reversal symmetry (TRS) is present or absent. When TRS is absent, the edge states are chiral and stable. We prescribe, in particular, how to arrive at all the edge states described by the unitary CFT minimal models with central charges $c < 1$. These non-Abelian spin liquid states have vanishing quantum Hall conductivities, but non-zero thermal ones. When TRS is present, we describe scenarios where the bulk state can be a non-Abelian, non-chiral, and gapped quantum spin liquid, or a gapless one. In the former case, we find that the edge states are also gapped. The paper provides a brief review of non-Abelian bosonization and affine current algebras, with the purpose of being self-contained. To illustrate the methods in a warm-up exercise, we recover the ten-fold way classification of two-dimensional non-interacting topological insulators using the Majorana representation that naturally arises within non-Abelian bosonization. Within this scheme, the classification reduces to counting the number of null singular values of a mass matrix, with gapless edge modes present when left and right null eigenvectors exist.

[1] Po-Hao Huang, Jyong-Hao Chen, Pedro R. S. Gomes, Titus Neupert, Claudio Chamon, and Christopher Mudry, arXiv:1601.01094.

Scaling theory of topological phase transitions

Wei Chen
Institute for Theoretical Physics, ETHZ

Abstract: Topologically ordered systems are characterized by topological invariants that are often calculated from the momentum space integration of a certain function that represents the curvature of the many-body state. The curvature function may be Berry curvature, Berry connection, or other quantities depending on the system. Akin to stretching a messy string to reveal the number of knots it contains, a scaling procedure is proposed for the curvature function in inversion symmetric systems, from which the topological phase transition can be identified from the flow of the driving energy parameters that control the topology (hopping, chemical potential, etc.) under scaling. At an infinitesimal operation, one obtains the renormalization group (RG) equations for the driving energy parameters. A length scale defined from the curvature function near the gap-closing momentum is suggested to characterize the scale invariance at critical points and fixed points, and displays a universal critical behavior in a variety of systems examined.

[1] Wei Chen, Manfred Sigrist, and Andreas P. Schnyder, arXiv:1604.07662.

Dimerization transitions in spin-1 chains,

Natalia Chepiga
Chair of Condensed Matter Theory, EPFL

Abstract: We study spontaneous dimerization transitions in a Heisenberg spin-1 chain with additional next-nearest neighbor (NNN) and 3-site interactions using extensive numerical simulations and a conformal field theory analysis. We show that the transition can be second order in the WZW $SU(2)_2$ or Ising universality class, or first-order. We argue that these features are generic because of a marginal operator in the WZW $SU(2)_2$ model, and because of two topologically distinct non-dimerized phases with or without edge states. We also provide explicit numerical evidence of conformal towers of singlets inside the spin gap at the Ising transition. Implications for other models are briefly discussed.

[1] Natalia Chepiga, Ian Affleck, and Frederic Mila, arXiv:1603.01395

Torsional chiral magnetic effect in a Weyl semimetal with a topological defect

Satoshi Fujimoto
Department of Materials Engineering Science, Osaka University

Abstract: It is known that the chiral anomaly inherent in Weyl fermions gives rise to various exotic transport phenomena such as the anomalous Hall effect, negative magnetoresistivity and chiral magnetic effect. Among them, the anomalous Hall effect and negative magnetoresistivity have been experimentally established in Weyl semimetal materials. On the other hand, the chiral magnetic effect, which implies an equilibrium current induced by an applied static magnetic field, is problematic, because it contradicts with the Bloch theorem, which prohibits the existence of the ground state transport current. In fact, the chiral magnetic effect does not occur in solid state lattice systems. In this talk, we discuss a novel transport phenomenon akin to the chiral magnetic effect, which is induced not by magnetic fields, but by topological lattice defects such as dislocations. In this scenario, lattice dislocations act as fictitious magnetic fields for Weyl fermions, and result in dissipationless current flow in dislocation lines, which is referred to as the torsional chiral magnetic effect. In contrast to the chiral magnetic effect, which is absent in lattice systems, the torsional chiral magnetic effect is realized for realistic solid state electron systems, and experimentally detectable via a scanning SQUID and non-local transport measurements, characterizing the chiral anomaly of Weyl semimetals. [1] We also verify the relation between the torsional chiral magnetic effect and the Bloch's no-go theorem.

[1] H. Sumiyoshi and S. Fujimoto, Phys. Rev. Lett. **116**, 166601 (2016).

Topological phase transitions on multi-layer honeycomb lattices induced by circular polarized light

Nobuo Furukawa
Department of Physics, Aoyama Gakuin University

Abstract: We present phase diagrams of topological phase transitions on single- and multi-layer honeycomb lattices induced by circular polarized light. It has been shown by Kitagawa et al. [1] and Mikami et al. [2] that a coherent vector potential of a circular polarized light induces a Floque state which can be mapped to the Haldane model with nontrivial Chern numbers. We apply this approach to various lattice systems including stacked graphene lattices and show numbers of edge current channels as a function frequencies and amplitudes of the light.

[1] Kitagawa et al., Phys. Rev. B **84**, 235108 (2011).
[2] Mikami et al., arXiv:1511.00755.
[3] Y. Sasaki, thesis (2015). Y. Sasaki, M. Sato and N. Furukawa, in preparation.

Magnetic properties of volborthite determined by a coupled-trimer model

Shunsuke Furukawa
Department of Physics, University of Tokyo

Abstract: The natural mineral volborthite hosts layers of spin-1/2 moments forming a kagome lattice. While this material was initially considered as a candidate of a spin-1/2 kagome antiferromagnet, it exhibits rich magnetic behavior which is in many respects distinct from the known features of a kagome antiferromagnet. In particular, recent single-crystal experiments have revealed a wide 1/3 magnetization plateau starting at $H = 26$ T, an incommensurate spin-density-wave phase below $H = 23$ T, and the novel "N" phase inbetween them.

To explain these rich field-induced phenomena, we have performed microscopic modeling of volborthite by means of density functional theory (DFT) with the single-crystal structural data as a starting point. Using DFT+U, we find four leading magnetic exchanges: antiferromagnetic J and J_2, as well as ferromagnetic J' and J_1 with a remarkable hierarchy $J > |J_1| > J_2, |J'|$. Due to the dominance of J, the magnetic planes break up into magnetic trimers. The 1/3-plateau state can be naturally interpreted as a product of polarized trimers, and a wide plateau extending to $H = 225$ T is predicted. Furthermore, we derive an effective pseudospin-1/2 model by restricting ourselves to the lowest-energy doublet on each trimer and treating the inter-trimer couplings perturbatively. This model shows a tendency towards condensation of magnon bound states preceding the plateau, providing a scenario for the observed "N" phase.

[1] O. Janson, S. Furukawa, T. Momoi, P. Sindzingre, J. Richter, and K. Held, arXiv: 1509.07333v1.

Reduction of the classification of topological insulators and superconductors by quartic interactions

Akira Furusaki
Condensed Matter Theory Laboratory, RIKEN

Abstract: The conditions for both the stability and the breakdown of the topological classification of gapped ground states of noninteracting fermions, the tenfold way, in the presence of quartic fermion-fermion interactions are given for any dimension of space. This is achieved by encoding the effects of interactions on the boundary gapless modes in terms of boundary dynamical masses. Breakdown of the noninteracting topological classification occurs when the quantum nonlinear sigma models for the boundary dynamical masses favor quantum disordered phases. For the tenfold way, it is found that (i) the noninteracting topological classification Z_2 is always stable, (ii) the noninteracting topological classification Z in even dimensions is always stable, (iii) the noninteracting topological classification Z in odd dimensions is unstable and reduces to Z_N that can be identified explicitly for any dimension and any defining symmetries. The method can be applied to the three-dimensional topological crystalline insulator SnTe from the symmetry class AII+R, for which the reduction $Z \to Z_8$ is obtained. This talk is based on the work [1] done in collaboration with Takahiro Morimoto and Christopher Mudry.

[1] T. Morimoto, A. Furusaki, and C. Mudry, Phys. Rev. B **91**, 235111 (2015).

Out-of-equilibrium phenomena and Transport in Cold Atoms

Thierry Giamarchi
University of Geneva

Abstract: Transport of particle or charge current between two reservoirs is one of the most studied phenomenon in the context of condensed matter. Despite its apparent simplicity this phenomenon is in fact a case of an out of equilibrium situation requiring in principle new theoretical tools and concepts for its solution. One way to sweep the difficulty under the rug has been usually to tackle this problem in the linear response, where one can come back to the comfortable case of equilibrium. There are however many cases when the linear response is not enough and when a full solution of the non-equilibrium problem is needed. This is in particular the case for quantum point contacts or junctions where the full current-voltage characteristics gives direct information on the physics of the problem. In the recent years, in complement to condensed matter experimental realizations, due to the full control on the parameters of the problem and the fact that they realize isolated quantum systems cold atoms have proven a fantastic laboratory to produce out of equilibrium situations. This ranges from the case of quenches, to more recently via experiments of the ETHZ group to the case of real transport between reservoirs. This experimental activity has in turn thus stimulated strongly theoretical developments in this field. I will discuss in this talk some of the recent advances and realizations both at the experimental and of course the theoretical level. I will in particular focus on a recent study [1] which was able to realize a tunable, ballistic quantum point contact between two fermi reservoirs with a tunable interaction allowing to reach unitarity and to provide a theoretical description of the out-of equilibrium corresponding problem. In such a system the current has been shown to originate from multiple Andreev reflections which leads to a non-linear current-chemical potential characteristics. The geometry of the contact can be changed showing a competition between superfluidity and thermally activated transport which leads to a conductance minimum and poses several theoretical questions for its theoretical description.

[1] "Connecting strongly correlated superfluids by a quantum point contact", D. Husmann, S. Uchino, S. Krinner, M. Lebrat, T. Giamarchi, T. Esslinger, and J.-P. Brantut, arXiv:1508.00578 (2015), Science 350, 1498-1501 (2015).

Roles of edge states in topological pumping

Yasuhiro Hatsugai
Division of Physics, University of Tsukuba

Abstract: A topological pump as an adiabatic charge transport proposed by Thouless is realized in cold atoms last year. Although edge states are fundamental in topologically non trivial phases, they have never been considered seriously for the pump. We have recently revisited the problem and discussed their roles in Ref. [1]. The boundary effects in the pumping are more than analogues of the 2D quantum Hall effects and indicate new aspects of the bulk-edge correspondence. The pumped charge shows discontinuous jump when the edge state crosses the fermi energy, which is associated with the breakdown of the adiabaticity. A set of the singularities supplemented with the periodicity in time guarantees quantization of the pumped charge in a cycle as the Chern number for a non periodic parameter space of the bulk.

[1] Y. Hatsugai and T. Fukui, arXiv:1601.03537.

A mechanical topological insulator

Sebastian Huber
Institute for Theoretical Physics, ETHZ

Abstract: A topological insulator, as originally proposed for electrons governed by quantum mechanics, is characterized by a dichotomy between the interior and the edge of a finite system: The bulk has an energy gap, and the edges sustain excitations traversing this gap. However, it has remained an open question whether the same physics can be observed for systems obeying Newtons equations of motion. We conducted experiments to characterize the collective behavior of mechanical oscillators exhibiting the phenomenology of the quantum spin Hall effect. The phononic edge modes are shown to be helical, and we demonstrate their topological protection via the stability of the edge states against imperfections. Our results may enable the design of topological acoustic metamaterials that can capitalize on the stability of the surface phonons as reliable wave guides.

Engineering topological states in 2D systems

Jelena Klinovaja
Department of Physics, University of Basel

Abstract: I will discuss low-dimensional condensed matter systems, in which topological properties could be engineered per demand. The goal is to go beyond Majorana fermions [1,2] and to identify systems that can host quasiparticles with more powerful non-Abelian statistics such as parafermions in double wires coupled by crossed Andreev reflections [3,4]. Next, I will focus on strip of stripes model consisting of weakly coupled one-dimensional wires [5-7], where interaction effects in the wires can be treated non-perturbatively via bosonization. Such systems can exhibit the integer or fractional quantum Hall effect, spin Hall effect, and anomalous Hall effect.

[1] J. Klinovaja and D. Loss, Phys. Rev. B 86, 085408 (2012).
[2] J. Klinovaja, P. Stano, A. Yazdani, and D. Loss, Phys. Rev. Lett. **111**, 186805 (2013).
[3] J. Klinovaja and D. Loss, Phys. Rev. B **90**, 045118 (2014).
[4] J. Klinovaja, A. Yacoby, and D. Loss, Phys. Rev. B **90**, 155447 (2014).
[5] J. Klinovaja and D. Loss, Phys. Rev. Lett. **111**, 196401 (2013); J. Klinovaja and D. Loss, Eur. Phys. J. B **87**, 171 (2014).
[6] J. Klinovaja and Y. Tserkovnyak, Phys. Rev. B **90**, 115426 (2014).
[7] J. Klinovaja, Y. Tserkovnyak, and D. Loss, Phys. Rev. B **91**, 085426 (2015).

Chiral spin liquid phases of $SU(N)$ fermionic Mott insulators,

Miklos Lajko
Chair of Condensed Matter Theory, EPFL

Abstract: We show that, in the presence of a $\pi/2$ artificial gauge field per plaquette, Mott insulating phases of ultra-cold fermions with $SU(N)$ symmetry and one particle per site generically possess an extended chiral phase with intrinsic topological order characterized by a multiplet of N low-lying singlet excitations for periodic boundary conditions, and by chiral edge states described by the $SU(N)_1$ Wess-Zumino-Novikov-Witten conformal field theory for open boundary conditions. This has been achieved by extensive exact diagonalizations for N between 3 and 9, and by a parton construction based on a set of N Gutzwiller projected fermionic wave-functions with flux π/N per triangular plaquette. Experimental implications are briefly discussed.

[1] Pierre Nataf, Miklos Lajko, Alexander Wietek, Karlo Penc, Frederic Mila, and Andreas M. Laeuchli, arXiv:1601.00958

Quantum-Monte-Carlo study of mass-imbalanced Hubbard models,

Ye-Hua Liu
Institute for Theoretical Physics, ETHZ

Abstract: Building on recent solutions of the fermion sign problem for specific models we present two continuous-time quantum Monte Carlo methods for efficient simulation of mass-imbalanced Hubbard models on bipartite lattices at half-filling. For both methods we present the solutions to the fermion sign problem and the algorithms to achieve efficient simulations. As applications, we calculate the dependence of the spin correlation on the mass imbalance in a one-dimensional lattice and study the thermal and quantum phase transitions to an antiferromagnetic Ising long-range ordered state in two dimensions. These results offer unbiased predictions for experiments on ultracold atoms and bridge known exact solutions of Falicov-Kimball model and previous studies of the SU(2)-symmetric Hubbard model.

[1] Ye-Hua Liu and Lei Wang, arXiv:1510.00715

Topological Phases of Inhomogeneous Superconductivity,

Silas Hoffman
Department of Physics, University of Basel

Abstract: We theoretically consider the effect of a spatially periodic modulation of the superconducting order parameter on the formation of Majorana fermions induced by a one-dimensional system with magnetic impurities brought into close proximity to an s-wave superconductor. When the magnetic exchange energy is larger than the inter-impurity electron hopping we model the effective system as a chain of coupled Shiba states, while in the opposite regime, the effective system is accurately described by a quantum wire model. Upon including a spatially modulated superconducting pairing, we find, for sufficiently large magnetic exchange energy, that the system is able to support a single pair of Majorana fermions with one Majorana fermion on the left end of the system and one on the right end. When the modulation of superconductivity is large compared to the magnetic exchange energy, the Shiba chain returns to a trivially gapped regime while the quantum wire enters a new topological phase capable of supporting two pairs of Majorana fermions

Entanglement Dynamics in Optical Lattice Systems

Isao Maruyama
Faculty of Information Engineering, Fukuoka Institute of Technology

Abstract: We investigate time evolution of entanglement entropy $S_A(t)$ for the time-dependent Hamiltonian $H(t)$, changing from a uniform gapless system H_{A+B} to decoupled subsystems $H_A + H_B$. As a demonstration of entanglement-loss in this separation, we calculate the time-dependent Scrödinger equation numerically and compare several spatial-modifications, for non-interacting fermions. As a result, the spatial separation with the sine-square deformation (SSD)[1] works well to preserve entanglement without disturbing the Fermi sea. We discuss a model Hamiltonian in optical lattice systems for the entanglement preservation. This multipartition operation in optical lattice systems opens a way to real-time manipulation for separating the Fermi sea spatially into decoupled systems without losing quantum entanglement among them.

[1] A. Gendiar, et.al., Prog. Theor. Phys. 122, 953 (2009); ibid, Phys. 123, 393 (2010).

Spin-Wave Spin Current in Multiferroics

Shin Miyahara
Department of Applied Physics, Fukuoka University

Abstract: In magnetoelectric multiferroics, there is a strong coupling between magnetization and electric polarization. Such a coupling induces an electro-active spin-wave excitation and such a spin-wave may show novel features as a spin-wave spin current. As a typical multiferroics, we discuss the spin-wave spin current in helical spin structures.

Classical impurities and boundary Majorana zero modes in quantum chains

Markus Mueller
Condensed Matter Theory Group, PSI

Abstract: We study the response of classical impurities in quantum Ising chains. They entail an exact degeneracy which implies a Curie susceptibility in the magnetically disordered phase. The two ground states differ only close to the impurity, being related by the action of an explicitly constructed local operator. The critical response of a boundary impurity is logarithmically divergent and maps to the 2-channel Kondo problem, while it saturates for critical bulk impurities and in the ordered phase. The results for the Ising chain translate to the related problem of a resonant level coupled to a 1d p-wave superconductor or a Peierls chain, whereby the magnetic order is mapped to topological order. We find that the topological phase always exhibits a continuous impurity response to local fields as a result of the level repulsion of local levels from the boundary Majorana zero mode. In contrast the disordered phase generically features a discontinuous magnetization or charging response. This difference constitutes a robust and generic thermodynamic fingerprint of topological order in one dimension.

Tensor network study on magnetization process of the kagome lattice Heisenberg antiferromagnets,

Tsuyoshi Okubo
ISSP, The University of Tokyo

Abstract: The kagome lattice Heisenberg antiferromagnet is a typical example of a two-dimensional frustrated spin systems. Due to strong quantum fluctuations, the ground state of the $S = 1/2$ quantum spin kagome lattice Heisenberg model is expected to be a spin-liquid state without any magnetic long-range orders. Under magnetic fields, it has been proposed that several magnetization plateaus at 1/9, 1/3, 5/9, and 7/9 of the saturation magnetization appear based on a density matrix renormalization group (DMRG) calculation [1]. Recently, a tensor network calculation has also shown the existence of these magnetization plateaus [2].

In this talk, I will present the ground state properties of $S = 1/2$ kagome lattice Heisenberg antiferromagnet under external magnetic fields using a infinite Projected Entangled Pair State (iPEPS) tensor network method. In this iPEPS method, we represent the ground state wave-function as the two-dimensional network of tensors. By optimizing each tensor so as to minimize the total energy, we obtained wave-functions close to the ground state under magnetic fields. The magnetization curve obtained by iPEPS contains clear 1/9, 1/3, 5/9, and 7/9 plateaus that are consistent with the previous calculations. We also investigate effects of the Dzyaloshinskii-Moriya (DM) interaction, which exists in real kagome lattice compounds. Our calculation shows that the plateau width becomes smaller when we increase the amplitude of the DM interaction and the plateaus disappear for D_z/J 0.1.

[1] S. Nishimoto, N. Shibata, and C. Hotta, Nat. Commun. **4**, 2287 (2013).
[2] T. Picot, M. Ziegler, R. Orus, and D. Poilblanc, Phys. Rev. B **93**, 060407(R) (2016).

Polarization and Large Gauge Invariance

Masaki Oshikawa
ISSP, The University of Tokyo

Abstract: Quantum systems on a non-simply connected space possess a "large" gauge invariance. Laughlin utilized this to explain quantum Hall effect. Later, it was applied to elucidate a universal relation between filling factor and energy spectrum in quantum many-body systems on periodic lattices (Lieb-Schultz-Mattis-M.O.-Hastings). Somewhat surprisingly, the large gauge invariance is also deeply related to modern theory of electric polarization developed by Resta et al. I will discuss our most recent results obtained by combining the theory of polarization with the large gauge invariance.

Perturbation Theory around the Dynamical Mean-Field Approximation: New Insight into Heavy-Fermion Superconductivities

Junya Otsuki
Condensed matter physics theory, Faculty of Science, Department of Physics, Tohoku University

Abstract: Magnetism and superconductivity appear nearby in typical phase diagrams of d- and f-electron compounds. So far, unconventional superconductivities have been treated by variants of perturbation theory such as the fluctuation exchange approximation (FLEX). On the other hand, strong local correlations, which are responsible for magnetism, can be described by the dynamical mean-field theory (DMFT). It is highly desirable to integrate them for a unified treatment of magnetism and superconductivity.

The dual-fermion approach is a framework which enables us to perform a diagrammatic expansion around the DMFT. With this framework, we construct a FLEX-like approximation on the top of the DMFT. In my talk, I will present our recent numerical results for superconductivity in the two-dimensional Hubbard model and the Kondo lattice model.

Spin-orbital entangled exotic insulators in the $(t_{2g})^4$ correlated electron system

Toshihiro Sato
Computational Condensed Matter Physics Laboratory, RIKEN

Abstract: Recently, 5d transition metal oxides have attracted increasing attention both experimentally and theoretically because the interplay between the electron correlations and the relativistic spin-orbit coupling (SOC), besides the multi-orbital nature of d orbitals, can induce a variety of unique quantum states such as relativistic Mott insulator, spin liquid, topological insulator, and unconventional superconductor. Most of the researches thus far have been concentrated on $(t_{2g})^5$ electron systems, i.e., a single hole in the t_{2g} manifold. However, the focus has started to move onto other electron fillings. The main purpose of our study is to explore possible exotic electronic states of $(t_{2g})^4$ correlated electron systems, which emerge as a result of the interplay between the electron correlations and the SOC. To this end, we have employed the multi-orbital dynamical mean field theory and solved a three-orbital Hubbard model with the SOC using the continuous-time quantum Monte Carlo method.

The most significant finding is that we have found two excitonic insulators with and without a magnetic order. The excitonic insulator without any magnetic order appears in the moderate electron correlation regime and is induced by the electron correlation with the condensation of an electron-hole pair in the effective total angular momentum $j = 1/2$ and $3/2$ based bands. The excitonic insulator with a magnetic order is induced by the interplay between the strong electron correlation and the SOC, and is characterized as the Van Vleck-type excitonic insulator where the local total angular momentum $J = 0$ state of the $(t_{2g})^4$ manifold hybridizes with the magnetic $J \neq 0$ excited states, similar to the previous theoretical prediction from Ref. [1]. The former excitonic insulator is stable for the intermediate SOC and becomes the relativistic band insulator with further increasing the SOC, whereas the latter excitonic insulator is stable only for the small SOC and becomes the Van Vleck-type nonmagnetic insulator with further increasing the SOC. We have also calculated the momentum resolved single-particle spectral function and discuss the characteristic features in the single-particle excitations among the different insulators (see Ref. [2]).

[1] G. Khaliullin, Phys. Rev. Lett. **111**, 197201 (2013)
[2] Toshihiro Sato, Tomonori Shirakawa, and Seiji Yunoki, arXiv:1603.01800.

Gravitational Chiral Anomaly and Spin Chiral Magnetic Effect

Atsuo Shitade[1] and Masatoshi Sato[2]
[1] RIKEN Center for Emergent Matter Science
[2] Yukawa Institute for Theoretical Physics, Kyoto University

Abstract: In a classical theory, a massless Dirac fermion has the chiral symmetry, leading to the conservation of a chiral current. However, a chiral current is not conserved in a quantum theory with a background gauge field, which is dubbed a chiral anomaly, because the path-integral measure is not invariant under the chiral transformation [1]. As a physical consequence, Weyl fermions give rise to a θ term in the action of electromagnetic fields, which describes the anomalous Hall and chiral magnetic effects when the time-reversal and inversion symmetries are broken, respectively [2]. Although the chiral magnetic effect is intriguing, it is forbidden in lattice systems [3].

A chiral current is not conserved in a quantum theory with a background gravitational field, which is dubbed a gravitational chiral anomaly [1]. As a result, another θ term is induced in the action of a Riemann curvature. In the presence of a Riemann curvature, an arrow is rotated during a parallel transport. If this arrow is interpreted as spin, spin acquires the SU(2) Aharonov-Bohm phase, and a Riemann curvature is interpreted as an SU(2) magnetic field. In condensed matter physics, a Riemann curvature is realized by disclinations.

Here we propose a new kind of chiral magnetic effect, the spin chiral magnetic effect. Based on a gravitational chiral anomaly, we predict that a spin current flows parallel to a disclination line in noncentrosymmetric Weyl semimetals. It does not contradict the no-go theorem in lattice systems [3] since a Riemann curvature describing disclinations is nonuniform [4]. This spin current is an equilibrium current and is not observed in any transport experiments. Instead, we discuss thermodynamic properties modified by the spin chiral magnetic effect.

[1] K. Fujikawa, Phys. Rev. Lett. **42**, 1195 (1979); Phys. Rev. D **21**, 2848 (1980).
[2] A. A. Zyuzin and A. A. Burkov, Phys. Rev. B **86**, 115133 (2012).
[3] M. M. Vazifeh and M. Franz, Phys. Rev. Lett. **111**, 027201 (2013).
[4] H. Sumiyoshi and S. Fujimoto, Phys. Rev. Lett. **116**, 166601 (2016); Y. Ibe and H. Sumiyoshi, submitted.

Topological aspects of symmetry breaking in triangular-lattice Ising antiferromagnets

Andrew James Smerald
Chair of Condensed Matter Theory, EPFL

Abstract: We investigate the triangular lattice Ising antiferromagnet with coupling beyond nearest neighbour, focussing in particular on the interplay between topology and symmetry. Using a specially designed Monte Carlo algorithm with directed loops, we show that a first order phase transition from a low-temperature, broken-symmetry stripe state to the paramagnet can be split, revealing an intermediate nematic phase. Furthermore, we demonstrate the emergence of several properties of a more topological nature, such as fractional edge excitations in the stripe state, the proliferation of double domain walls in the nematic phase and the coexistence of a broken symmetry and algebraically decaying spin correlations. Finally we investigate the nature of the second order phase transition between the stripe and nematic phases and demonstrate that it is of the Kasteleyn type and in the Pokrovsky-Talapov universality class.

New fermionic excitations is solids

Alexey Soluyanov
Institute for Theoretical Physics, ETHZ

Abstract: Recent discovery of Weyl, Dirac and Majorana quasiparticles in solids allows for a direct parallelism between the elementary particles of relativistic quantum field theories and elementary excitations in solids. This leads to the possibility to test many of the predictions of the fundamental theories in a relatively cheap condensed matter experiments. However, there is another side to this story: Condensed matter theories are intrinsically non-relativistic, describing low energy excitations. Thus, the symmetry constraints on elementary particles of the Standard Model and on possible quasiparticles in solids are drastically different, condensed matter symmetries providing much more freedom. As a consequence, quasiparticle excitations in real materials can come in flavors, not known in high energy physics. However, the analog of the Standard Model in solids is still not fully known, even in the simplest case of non-interacting, crystalline solids. In this talk I will introduce two topologically protected fermionic excitations that do not have direct analogues in relativistic QFT: type-II Weyl fermion and triple point fermions, that occur in real materials, examples of which will be given. I will discuss the physical phenomena, associated with these new excitations, and provide illustrations from recent experiments.

Self-consistent soliton dynamics in unconventional Fermi superfluids

Daisuke A. Takahashi
Quantum Matter Theory Research Team, RIKEN

Abstract: Exact construction of self-consistent gap order parameters and quasiparticle wavefunctions in 1D systems based on the Bogoliubov-de Gennes formalism has been studied extensively both in condensed-matter and high-energy physics. In this talk, I report new time-dependent soliton solutions in multicomponent superfluids/superconductors, including triplet p-wave superfluids such as helium 3 and SU(n)-symmetric fermions in cold atoms. The nature of quasiparticles localized around a kink will be also discussed.

[1] Daisuke A. Takahashi, 1509.04242; 1512.07764.

Laser-induced phenomena in quantum spin systems

Shintaro Takayoshi
Theory of Quantum Matter Group, Geneva University

Abstract: Quantum magnets have been intensively studied for their rich many-body physics such various phase transitions, topological order, and spin liquid. Due to the recent advance of experimental technique of laser, it is important to find a scheme to realize nontrivial coherent states in quantum magnets by laser application. If we consider laser as a temporally periodic external field, the magnetic component is coupled to magnets through the Zeeman effect, and in multiferroics, the electric component is coupled to electric polarization. To analyze these effects, we use a Floquet theory and map the original time-dependent system into an effective static one. We demonstrate net magnetization can be induced and manipulated by circularly polarized laser. Even dynamical magnetization curves are realized with a technique of frequency modulation of laser (chirping). In the case of multiferroic materials, the direction of Dzyaloshinskii-Moriya interaction is effectively modified through the coupling between spin chirality and electric polarization.

Snake states and their symmetries in graphene

Rakesh P. Tiwari
Condensed Matter Theory and Quantum Comupting, Basel University

Abstract: Snake states are open trajectories for charged particles propagating in two dimensions under the influence of a spatially varying perpendicular magnetic field. In the quantum limit they are protected edge modes that separate topologically inequivalent ground states and can also occur when the particle density rather than the field is made nonuniform. We examine the correspondence of snake trajectories in single-layer graphene in the quantum limit for two families of domain walls: (a) a uniform doped carrier density in an antisymmetric field profile and (b) antisymmetric carrier distribution in a uniform field. These families support different internal symmetries but the same pattern of boundary and interface currents. We demonstrate that these physically different situations are gauge equivalent when rewritten in a Nambu doubled formulation of the two limiting problems. Using gauge transformations in particle-hole space to connect these problems, we map the protected interfacial modes to the Bogoliubov quasiparticles of an interfacial one-dimensional p-wave paired state.

$\mathbb{Z}_3$ symmetry breaking and parasitic ferro quadrupole orders in Pr compounds

Hirokazu Tsunetsugu
ISSP, The University of Tokyo

Abstract: Several heavy-fermion compounds have a rich phase diagram related to multipole orders in electron orbital and spin degrees of freedom. We have been investigating orderings of electric quadrupoles in the cubic compound $PrIr_2Zn_{20}$. Pr ions have a non-Kramers doublet ground state at each site, and their electric quadrupoles show antiferro orderings below T_Q=0.11 K. At the TTCM2013 Meeting in Lausanne, I presented a paper of our mean-field study and reported that $\mathbb{Z}_3$ anisotropy in quadrupole space plays important roles in this ordering [1]. This time, I will show our Monte-Carlo results for two effective models and discuss in detail an unexpected criticality of the parasitic ferro quadrupole order.

This work is collaboration with Kazumasa Hattori, who is now at Tokyo Metropolitan University.

[1] Kazumasa Hattori and Hirokazu Tsunetsugu, J. Phys. Soc. Jpn. **83**, 034709 (2014).

Nonequilibrium dynamics of electron-boson systems

Philipp Werner
Physics Department, Fribourg University

Abstract: I will discuss the extension of the nonequilibrium dynamical mean-field formalism to electron-boson systems and use it to study the effect of strong static and pulsed electric fields on Mott insulators with coupling to optical phonons. I will also explain how the method can be used to study the dynamics of screening in photo-doped Mott insulators.

Topological superconductivity from gapless superconductivity

Yoichi Yanase
Department of Physics, Kyoto University

Abstract: We propose a generic scenario for realizing gapful topological superconductors (TSCs) from gapless spin-singlet superconductors (SCs). Noncentrosymmetric nodal SCs in two dimension are shown to be gapful under a Zeeman field, as a result of the cooperation of inversion-symmetry breaking and time-reversal-symmetry breaking. In particular, non-s-wave SCs acquire a large excitation gap. Such paramagnetically-induced gapful SCs may be classified into TSCs in the symmetry class D specified by the Chern number. We show nontrivial Chern numbers over a wide parameter range for spin-singlet SCs. A variety of the paramagnetically-induced gapful TSCs are demonstrated, including D+p-wave TSC, extended-S+p-wave TSC, p+D+f-wave TSC, and s+P-wave TSC. Natural extension toward three-dimensional Weyl SCs is also discussed.

Current-induced Magnetizations in Crystals with Helical Structure

Takehito Yokoyama
Department of Physics, Tokyo Institute of Technology

Abstract: I will show that in a crystal with a helical lattice structure, orbital and spin magnetizations along a helical axis are induced by an electric current along the helical axis, based on a simple tight-binding model. The induced magnetizations are opposite for right-handed and left-handed helices. The current-induced spin magnetization along the helical axis comes from a radial spin texture on the Fermi surface. This is in sharp contrast to Rashba systems where the induced spin magnetization is perpendicular to the applied current.

[1] T. Yoda, T. Yokoyama, and S. Murakami, Sci. Rep. **5**, 12024 (2015).