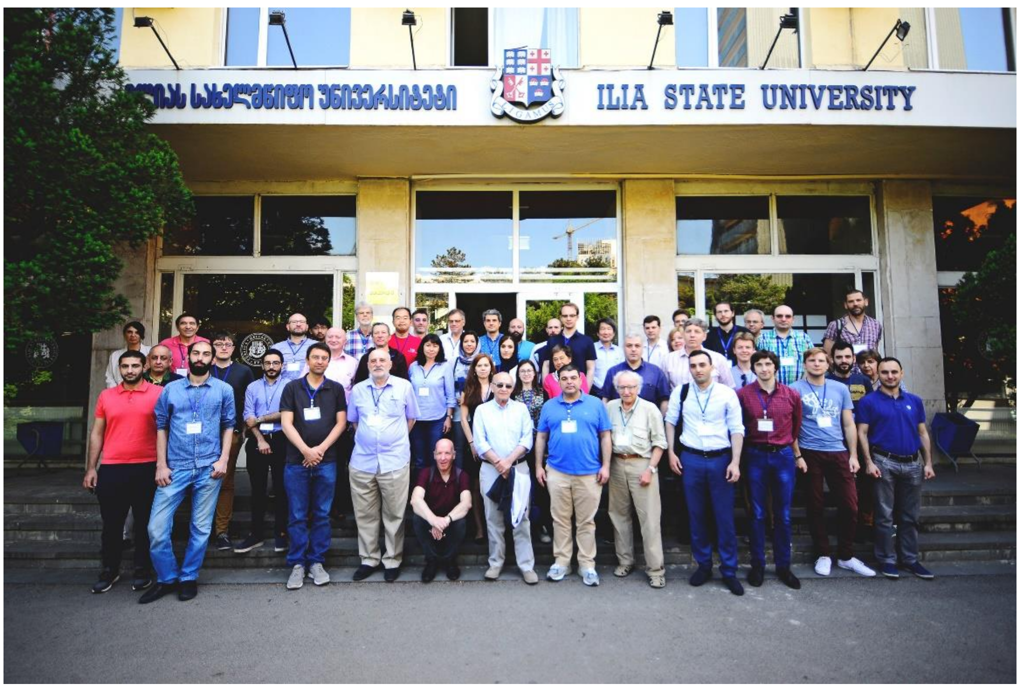
Low-dimensional emergent phenomena in
strongly correlated
and
topological quantum matter

Book of abstracts



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1. Many body quantum chaos of the Sachdev-Ye-Kitaev Model

Alexander Altland
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The Sachdev-Ye-Kitaev (SYK) model is a system of a large number of randomly interacting Majorana fermions. It stands in the tradition of the random k-body interaction models pioneered in nuclear physics and later applied in condensed matter contexts. The SYK model can be looked at from three interrelated perspectives: a) a system showing many body chaos and random matrix correlations, b) a paradigm of strongly correlated (Majorana) quantum matter, and c) the holographic shadow of a two-dimensional AdS2 gravitational bulk. The interplay of these three has made it a focus of intensive current research. Previous analytic research has focused on the manifestations of quantum correlations at time scales short compared to the inverse of the many body level spacing. In this talk the focus will be on the complementary regime of large times. We will apply a matrix integral formalism to identify a set of collective modes in Fock space describing the relaxation of the system towards an ergodic long time limit. We will discuss universal signatures of these modes in spectral correlations, and compare our results to numerics. Finally, we will discuss the structure of the SYK many body wave functions and point out differences to the wave functions of chaotic single particle systems.

2. Strategies for transforming the band structure of 2D materials

Eva Andrei
Department of Physics and Astronomy, *Rutgers University USA*

Historically materials discovery has been the result of serendipity or painstaking exploration of a large phase space of chemically synthesized compounds. A new era of materials started with the breakthrough isolation of a free standing 2D material, graphene, followed by many others. The distinctive characteristic of these 2D materials is that, with all the atoms residing at the surface, it is possible to access and manipulate their properties without changing their chemical composition. I will discuss a few examples: inducing magnetism and Kondo screening by removing single Carbon atoms in graphene [1,2]; generating flat bands and pseudo-magnetic fields by introducing a twist between layers [3,4] by buckling [5] or by introducing strain [6].

[1] Jiang, Y. *et al.* Inducing Kondo screening of vacancy magnetic moments in graphene with gating and local curvature. *Nature Communications* **9**, 2349 (2018).

[2] May, D. *et al.* Modeling of the gate-controlled Kondo effect at carbon point defects in graphene. *Physical Review B* **97**, 155419 (2018).

[3] Jiang, Y. *et al.* Evidence of charge-ordering and broken rotational symmetry in magic angle twisted bilayer graphene. *arXiv:1904.10153* (2019).

[4] Li, G. *et al.* Observation of Van Hove singularities in twisted graphene layers. *Nature Physics* **6**, 109-113 (2010).

[5] Jiang, Y. *et al.* Flat Bands in Buckled Graphene Superlattices. *arXiv:1904.10147* (2019).

[6] Jiang, Y. *et al.* Visualizing Strain-Induced Pseudomagnetic Fields in Graphene through an hBN Magnifying Glass. *Nano Letters* **17**, 2839-2843 (2017).

3. Superconductivity from repulsion: variational results in the limit of weak interactions

Dionys Baeriswyl
University of Fribourg, Switzerland

The problem of pairing in many-fermion systems with purely repulsive interactions has been extensively studied in the framework of the two-dimensional Hubbard model, using a variety of methods. Numerical simulations are typically limited to relatively small lattices (hundreds of sites) and therefore not capable of revealing the dominant ordering tendencies for small values of the on-site repulsion U. In this regime, analytical approaches, in particular the functional Renormalization Group, have provided some answers, but many issues remain to be clarified. In this talk, after a brief review of the status of research, a variational approach is presented, which gives accurate results for small U [1]. Expanding the expectation value of the energy in powers of U, one obtains explicit expressions which are readily evaluated for very large system sizes (millions of sites). Superconductivity with d-wave symmetry is indeed obtained with a dome-like shape for the order parameter as a function of density. A detailed study of size dependences sheds light on the question of the minimal size above which superconductivity appears and also explains why in Monte Carlo studies no superconductivity is found for small values of U.

[1] D. Baeriswyl, submitted to Phys. Rev. B.

4. Chiral spin liquids: thermodynamics

Leon Balents
Kalvi Institute of Theoretical Physics, Santa-Barbara, USA

In this talk we discuss excitation structure in a one-dimensional antiferromagnet α -Na0.9MnO2. In particular we analyze bound states in a 1d in α -Na0.9MnO2 and generally excitations in an antiferromagnet subjected by strong optical fields

5. Superconductivity from piezoelectric interactions in Weyl semimetals

Francesco Buccheri
University of Duesseldorf, Germany

I will introduce the piezoelectric electron-phonon interactions in undoped Weyl semimetals and show that they generate a long-range attractive potential between Weyl fermions, exhibiting a characteristic angular anisotropy. I will argue that superconducting phases with either conventional s-wave singlet pairing or nodal-line triplet pairing could be realized for sufficiently strong piezoelectric coupling.

6. Interplay between superconductivity and non-Fermi liquid a quantum critical point in a metal

Andrey Chubukov
University of Minnesota, Minneapolis, USA.

I discuss the interplay between non-Fermi liquid behaviour and superconductivity near a quantum-critical point (QCP) in a metal. It is widely thought that the tendency towards superconductivity and towards non-Fermi liquid behaviour compete, such that when the pairing interaction is reduced below a certain threshold, the system displays a naked non-Fermi liquid QC behaviour. I show that the situation is more complex as there are multiple

solutions for Tc at a QCP. For all solutions, except one, Tc vanishes when the pairing interaction drops below the threshold. However, for one solution Tc remains finite even at arbitrary small pairing interaction, despite that there is no Cooper logarithm. I argue that superconductivity between this Tc and a lower T, when other solutions appear, is special, as it is entirely induced by fermions with the first Matsubara frequency. I discuss the implications for the density of states and the spectral function. I argue that there are two qualitatively different regimes of system behaviour below the onset of pairing – at low T the pairing gap closes with increasing T, while at higher T it gets filled in, but remains finite. I discuss pairing fluctuations and argue that in the "gap filling" regime long-range superconducting order is destroyed, and the system displays a pseudogap behaviour.

7. Anisotropic-Exchange Magnets on a Triangular Lattice: Spin Waves, Accidental Degeneracies, and Dual Spin Liquids

Sasha Chernyshev
University of California, Irvine, USA

I will describe our efforts to understand the phase diagram of a model that combines the paradigmatic geometrical frustration of spins on a triangular lattice with strong spin-orbit-induced interactions. This model is relevant to a growing family of rare-earth-based magnets and other related materials and our work sets up a consistent interpretation of current and future experiments in them.

8. Lattice gauge theories and Schwinger pair production in synthetic quantum magnets

Marcello Dalmonte
SISSA and ICTPTrieste, Italy

In this talk, I will discuss how Rydberg atom chains offer unprecedented opportunities to observe paradigmatic properties of quantum field theories related to the recent observation of anomalous-ly slow dynamics after a quantum quench. I will discuss how the dynamics of Rydberg excitati-ons maps exactly onto a U(1) lattice gauge theory, the Schwinger model at topological angle $\theta=\pi$. This establishes the first large scale realization of a synthetic lattice gauge theory, and provides a simple field theoretical framework to understand the generality of the slow dynamics (that, as I will show, is a rather common feature well beyond the model discussed).

9. A criterion for topological phases: cases of the Kitaev wire and the AKLT chain

Pierre Fromhlz
ICTP Trieste, Italy

While topological phases' popularity increases as more of them are being imagined, no confirmed generic measurable quantities exist to probe directly the topological nature of their possible realization.

I will focus on the case of one of such candidate in 1D (but generalizable), the 'quadri-topological entanglement entropy', using experimentally measurable multipartite Rényi entanglement entropies. Specifically, I apply it for both the AKLT chain and the Kitaev wire with interactions known to display bosonic and fermionic symmetry-protected topological phase. Numerically at least (using DMRG and exact diagonalization) , the quantity does act like an order parameter for the phase, including scaling properties and possible access to critical exponent-like quantities. I will also give analytical insight on the reason why this quantity is relevant because of both the non nullity and additivity of the multipartite entanglement entropies, and give a (generalizable) interpretation of this result in terms Bell pairs.

10. Fermi Surface Reconstruction in underdoped Cuprates

Alvaro Ferraz
International Institute of Physics, Natal, Brazil

Using a phenomenological model we describe the evolution of the Fermi surface as a function of doping in the pseudogap phase of the hole doped cuprates. We show that while strong correlation effects produce an arc like FS, charge density waves (CDW) give rise to the Fermi surface reconstruction observed in those materials at a specific doping range.

11. Edge state structures in topological Insulators

Yuval Gefen
Weizmann Institute, Israel

It has been known for quite some time how the interplay between external drive and coupling to dissipative environment can be harnessed for the engineering of non-trivial many-body states. Such states are "dark states" of the related Lindbladian. What happens when we have several degenerate dark states? One then needs to deal with a mlti-dimensional "dark space". We discuss here the pronciples of contructing and manipulating such dark spaces, and provide an example of Laughlin states on a thin torus

12. Tunable Berry Curvature Through Magnetic Phase Competition in a Topological Kagome Magnet $Co_3Sn_2S_2$

Zurab Guguchia [1,2] J. Verezhak,[1] D. Gawryluk,[3] S.S. Tsirkin,[4] J.-X. Yin,[2] I. Belopolski,[2] H. Zhou,[5,6] G. Simutis,[1] S.-S. Zhang,[2] T.A. Cochran,[2] G. Chang,[2] E. Pomjakushina,[3] L. Keller,[7] Z. Skrzeczkowska,[3,8] Q. Wang,[9] H.C. Lei,[9] R. Khasanov,[1] A. Amato,[1] S. Jia,[5,6] T. Neupert,[4] H. Luetkens,[1] and M.Z. Hasan[2],

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Magnetic topological phases of quantum matter are an emerging frontier in physics and material science. Along these lines, several kagome magnets have appeared as the most promising platforms. However, the magnetic nature of these materials in the presence of topological state remains an unsolved issue. I will present our recent results on magnetic correlations in the kagome magnet $Co_3Sn_2S_2$ [1]. Using muon spin-rotation, we show the evidence for competing magnetic orders in the kagome lattice of this compound. Our results reveal that while the sample exhibits an out-of-plane ferromagnetic ground state, an in-plane antiferromagnetic state appears at temperatures above 90 K, eventually attaining a volume fraction of 80 % around 170 K, before reaching a nonmagnetic state. Strikingly, the reduction of the anomalous Hall conductivity above 90 K linearly follows the disappearance of the volume fraction of the ferromagnetic state. We further show that the competition of these magnetic phases is tunable through applying either an external magnetic field or hydrostatic pressure. Our results taken together suggest the thermal and quantum tuning of Berry curvature field via external tuning of magnetic order. Our study shows that $Co_3Sn_2S_2$ is a rare example where the magnetic competition drives the thermodynamic evolution of the Berry curvature field, thus tuning its topological state.

13. Two topics in the theory of chiral superconductors

Thors Hans Hansson
University of Stokholm and Nordita, Sweden

I will explain in simple terms what are two-dimensional chiral liquids, and why they are interesting objects to study. I quickly specialize to Quantum Hall liquids and topological superconductors and explain the concept of orbital spin and how it can be related to observable quantities. I will then introduce “Majorinos” or “half fermions” that are signatures of odd pairing topological phases, and discuss a couple of amusing thought experiments where geometrical effects play an important role. The talk is aimed at a general theoretical physics audience.

14. Robustness of symmetry-protected topological states against time-periodic perturbations

Henrik Johannesson
University of Gothenburg (Sweden)

The existence of gapless boundary states is a key attribute of any topological band insulator. Conventional band theory predicts that these states are robust against static perturbations that preserve the relevant symmetries. In this talk I will discuss how the symmetry-protection may extend also to states subject to time-periodic boundary perturbations – in Floquet topological insulators as well as in ordinary time-independent topological insulators. Notably, boundary states in a time-independent topological insulator are found to exhibit an enhanced resilience against time-periodic perturbations, beyond that for static perturbations. Implications for experiments on transport in quantum wires will be discussed.

15. Pseudo-fermion functional renormalization group: a new approach to frustrated quantum magnetism and quantum spin liquids

Yasir Iqbal
Indian Institute of Technology, Madras, India

I will introduce the pseudo-fermion functional renormalization (PFFRG) approach for quantum spin Hamiltonians. Its application to three-dimensional frustrated magnets such as the pyrochlore and hyperkagome lattices is discussed and the quantum phase diagram for the Heisenberg models on these lattices is presented. Comparison with inelastic neutron scattering data demonstrates that the method accurately captures the relevant magnetic fluctuations.

16. Exotic magnetism in spin-orbit Mott insulators

Giniyat Khaliullin
Max Planck Institute for Solid State Research, Stuttgart, Germany

Spin-orbit coupling entangles the spin and orbital subspaces leading to a rich variety of effective Hamiltonians and exotic phases depending on lattice geometry and orbital structure. One prominent example is the Kitaev honeycomb model with spin liquid ground state that can be realized in spin-orbit pseudospin J=1/2 compounds [1]. I will also discuss spin-orbit J=0 Mott insulators with gapped singlet-triplet excitations. Exchange interactions and crystalline electric fields may close the spin gap, resulting in a Bose condensation of spin-orbit excitons. In addition to usual magnons, a Higgs amplitude mode, most pronounced near quantum critical point, is expected [2,3]. Upon electron doping, ferromagnetic correlations and triplet superconductivity may emerge [4]. I will also introduce highly frustrated J=0 models where magnetic order is suppressed and the spin-orbit excitons condense in a form of nonmagnetic pairs [5]. These theoretical ideas will be discussed in the context of recent experiments in iridium and ruthenium oxides.

[1] G. Jackeli and G. Khaliullin, Phys. Rev. Lett. **102**, 017205 (2009).
[2] G. Khaliullin, Phys. Rev. Lett. **111**, 197201 (2013).
[3] A. Jain *et al.*, Nature Phys. **13**, 633 (2017).
[4] J. Chaloupka and G. Khaliullin, Phys. Rev. Lett. **116**, 017203 (2016).
[5] P. Anisimov *et al.*, Phys. Rev. Lett. **122**, 177201 (2019).

17. Electric activity of different magnetic textures

Daniel Khomskii
University of Cologne, Germany

Close connection between electricity and magnetism is one of the cornerstone of modern physics. In application to solids this connection takes different forms. In particular, there exist materials with linear magnetoelectric effect, and multiferroics - the systems which simultaneously have magnetic and ferroelectric ordering [1]. In my talk I will discuss electric properties of different magnetic objects: spin triangles; monopoles in spin ice systems; domain walls and cylindrical magnetic domains (CMD); skyrmions; systems with spin fragmentation; ordinary spin waves, and the inverse effect: the appearance of magnetic monopoles on charges in magnetoelectrics.

I will pay special attention to the purely electronic mechanisms of such phenomena and will discuss the appearance of spontaneous currents, electric dipoles and magnetic monopoles in frustrated Mott insulators [2-5].

[1] D.I. Khomskii, Physics (Trends) **2**, 20 (2009)
[2] L.N.Bulaevskii, C.D.Batista, M.V.Mostovoy and D.I.Khomskii, Phys.Rev.B **78**, 028402 (2008)
[3] D.I.Khomskii, JPCM 22, 164209 (2010)
[4] D.I.Khomskii, Nature Communications **3**, 904 (2012)
[5] D.I.Khomskii, Nature Communications **5**, 4793 (2014)

18. High-velocity spin waves in the $Sr_2IrO_4/Sr_3Ir_2O_7$ heterostructure

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Pohang 790-784, Korea

Oxide heterestructures offer a fertile ground for novel phenomena not found in the bulk constituents such as interface superconductivity, magneto-elastic coupling, and the quantum Hall effect, through the reconstruction of the charge, spin, and orbital states at the interface on the nanometer scale. However, how the spin dynamics changes under the constraints set by interfaces remains largely unexplored. In this talk, I will discuss the effect of magnon velocity renormalization in a magnetic heterostructure composed of Sr2IrO4 and Sr3Ir2O7, which are magnetic insulators with predominantly Heisenberg and Ising interactions, respectively. Using resonant inelastic x-ray scattering, we observe that the magnon velocity in the Sr2IrO4 layer near the magnetic zone center is enhanced by almost a factor of two relative to its bulk counterpart. I will discuss possible origins of this phenomenon, in particular in connection with the suppression in the heterostructure of the magnetoelastic coupling which is manifest in the bulk Sr2IrO4.

19. Thermoelectric transport through SU(N) quantum impurity

Mikhail Kiselev
ICTP, Trieste Italy

We investigate thermoelectric transport through a SU(N) quantum impurity in the Kondo regime. The strong-coupling fixed-point theory is described by the local Fermi-liquid paradigm. Using Keldysh technique we analyze the electric current through the quantum impurity at both finite bias voltage and finite temperature drop across it. The theory of a steady state at zero current provides a complete description of the Seebeck effect. We find pronounced nonlinear effects in temperature drop at low temperatures. We illustrate the significance of then onlinearities for enhancement of thermopower by two examples of SU(4) symmetric regimes characterized by a filling factor m: (i) particle-hole symmetric at m=2 and (ii) particle-hole non-symmetric at m=1. We analyze the effects of potential scattering and coupling asymmetry on the transport coefficients. We discuss connections between the theory and transport experiments with coupled quantum dots and carbon nanotubes.

20. Topological excitations in low-dimensional magnets with competing interactions

Oleksiy Kolezhuk
Taras Shevchenko University of Kiev, Ukraine

We study the stabilization of an isolated magnetic skyrmion in a magnetic monolayer on a nonmagnetic conducting substrate via the Ruderman-Kittel-Kasuya-Yosida (RKKY) exchange interaction. Two different types of the substrate are considered, usual normal metal and single-layer graphene. While the full stability analysis for skyrmions in the presence of the RKKY coupling requires a separate effort that is outside the scope of this work, we are able to study the radial stability (stability of a skyrmion against collapse) using variational energy estimates obtained within first-order perturbation theory, with the unperturbed Hamiltonian describing the isotropic Heisenberg magnet, and the two perturbations being the RKKY exchange and the easy-axis anisotropy. We show that a proper treatment of the long-range nature of the RKKY interaction leads to a qualitatively different stabilization scenario compared to previous studies, where solitons were stabilized by the frustrated exchange coupling (leading to terms with the fourth power of the magnetization gradients) or by the Dzyaloshinskii-Moriya interaction (described by terms linear in the magnetization gradients). In the case of a metallic substrate, the skyrmion stabilization is possible under restrictive conditions on the Fermi surface parameters, while in the case of a graphene substrate the stabilization is naturally achieved in several geometries with a lattice-matching of graphene and magnetic layer

21. Between one and infinite dimensions: surprises of Anderson localization

Vladimir Kravtsov
ICTP, Trieste Italy

The Bethe lattice shares the properties of one and infinite dimensions: it has no loops as in 1D and its volume grows exponentially with the size as in infinite dimensions. It is believed that this exponential proliferation of sites is a property of the Hilbert space of all the interacting systems, where the "sites" are the single-particle orbitals. Therefore the one-particle Anderson localization on the regularized Bethe lattices, the random regular graphs (RRG), attracted a lot of attention recently in connection with Many Body Localization. Such graphs are locally like a Bethe lattice but in contrast to the latter they do not have a boundary due to large loops connecting the "leaves". We review our recent papers on Anderson localization on RRG and also in 1D systems with long-range hopping and show that in such systems a new Non-

Ergodic-Extended phase may exist which is separated from the localized phase by the Anderson localization transition and from the extended ergodic phase by the new ergodic transition. We also uncover the role of correlations in the hopping matrix elements on the fate of Anderson localization in 1D systems with long-range hopping.

22. Topological Solitons in doped Zigzag Graphene Nanoribbons

M. Pilar López-Sancho
Instituto de Ciencia de Materiales de Madrid, Spain

Graphene nanoribbons with zigzag-terminated edges have a magnetic ground state characterized by edge ferromagnetism with antiferromagnetic coupling between opposite edges. This ground state appears because of a broken symmetry in the spin sector. By inverting the spin polarization of the full system there is another energy degenerate ground state. The band structures of the degenerate ground states are inverted. When connecting two domains with opposite mass, i.e. spin orientation, a symmetry protected zero energy topological state appears at the interface between the degenerate ground states. These topological states are soliton-like excitations that carry charge ±e with half electron localized at each edge of the nanoribbon. The connection between topological defects and electric charge suggests that solitons can be the relevant charge excitations in zigzag graphene nanoribbons. Then whenever adding (subtracting) charge to the system an array of solitons can be formed, creating a solitonic phase [1].

[1]-M. P. López-Sancho and Luis Brey, 2D Mater. 5, 015026 (2018)

23. Competition between magnetism and superconductivity in the Hubbard model and in the cuprates

Walter Metzner
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We analyze the competition of magnetism and superconductivity in the two-dimensional Hubbard model with a moderate interaction strength, including the possibility of income-mensurate spiral magnetic order. Using an unbiased renormalization group approach, we compute magnetic and superconducting order parameters in the ground state. In addition to previously established regions of Neel order coexisting with d-wave superconductivity, the calculations reveal further coexistence regions where superconductivity is accompanied by a very delicate incommensurate magnetic order [1].

We further show that a Fermi surface reconstruction due to spiral antiferromagnetic order may explain the rapid change in the Hall number in a strong magnetic field as recently observed near optimal doping in cuprate superconductors. The single-particle spectral function in the spiral state exhibits hole pockets which look like Fermi arcs due to a strong momentum dependence of the spectral weight [2,3].

[1] H. Yamase, A. Eberlein, and W. Metzner, Phys. Rev. Lett. **116**, 096402 (2016).
[2] A. Eberlein, W. Metzner, S. Sachdev, and H. Yamase, Phys. Rev. Lett. **117**, 187001 (2016).
[3] J. Mitscherling and W. Metzner, Phys. Rev. B **98**, 195126 (2018).

24. There is plenty of room at the bottom... but even more in a fractal

Criatiane Morais Smith
Institute for Theoretical Physics, Utrecht University, The Netherlands

Feynman's original idea of using one quantum system that can be controlled and manipula-ted at will to simulate the behavior of another more complex one has flourished during the last decades in the field of cold atoms. More recently, this concept started to be developed in nanophotonics and in condensed matter. In this talk, I will discuss a few recent experiments, in which 2D electron lattices were engineered on the nanoscale. The first is the Lieb lattice [1], and the second is a Sierpinski gasket [2], which has dimension D = 1.58. The realization of fractal lattices opens up the path to electronics in fractional dimensions. Finally, I will show how to control the electronic orbital degree of freedom [3] and how to realized topolo-gical states of matter using the same procedure [4]. In all cases, we observe an excellent agreement between the theoretical predictions and the experimental results. This technique is proving itself to be a very versatile framework for the engineering and control of electronic systems.

[1] M.R. Slot, T.S. Gardenier, P.H. Jacobse, G.C.P. van Miert, S.N. Kempkes, S.J.M. Zevenhuizen, C. Morais Smith, D. Vanmaekelbergh, and I. Swart, *"Experimental realisation and characterisation of an electronic Lieb lattice"*, Nature Physics **13**, 672 (2017).

[2] S.N. Kempkes, M.R. Slot, S.E. Freeney, S.J.M. Zevenhuizen, D. Vanmaekelbergh, I. Swart, and C. Morais Smith, *"Design and characterization of electronic fractals*", Nature Physics **15,** 127(2019).
[3] M. R. Slot et al., *"p-band engineering in artificial electronic lattices"*, Phys. Rev. X **9**, 011009 (2019).
[4] S.N. Kempkes, M. R. Slot, … & C. Morais Smith "*Robust zero-energy modes in an electronic higher-order topological insulator: the dimerized Kagome lattice"*, submitted (2019).

25. Universal gap scaling in finite quantum Ising chains

Masaki Oshikawa
University of Tokio, Japan

The quantum (transverse-field) Ising chain has been studied for a long time as a canonical model exhibiting a quantum phase transition, and is also deeply related to the Kitaev chain which hosts Majorana zero modes as edge states. I will discuss the lowest gap of the finite-size quantum Ising chains for general boundary conditions with a "defect". Although this problem has been naturally studied in many papers, apparently not much attention was paid to the universal scaling function describing the crossover between the ordered and disordered phases except for Sachdev's paper in 1996 on the problem equivalent to the finite-size gap under the periodic boundary condition. I will generalize it to the more general boundary conditions, and elucidate a rather rich structure behind the asymmetry between the ordered and disordered phases.

26. Quantum spin circulator for Heisenberg chains

Rodrigo Pereira
International Institute of Physics, Natal, Brazil

Chiral spin liquids are long-range-entangled phases of interacting spins which break time reversal and reflection symmetries. The usual analytical approach to describe these phases is based on parton mean-field theories that neglect fluctuations of the emergent gauge fields. I will talk about an alternative approach that employs junctions of Heisenberg spin chains as building blocks for two-dimensional networks. This approach reveals a connection between chiral spin liquids and chiral fixed points of boundary conformal field theory.

27. Bond disordered spin liquid and the honeycomb iridate $H_3LiIr_2O_6$

Natalya Perkins
University of Minnesota, Minneapolis, USA.

Recent years have seen remarkable progress in identifying candidate materials that can realize Kitaev quantum spin liquid. However, at sufficiently low temperatures almost all known Kitaev materials order magnetically rather than exhibiting spin-liquidity. A recent exception, the hydrogen intercalated iridate $H_3LiIr_2O_6$ [K. Kitagawa et al., Nature 554, 341-345 (2018)], remains in a liquid state down to lowest temperatures without any sign of long ranged ordered magnetism. In this intercalated spin-orbital compound, a remarkable pile up of low-energy states was experimentally observed in specific heat and nuclear magnetic (NMR) spin relaxation. We show [**J. Knolle, R. Moessner, N. B. Perkins, Phys. Rev. Lett. 122, 047202 (2019)**] that a bond disordered Kitaev model can naturally account for this phenomenon, suggesting that disorder plays an essential role in its theoretical description. In an exactly soluble Kitaev model, we obtain, via spin fractionalization, a random bipartite hopping problem of Majorana fermions in a random flux background. This has a divergent low-energy density of states (DOS) of the required power-law form. Breaking time reversal symmetry (TRS) removes the divergence of the DOS, as does applying a magnetic field in experiment.

28. Zeeman spin-orbit coupling and magnetic quantum oscillations in antiferromagnetic conductors

Revaz Ramazashvili
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We find that the Neel state of layered organic conductor κ-$(BETS)_2FeBr_4$ shows no spin modulation of the Shubnikov-de Haas oscillations, contrary to the paramagnetic state of the same material. We argue that this is a manifestation of the generic Zeeman spin-orbit coupling in antiferromagnetic conductors. Likewise, we find no spin modulation in the angular dependence of the slow Shubnikov-de Haas oscillations in the optimally electron-doped cuprate $Nd_{2-x}Ce_xCuO_4$ which points to the antiferromagnetic origin of the Fermi surface reconstruction even at the optimal doping.

29. Magnetotransport in Topological insulators and Dirac materials: Theory and Experiment

Achim Rosch
Institute of Theoretical Physics. University of Cologne, Germany

We argue that the interplay of disorder and interaction leads to a number of large effects affecting transport in topological insualtors and Dirac matter. Charged impurities in (compensation-doped) insulators lead to the formation of electron and hole puddles. They determine the bulk properties of topological insulators and show a peculiar temperature dependence. A magnetic field can induce a percolation transition of the puddles, leading to a giant negative magnetoresistance. We furthermore show that the change of the orientation of the magnetic field in Dirac materials can change the resistivity substantially. This effect arises most likely from an interplay of disorder and interactions affecting the inter- and intra-nodal scattering rates.

30. Spin-valley density waves in moiré materials

Constantin Schrade
Massachusetts Institute of Technology, USA

We introduce and study a minimum two-orbital Hubbard model on a triangular lattice, which captures the key features of both the trilayer ABC-stacked graphene-boron nitride heterostructure and twisted transition metal dichalcogenides in a broad parameter range. Our model comprises first- and second-nearest neighbor hoppings with valley-contrasting flux that accounts for trigonal warping in the band structure. For the strong-coupling regime with one electron per site, we derive a spin-orbital exchange Hamiltonian and find the semiclassical ground state to be a spin-valley density wave. We show that a relatively small second-neighbor exchange interaction is sufficient to stabilize the ordered state against

quantum fluctuations. Effects of spin- and valley Zeeman fields as well as thermal fluctuations are also examined.

31. Braiding errors in interacting Majorana wires

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Andronikashvili Institute of Physics, Tbilisi, Georgia

Avenues of Majorana bound states (MBSs) have become one of the primary directions towards a possible realization of topological quantum computation. For a Y-junction of Kitaev quantum wires, we numerically investigate the braiding of MBSs while considering the full quasi-particle background. The two central sources of braiding errors are found to be the fidelity loss due to the incomplete adiabaticity of the braiding operation as well as the hybridization of the MBS. The explicit extraction of the braiding phase in the low-energy Majorana sector from the full many-particle Hilbert space allows us to analyze the breakdown of the independent-particle picture of Majorana braiding. Furthermore, we find nearest-neighbor interactions to significantly affect the braiding performance to the better or worse, depending on the sign and magnitude of the coupling.

32. Surprisingly similar response of superconductivity and stripe order to in-plane impurities in cuprates

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Since the discovery of high temperature superconductivity (HTS) in cuprates much effort was invested in the investigation of the effect of the impurity substitution at the Cu site. It is now well established that in HTSs nonmagnetic Zn ions suppress *Tc* even stronger than magnetic ions. This behavior, which is in sharp contrast to that of conventional superconductors, led to the formulation of an unconventional pairing mechanism and a

symmetry of the order parameter for cuprate HTSs. However, up to now surprisingly little is known concerning impurity effects on static stripe phase in cuprates.

We performed muon spin rotation (μSR) and neutron scattering experiments in Zn-doped cuprates $La_{2-x}Ba_xCuO_4$ and $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ (x=1/8) to systematically study the effect of nonmagnetic impurities on static stripe order. Remarkably, it was found that the spin-stripe ordering temperature T_{so} decreases linearly with Zn doping and disappears at ≈ 4% Zn concentration, demonstrating a high sensitivity of static spin-stripe order to impurities within a CuO_2 plane. Moreover, T_{so} is suppressed by Zn in the same manner as the superconducting transition temperature T_c for samples near optimal hole doping. This surprisingly similar sensitivity suggests that the spin-stripe order is dependent on intertwining with superconducting correlations. More generally, since stripe order is also observed in other transition metal oxides, investigation of impurity effects on stripe formation can become an interesting research direction in correlated electron compounds.

33.Collective modes of magnetized spin liquids.

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The search for the enigmatic quantum spin liquid (QSL) state has switched into high gear in recent years. Amazing experimental progress has resulted in several highly promising QSL materials such as $ZnCu_3(OH)_6Cl_2$, $YbMgGaO_4$, and $NaYbO_2$, to list just a few. All of these quasi-two-dimensional materials are characterized by a broad continuum of spin excitations observed in neutron scattering experiments. Unfortunately many, if not all, of these QSL candidates suffer from the presence of significant substitutional disorder which often tends to strongly broaden inelastic neutron spectra and thus calls into question the QSL interpretation of the experimental data. It is therefore incumbent upon the theoretical community to identify specific experimental signatures, more detailed than a “broad continuum” arguments, that evince the unique aspects of spin liquid states of magnetic matter.

In this talk I focus on the prominent metal-like magnetic insulators – U(1) quantum spin liquids with spinon Fermi surface – excitations of which are represented by neutral spin-1/2 fermions (spinons) and emergent gauge fields. The gauge field mediates strong interactions between spinons. We argue that the full effect of this interaction becomes apparent when the spin liquid is partially **magnetized** by the Zeeman magnetic field. Under this condition, the spectrum of the spin liquid acquires a new transverse collective spin-1 mode, distinct from incoherent particle-hole excitations of the spinon continuum. Despite being located outside the spinon continuum, this novel collective excitation interacts with emergent gauge fluctuations which are responsible for partially damping it.

I present a tentative theory of this collective mode, including its dispersion, lifetime and other spectral characteristics, and identify conditions needed for its experimental observation.

34. Intertwined structural and magnetic transitions in rare-earth nickelates

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Rare-earth nickelates RNiO3 exhibit a unique phase diagram where a metal-insulator transition is accompanied by structural and magnetic transitions. It has experimentally been established that all rare-earth nickelates except LaNiO3 are metallic paramagnets with an orthorhombic structure at high temperatures. At low temperature, the metal-insulator and an orthorhombic to monoclinic structural transitions occur simultaneously. The transition temperature can be lowered by increasing the size of the rare-earth ion, and it approaches zero for LaNiO3. I will present a theory to describe the structural, electronic and magnetic transitions in these materials

35. Exotic spin-orbital entangled phases in 4d and 5d transition metal oxides

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The exploration of novel phases of interacting electrons (correlated electrons) has long been a major stream of condensed-matter research. Many-body interactions among electrons give rise to a huge variety of phases, grouped into electron-solid, -liquid-crystal, -liquid and -gas states. The wealth of possibilities arises from a complicated interplay of lattice geometry, quantum effects and the multiple degrees of freedom of the electron (charge, spin and orbital). In the past, the two dominant areas of exploration have been the 3d transition-metal (TM) oxides and the 4f intermetallic compounds but recently 5d TM oxides and related compounds have emerged as the next arena of correlated-electron physics. Significant new physics is expected due to the presence of a large spin-orbit coupling in heavy 5d elements, tying together the otherwise independent spin and orbital degrees of freedom. This can be of order 0.5eV and is often larger than the crystal-field splitting of the orbital states, resulting in a spin-orbital-entangled state of correlated electrons. The nature of the spin-orbital entanglement depends significantly on the d-electron number and the chemical bonding, and it is anticipated that, in combination with electron correlations, a rich variety of novel electronic phases are waiting to be discovered. To name just a few, the proposed phases include Kitaev quantum spin liquids, correlated topological semimetals, excitonic magnets and multipolar-ordered states.

In this talk, I will present our recent exploration of such exotic faces of spin-orbital entangled matter in 5d (and 4d) transition metal oxides. Topics will include the following.

(I) Spin-orbital quantum liquid on honeycomb lattice in $5d^5$ $H_3LiIr_2O_6$ [1].

(II) $J_{eff} = 0$ Mott insulator [2] in $4d^4$ Ru^{4+} oxides and proximity to excitonic magnetism.

(III) Multipolar ordering in $5d^1$ Ta^{4+} chlorides [3].

References

[1] K. Kitagawa, T. Takayama, Y. Matsumoto, A. Kato, R. Takano, Y. Kishimoto, S. Bette, R. Dinnebier, G. Jackeli, and H. Takagi, Nature, **554**, 341–345 (2018).

[2] G. Khaliullin, Phys. Rev. Lett. 111, 197201 (2013).

[3] H. Ishikawa, T. Takayama, R. Kremer, J. Nuss, R. Dinnebier, K. Kitagawa3, K. Ishii and H. Takagi, submitted.

36. New anomaly induced transport in 3D Dirac matter

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After the synthesis of graphene (described at low energies as massless Dirac fermions in 2+1 dimensions) in 2005, Weyl semimetals were synthesized in 2015 . Although they can be seen as 3D graphene, a series of new phenomena arise from the fundamental differences between chiral fermions in two and three dimensions. Chiral imbalance in 3D implies a set of anomaly related transport phenomena first discussed in the context of high energy collisions (quark-gluon plasma). Examples are the chiral magnetic effect: generation of an electric current parallel to en applied magnetic field, or the axial magnetic effect: generation of an energy current parallel to an axial magnetic field [1]. In this talk we will see some of the implications of these phenomena to the novel Dirac materials. I will explain the origin of the anomaly--induced response functions and review the experimental evidences found so far. Finally I will describe novel response functions associated to the scale anomaly in Dirac and Weyl semimetals [2].

References:

[1] The Chiral Magnetic Effect and Anomaly-Induced Transport, Dmitri E. Kharzeev, arXiv:1312.3348.
[2] Generation of a Nernst current from the conformal anomaly in Dirac and Weyl semimetals, Maxim N. Chernodub, Alberto Cortijo, and M. A. H. Vozmediano, Phys. Rev. Lett. 120, 206601 (2018).
[3] Thermoelectric relations in the conformal limit in Dirac and Weyl semimetals, Vicente Arjona, Juan Borge, and María A.H. Vozmediano, arXiv:1903.00019.
[4] Direct measurement of a beta function and an indirect check of the Schwinger effect near the boundary in Dirac-Weyl semimetals, M. N. Chernodub, M. A. H. Vozmediano, arXiv:1902.02694.
[5] Fingerprints of the conformal anomaly on the thermoelectric transport in Dirac and Weyl semimetals: Result from a Kubo formula, Vicente Arjona, Maxim N. Chernodub, María A. H. Vozmediano, arXiv:1902.02358.

37. Hydrodynamics of the edge modes

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Recently developed hydrodynamics theory of fractional quantum Hall effect identifies electrons with vortices in rotating superfluid. Hence, hydrodynamics of rotating superfluid, like helium, and hydrodynamics of electronic fluid in FQHE could be studied in parallel. I will present a theory of edge modes of FQHE developed from this perspective. It also solves a long standing problem of classical hydrodynamics of chiral turbulent flow (Phys. Rev. Lett, May 2019).

The theory predicts a formation of a special boundary layer and non-linear very special waves propagating along the edge. It suggests that the edge wave is governed by the integrable Benjamin-Davis-Ono equation exhibiting solitons with a quantized total vorticity and identified with the action of the Virasoro-Bott group, the centrally extended diffeomorphisms of the circle.

38. Fermi liquid theory for superconducting Kondo problems

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We present a general yet simple Fermi liquid approach to the Kondo problem in a superconducting host material. Our theory is applicable as long as the Kondo temperature is large compared to the superconducting gap. As a concrete example, we study the current-phase relation for an Anderson impurity sandwiched between two s-wave superconductors. In the particle-hole symmetric Kondo limit, we predict a 4\pi periodic Josephson relation. The 4\pi periodicity persists under a small voltage bias which however causes an asymmetric distortion of Andreev levels. The latter distinguishes the present 4\pi effect from the one in topological Majorana junctions.

39. Spin nematics on a square lattice: experiment

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Conventional magnetic order spontaneously produces a static periodically modulated magnetization in the sample. It thus breaks rotational and time-reversal symmetries of the underlying spin Hamiltonian. A **spin nematic** is an exotic state that only breaks rotational but not time reversal symmetries. The spins remain disordered and fluctuating, but these **fluctuations are spontaneously anisotropic**. Theory predicts a spin nematic ground state for quantum spin systems with competing ferromagnetic (FM) and antiferromagnetic (AFM) interactions in high magnetic fields. The simplest model is a FM-AFM S=1/2 square lattice. To date there seems to be only one family of materials that approximate this scenario, namely the layered vanadophosphate. Unfortunately, our understanding of these compounds has been severely limited by a lack of single crystal samples. This is particularly problematic for experiments in magnetic fields where any features or phase transitions are smeared out by the powder averaging of the material's anisotropic properties. In my talk I will present breakthrough magnetic,

thermodynamic, ESR, NMR and neutron scattering studies on **single crystals** of two vanadophosphate species, namely $BaCdVO(PO_4)_2$ and $Pb_2VO(PO_4)_2$. Neither turned out to be quite the proximate FM-AFM square lattice that it was advertised to be. Nevertheless, in both systems we find clear indications of "hidden" nematic order, just below saturation in high magnetic fields.

40. Noncoplanar multi-k states in frustrated magnets

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Collinear and coplanar spin structures are ubiquitous in nature and are thoroughly studied both experimentally and theoretically. Recently, there is a growing interest in noncoplanar magnetic states which may exhibit peculiar topological properties and find novel spintronic applications. We demonstrate that noncoplanar spin structures develop as multi-k states of Heisenberg antiferromagnets. We investigate Heisenberg models on pyrochlore and kagome lattices in the presence of several competing exchanges. The former model is motivated by spinels $GeCo_2O_4$ and $GeNi_2O_4$ which order with the commensurate propagation vector Q = (1/2,1/2,1/2). The star of the ordering wave vector has 4 arms and allows various multi-k structures. For isotropic spin interactions the equilibrium magnetic structure is a 20-sublattice triple-k noncoplanar state. In strong magnetic fields the 3-k structure transforms into a planar double-k state. The same behavior is also found for the J_1-J_3 kagome antiferromagnet. We show that such universality is related to dimensionality of ordered magnetic moments.