17-19 JANUARY, 2024

UNIVERSITY OF GENEVA

THE MAGIC OF DISORDER AND CORRELATIONS

CONFERENCE

2024

CONFERENCE BOOKLET

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INVITED SPEAKERS

ALAIN ASPECT	*Université Paris-Saclay*
IMMANUEL BLOCH	*Max Planck Institute of Quantum Optics; Ludwing-Maximilians University*
MIGUEL CAZALILLA	*Donostia International Physics Center*
ROBERTA CITRO	*University of Salerno*
TILMAN ESSLINGER	*ETH Zürich*
MICHELE FILIPPONE	*CEA, Grenoble*
THIERRY KLEIN	*Université Grenoble-Alpes*
CORINNA KOLLATH	*University of Bonn*
VIVIEN LECOMTE	*Université Grenoble-Alpes*
PIERRE LE DOUSSAL	*Ecole Normale Supérieure, Paris*
EDMOND ORIGNAC	*Ecole Normale Supérieure, Lyon*
PATRYCJA PARUCH	*University of Geneva*
ALBERTO ROSSO	*Université Paris-Saclay*
CHRISTIAN RUEGG	*EPFL; ETHZ; PSI; UNIGE*
SRIRAM SHASTRY	*University of California Santa Cruz*
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Program - The Magic of Disorder and Correlations

Wednesday January 17th	
09:00	Introductory remarks
	Chair: Antoine Georges
09:20	Pierre Le Doussal Counting trapped fermions
10:00	Alberto Rosso Creep motion of elastic interfaces driven in a disordered landscape
10:40	Coffee Break
	Chair: Dirk Van der Marel
11:20	Corinna Kollath Dynamical phenomena in interacting atomic gases coupled to optical cavities
12:00	Chandra Varma What remains unproven by experiments for a theory of high temperature superconductors?
12:40	Lunch
	Chair: Nirvana Caballero
14:30	Vivien Lecomte Hidden degrees of freedom in the motion of interfaces in disordered media
15:10	Patrycja Paruch Every (ferroelectric) wall is a door - exploring the links between structure, dynamics, and emergent functionalities
15:50	Coffee Break
	Chair: Christophe Berthod
16:30	Sriram Shastry A progenitor fermi surface tracking algorithm
17:10	Posters and Apero
19:00	

Thursday January 18th	
	Chair: Dmitry Abanin
09:00	Alain Aspect
09:40	Miguel Cazalilla Quantum dissipation in one dimensional systems and Thierry's "Magic Touch"
10:20	Coffee Break
	Chair: Eugene Demler
11:00	Immanuel Bloch New avenues for quantum simulation with atoms, molecules and photons
11:40	Michele Filippone Climbing the ladders of physics with Thierry
12:20	Brief information
12:30	Lunch
	Chair: Laura Foini
14:30	Joerg Schmidmeyer Probing 1D physics by correlations
15:10	Thierry Klein Probing exotic superconductors by high sensitivity microcalorimetry
15:50	Coffee Break & Special event
19:00	Conference dinner

Friday January 19th	
	Chair: Tony Jin
09:00	Roberta Citro Thermal phase and many-body parametric resonances in driven interacting one-dimensional systems
09:40	Edmond Orignac Extended symmetry in a 4-leg spin tube
10:20	Coffee Break
	Chair: Mark H. Fischer
11:00	Alexei Tsvelik A solvable 3D Kondo lattice exhibiting pair density wave, odd-frequency pairing and order fractionalization
11:40	Christian Rüegg The magic of quantum spin systems from 1D to 3D
12:20	Closing remarks
13:00	Lunch
14:30	Closing and free discussion

Posters - The Magic of Disorder and Correlations

ABSTRACTS

of the

oral presentations

Counting trapped fermions

Pierre Le Doussal

Laboratoire de Physique Théorique, Ecole Normale Supérieure, Paris

I will describe some simple approaches to the couting statistics of non-interacting fermions (and in some cases interacting) in external potentials, with connections to random matrix theory.

Creep motion of elastic interfaces driven in a disordered landscape

Alberto Rosso

CNRS/LPTMS

The thermally activated creep motion of an elastic interface weakly driven on a disordered landscape is one of the best examples of glassy universal dynamics. Its understanding has evolved over the past 30 years thanks to a fruitful interplay among elegant scaling arguments, sophisticated analytical calculations, efficient optimization algorithms, and creative experiments. I will discuss recent works unveiling the collective nature of such ultraslow motion in terms of elementary activated events. We show that these events control the mean velocity of the interface and cluster into "creep avalanches" statistically similar to the deterministic avalanches observed at the depinning critical threshold. The associated spatiotemporal patterns of activated events have been recently observed in experiments with magnetic domain walls. The emergent physical picture is expected to be relevant for a large family of disordered systems presenting thermally activated dynamics.

[1] Ezequiel E. Ferrero, Laura Foini, Thierry Giamarchi, Alejandro B. Kolton, and Alberto Rosso, Annual Review of Condensed Matter Physics **12**, 111 (2021).

Dynamical phenomena in interacting atomic gases coupled to optical cavities

Corinna Kollath

University of Bonn

The realization and control of non-trivial quantum phases by the coupling of quantum light and matter is currently of great interest. We investigate the coupling of atoms confined to optical lattices to a cavity field which leads to an effective long-range interaction between the atoms. We determine the coupled state of the cavity and the atoms beyond the typically employed mean field approach. We show that strong deviations from the predictions of the mean-field theory arise. We discuss both the steady states and also the dynamics of the coupled atom-cavity systems.

What remains unproven by experiments for a theory of high temperature superconductors?

Chandra Varma

Bell Labs (retired), University of California (retired)

I will summarize the current state of the theoretical work started with Thierry and others of what is understood and proved beyond doubt in experiments in problems of the normal and superconducting state of cuprates. This will include the proposal for loop-current order, the derivation of marginal Fermi-liquid spectral function for quantum-critical fluctuations and evidence for them both in the normal state and as the driving mechanism for superconductivity. I will follow this with proposal to understand Fermi-arcs and magneto-oscillations in cuprates through topological decorations of loop-current order which has not yet been proven in experiments.

Hidden degrees of freedom in the motion of interfaces in disordered media

Vivien Lecomte

Laboratoire Interdisciplinaire de Physique, Université Grenoble-Alpes

Interfaces are defined as the geometric boundary separating distinct coexisting phases in extended media. Effective models for the dynamics of such systems, in their simplest versions, focus on the (visible) position of the interface. However, certain (hidden) degrees of freedom internal to the materials can play an unexpected role: this is the case for instance of phases in magnetic material, or inertia in massive interfaces. Such internal degrees of freedom can play the role of a memory, influencing the dynamics of the extended domain walls they present. I will review results on this topic and focus on simple toy models of this phenomenon, illustrating the interplay between memory, dissipation and drive.

Every (ferroelectric) wall is a door - exploring the links between structure, dynamics, and emergent functionalities

Patrycja Paruch

DQMP, University of Geneva

Ferroelectric domain walls between regions with different polarisation orientation are a powerful model system for the rich physics of pinned elastic interfaces, accessible with nanoscale resolution via scanning probe microscopy. Understanding the structure, geometry, and nonlinear dynamics of these domains walls is key for controlling polarisation switching and domain size, shape, and stability in memory, electro-optic, electro-mechanical and catalytic applications. I will discuss the current state of the field, emphasising the interactions between the statistical physics approach and new insights into emergent functional properties at domain walls.

A progenitor fermi surface tracking algorithm

B. Sriram Shastry

University of California Santa Cruz, USA

An algorithm involving the use of photoemission derived spectral functions is described. It is obtained by combining a set of non-perturbative identities for the fermion number in an interacting fermi system, derived under specific conditions. This algorithm enables the tracking of the progenitor fermi surface of free fermions, as they suffer severe renormalization and quantum phase transitions, usually involving a breakdown of perturbation theory.

[1] "Fermi Surface Volume of Interacting Systems", B. Sriram Shastry, arXiv:1808.00405v3, Annals of Physics 405, 155 (2019). https://doi.org/10.1016/j.aop.2019.03.016.

Quantum dissipation in one dimensional systems and Thierry's "Magic Touch"

Miguel A. Cazalilla[1,2]

[1] *Donostia International Physics Center (DIPC)*
[2] *Ikerbasque, Basque Foundation for Science*

I will review several old and new results concerning one-dimensional quantum dissipative systems whose understanding greatly benefited from my interactions and collaboration with Thierry and Thierry's former collaborators over the years. Beginning with a brief review of some early studies on the effect of dissipation in Tomonaga-Luttinger liquids [1,2] and spin systems [3,4], I will conclude by describing some recent results [5] about the non-equilibrium dynamics induced by two-body losses of strongly interacting bosons in one-dimensional optical lattices. Along the way, some open problems will be also discussed.

[1] MAC, F. Sols, and F. Guinea, Phys. Rev. Lett. **97**, 076401 (2006).
[2] E. Malatsetxebarria, Z. Cai, U. Schollwöck, and MAC, Phys. Rev. A **88**, 063630 (2013).
[3] A. M. Lobos, MAC, and P. Chudzinski, Phys.Rev. B **86** 035455 (2012).
[4] A. M. Lobos and MAC, J. Phys: Cond. Mat. **25**, 094008 (2013).
[5] C.-H. Huang, T. Giamarchi, and MAC, Phys. Rev. Res. **5**, 043192 (2023).

New avenues for quantum simulation with atoms, molecules and photons

Immanuel Bloch[1,2]

[1] *Max Planck Institute of Quantum Optics*
[2] *LMU Munich*

40 years ago, Richard Feynman outlined his vision of a quantum computer for quantum simulations of complex calculations of physical problems. Today, his dream of analog and digital quantum simulations has become a reality and a highly active field of research across different platforms ranging from ultracold atoms and ions, to superconducting qubits and photons. In my talk, I will outline how ultracold atoms in optical lattices started this vibrant and interdisciplinary research field 20 years ago and now allow probing quantum phases in- and out-of-equilibrium with fundamentally new tools and single particle resolution and control. Novel (hidden) order parameters, entanglement properties, full counting statistics or topological features can now be measured routinely and provide deep new insight into the world of correlated quantum matter. I will introduce the measurement and control techniques in these systems and delineate recent applications regarding quantum simulations of strongly correlated electronic systems.

Climbing the ladders of physics with Thierry

Michele Filippone

CEA Grenoble

Quantum ladders are coupled one-dimensional systems and they offer a unique playground to advance our understanding of strongly correlated effects in quantum physics. I have started getting interested in ladder systems thanks to my repeated discussions with Thierry, and with many members of his group, during my four-year stay in Geneva. Quantum ladders are a minimal system to study the effects of interactions on the Hall effect in a conductor, namely the emergence of a finite "Hall" voltage drop perpendicular to the current flow and an applied magnetic field. The reason why measurements of the Hall voltage should bring information about the current carrier density remains still largely mysterious for strongly correlated systems, where even the existence of long-lived quasi-particles is not guaranteed. Our investigations [1,2] led to the discovery of universal Hall phenomena triggered by interactions in quantum ladder systems [3,4], which were also probed in a recent cold-atom experiment [5].

If time permits, I will also review our activity on quantum stochastic systems to enlighten the effects of inelastic processes in quantum transport [6–9].

Special recognition goes to Charles-Edouard Bardyn, João Ferreira, Sebastian Greschner and Tony Jin.

[1] M. Filippone, C.-E. Bardyn, and T. Giamarchi, *Controlled parity switch of persistent currents in quantum ladders*, Physical Review B **97**, 201408 (2018).

[2] C.-E. Bardyn, M. Filippone, and T. Giamarchi, *Bulk pumping in two-dimensional topological phases*, Physical Review B **99**, 035150 (2019).

[3] S. Greschner, M. Filippone, and T. Giamarchi, *Universal Hall response in interacting quantum systems*, Physical Review Letters **122**, 083402 (2019).

[4] M. Filippone, C.-E. Bardyn, S. Greschner, and T. Giamarchi, *Vanishing Hall response of charged fermions in a transverse magnetic field*, Physical Review Letters **123**, 086803 (2019).

[5] T.-W. Zhou, G. Cappellini, D. Tusi, L. Franchi, J. Parravicini, C. Repellin, S. Greschner, M. Inguscio, T. Giamarchi, M. Filippone, J. Catani, and L. Fallani, *Observation of universal Hall response in strongly interacting fermions*, Science **38**, 427 (2023).

[6] T. Jin, M. Filippone, and T. Giamarchi, *Generic transport formula for a system driven by Markovian reservoirs*, Physical Review B **102**, 205131 (2020).

[7] T. Jin, J. S. Ferreira, M. Filippone, and T. Giamarchi, *Exact description of quantum stochastic models as quantum resistors*, Physical Review Research **4**, 013109 (2022).

[8] T. Jin, J. Ferreira, M. Bauer, M. Filippone, and T. Giamarchi, *Semiclassical theory of quantum stochastic resistors*, Physical Review Research **5**, 013033 (2023).

[9] J. Ferreira, T. Jin, J. Mannhart, T. Giamarchi, and M. Filippone, *Exact description of transport and non-reciprocity in monitored quantum devices*, arXiv:2306.16452 (2023).

Probing 1D physics by correlations

Jörg Schmiedmayer

Vienna Center for Quantum Science and Technology (VCQ), Atominstitut, TU-Wien

Measurements and analysis of high order correlations [1], and equivalently full distribution functions of quantum observables [2] (full counting statistics) give deep insight into many-body quantum systems and allow us to verify their emerging theoretical descriptions. I will illustrate this in the example of the emergence of the Sine-Gordon quantum field theory from the microscopic description of two tunnel coupled superfluids [1] and in the emergence of Fermionic Pauli blocking in a weakly interacting Bose gas [3]. Special emphasis will be put on how to verify such emergent descriptions and how to characterize them. Thereby I will present three tools: High order correlation functions and their factorization [1], the evaluation of the quantum effective action and the momentum dependence of propagators and vertices (running couplings, renormalization of mass, etc...) of the emerging quantum field theory [4], and learning the emerging Hamiltonian directly from the correlations [5]. Together they establish general methods to analyse quantum systems through experiments and thus represent a crucial ingredient towards the implementation and verification of emergent quantum simulators.

Work performed in collaboration with the groups of P. Zoller (Innsbruck), Th. Gasenzer und J. Berges (Heidelberg) and E. Demler (Harvard/ETHZ). Supported by the DFG-FWF SFB ISOQUANT, and the ERC-AdG: *Emergence in Quantum Physcs* (EmQ).

[1] T. Schweigler *et al.*, Nature **545**, 323 (2017); arXiv:1505.03126 (2015).
[2] S. Hofferberth *et al.*, Nature Physics **4**, 489 (2008).
[3] F. Cataldini *et al.*, Phys. Rev. X **12**, 041032 (2022).
[4] T. Zache *et al.*, Phys. Rev. X **10**, 011020 (2020).
[5] R. Ott *et al.*, in preparation.

Probing exotic superconductors by high sensitivity microcalorimetry

Thierry Klein[1] and Christophe Marcenat[2]

[1] *Univ. Grenoble Alpes, CNRS, Institut Néel*
[2] *Univ. Grenoble Alpes, CEA, PHELIQS*

After a short description of the principle and methods of AC microcalorimetry, I will first focus on the thermodynamic properties of the normal state in high-T_c cuprates, giving evidence for quantum criticality at the onset of the pseudogap phase. Second, I will discuss how specific heat can be used to obtain fruitful information on the H–T phase diagram in "exotic" superconductors, or as a very efficient tool to probe the structure of the superconducting gap in the nematic FeSe superconductor.

Thermal phase and many-body parametric resonances in driven interacting one-dimensional systems

Roberta Citro

Department of Physics and CNR-Spin, University of Salerno, Via Giovanni Paolo II, 132 –84084–Fisciano–Italy

In the context of non-equilibrium physics the stability of periodically-driven many-body systems is the subject of several recent studies. As an example, we consider a periodically-driven sine-Gordon model. By performing a high-frequency expansion, we show the emergence of a sharp "parametric resonance", separating the absorbing from the non-absorbing regimes. This transition survives in the thermodynamic limit and leads to a non-analytic behavior of the physical observables. We then investigate the mode-resolved energy absorption of the slowly driven sine-Gordon model in the presence of a modulated tunnel coupling, obtained by quantizing the Hamiltonian for a chain of driven pendula. For weak driving amplitude, we find an exponentially fast energy absorption in the main resonant mode on short timescale. At later times, the highly excited main resonance provides effective resonant driving terms for its higher harmonics through the nonlinearities in the Hamiltonian. These results could be probed in systems of tunnel coupled parallel one-dimensional quasicondensates.

[1] I. Lovas *et al.*, *Many-body parametric resonances in the driven sine-Gordon model*, Physical Review B **106**, 075426 (2022).

[2] R. Citro *et al.*, *Dynamical stability of a many-body Kapitza pendulum*, Annals of Physics **360**, 694 (2015).

Extended symmetry in a 4-leg spin tube

Edmond Orignac

Univ Lyon, Ens de Lyon, CNRS, Laboratoire de Physique

I show that a four leg antiferromagnetic spin-1/2 tube admits a low-energy description in terms of a $SU(2)_4$ Wess-Zumino-Novikov-Witten model combined with two Ising models and a superconformal minimal model of central charge 1. The interchain interaction contains only $SU(2)_4$ primary operators that are also $SU(3)_1$ primaries, leading to an extended $SU(3)$ symmetry of the low-energy Hamiltonian, broken only by marginal terms. I discuss the consequences for the low-energy spectrum of the extended symmetry, and I identify operators whose correlation functions can reveal the extended symmetry.

A solvable 3D Kondo lattice exhibiting pair density wave, odd-frequency pairing and order fractionalization

Alexei Tsvelik

Brookhaven National Laboratory

The Kondo lattice model plays a key role in our understanding of quantum materials, but a lack of small parameters has posed a long-standing problem. We present a 3 dimensional $S = 1/2$ Kondo lattice model describing a spin liquid within an electron sea. Strong correlations in the spin liquid are treated exactly, enabling a controlled analytical approach. Like a Peierls or BCS phase, a logarithmically divergent susceptibility leads to an instability into a new phase at arbitrarily small Kondo coupling. Our solution captures a plethora of emergent phenomena, including odd-frequency pairing, pair density wave formation and order fractionalization. The ground-state state is a pair density wave with a fractionalized charge e, $S = 1/2$ order parameter, formed between electrons and Majorana fermions.

[1] P. Coleman, A. Panigrahi, and A. M. Tsvelik, *A solvable 3D Kondo lattice exhibiting odd-frequency pairing and order fractionalization*, Phys. Rev. Lett. **129**, 177601 (2022).

The magic of quantum spin systems from 1D to 3D

Christian Rüegg[1,2,3,4]

[1] *Paul Scherrer Institute*
[2] *Department of Quantum Matter Physics, University of Geneva*
[3] *Department of Physics, ETH Zurich*
[4] *Institute of Physics, EPFL*

Spins form well-defined lattices in many insulating quantum materials and serve as model systems in 1D, 2D and 3D to study many-body states such as correlated quantum dimers, Luttinger liquids, or magnon Bose-Einstein condensates. Neutrons and photons are unique tools for high-precision studies of such states under multi-extreme conditions in temperature, pressure and magnetic field. An overview of current frontiers in the field will be presented with special focus on exciting opportunities that close exchange between experiment, materials discovery, and theory offers.

ABSTRACTS

of the

poster presentations

Poster 1

Contrary to popular belief, $EuCd_2As_2$ is a magnetic semiconductor

Ana Akrap

University of Fribourg

$EuCd_2As_2$ has emerged as a topological material where magnetism may produce strong effects. This compound has been understood as a candidate Weyl semimetal, based mostly on transport and photoemission measurements. I will present our recent results on samples in which we control the carrier concentration through chemical synthesis. We find magneto-optical evidence of a sizeable band gap, remarkably sensitive to the local Eu magnetism. Our results contradict the current consensus on the ground state of this compound, bringing into question its topological nature.

[1] D. Santos-Cottin *et al.*, Phys. Rev. Lett. **131**, 186704 (2023).

Poster 2

Exact finite-time correlation functions for multi-terminal setups: Connecting theoretical frameworks for quantum transport and thermodynamics

Gianmichele Blasi,[1] Shishir Khandelwal,[2] and Géraldine Haack[1]

[1] *Department of Applied Physics, University of Geneva, 1211 Geneva, Switzerland*
[2] *Physics Department, Lund University, 22100 Lund, Sweden*

The dynamics of a quantum system in contact with one or more environments can be explored by using different theoretical frameworks, such as master equation, scattering-matrix, Green's functions and Heisenberg equation of motion. The choice of analyzing the quantum dynamics within a given framework takes into account several factors, for instance the presence of interactions within the quantum system, the coupling strength between the system and environment, and the focus on either the steady state or the transient regime. In general, it is challenging to provide a unified perspective on these frameworks. In this work we clarify the role and status of these approaches by considering a minimal single-level quantum dot in a two-terminal setup, subject to voltage and temperature biases. We provide analytical expressions of the particle and energy currents and their associated current fluctuations, both in the steady-state and transient regimes. Exact results are obtained from the Heisenberg equation, which we then show to be consistent with the ones obtained within the scattering-matrix and master equation approaches in their respective regimes of validity.

Poster 3

Dissipative mean-field theory of IBM utility experiment

Emanuele Dalla Torre and Mor Roses

Department of Physics, Bar-Ilan University

In spite of remarkable recent advances, quantum computers have not yet found any useful applications. A promising direction for such utility is offered by the simulation of the dynamics of many-body quantum systems, which cannot be efficiently computed classically. Recently, IBM used a superconducting quantum computer to simulate a kicked quantum Ising model for large numbers of qubits and time steps. By employing powerful error mitigation techniques, they were able to obtain an excellent agreement with the exact solution of the model. This result is very surprising, considering that the total error accumulated by the circuit is prohibitively large. In this letter, we address this paradox by introducing a dissipative mean-field approximation based on Kraus operators. Our effective theory reproduces the many-body unitary dynamics and matches quantitatively local and non-local observables. These findings demonstrate that the observed dynamics is equivalent to a single qubit undergoing rotations and dephasing. Our emergent description can explain the success of the quantum computer in solving this specific problem.

[1] Emanuele G. Dalla Torre and Mor M. Roses, arXiv:2308.01339 (2023).

Poster 4

|Hop> the quantum game

João Ferreira

University of Geneva

We introduce |Hop>, a strategic board game designed to introduce physics concepts found in quantum mechanics and statistical physics. As a teaching tool, it facilitates the grasping of such topics by promoting interaction in a tangible, collaborative setting. The game's mechanics are engaging enough to be enjoyed in informal environments, making it a unique medium for casual learning as well. We present the mechanics of the game and provide practical examples of how to utilize it in a classroom context.

Poster 5

Thermoelectric properties of an Aharonov-Bohm ring in presence of dephasing

Thomas Decultot, Gianmichele Blasi, and Géraldine Haack

Department of Applied Physics, University of Geneva

Few years ago, the AB ring has been shown to exhibit giant thermoelectric response in the linear and non-linear response regimes [1,2]. Remarkably, this device is fully tunable through the magnetic flux enclosed by the ring. A question which remained opened until now concerns the role of electronic quantum phase coherence in this device. In this work [3], we investigate the quantum-to-classical limit of thermoelectric properties of the AB ring, in presence of dephasing. We consider different models for dephasing and relaxation processes, and show that the large thermoelectric response in this nanoscale device originates in the electronic phase coherence of the electrons. This work contributes to the general question of demonstrating a quantum advantage of nanoscale devices operating in the quantum regime over their classical counterparts.

[1] G. Haack and F. Giazotto, Phys. Rev. B **100**, 235442 (2019).
[2] G. Haack and F. Giazotto, AVS Quantum Sci. **3**, 046801 (2021).
[3] G. Blasi, T. Decultot, F. Giazotto, and G. Haack, in preparation.

Poster 6

Bose-Hubbard triangular ladder in an artificial gauge field

Catalin-Mihai Halati and Thierry Giamarchi

DQMP, University of Geneva

We consider interacting bosonic particles on a two-leg triangular ladder in the presence of an artificial gauge field. We employ density matrix renormalization group numerical simulations and analytical bosonization calculations to study the rich phase diagram of this system. We show that the interplay between the frustration induced by the triangular lattice geometry and the interactions gives rise to multiple chiral quantum phases. Phase transition between superfluid to Mott-insulating states occur, which can have Meissner or vortex character. Furthermore, a state that explicitly breaks the symmetry between the two legs of the ladder, the biased chiral superfluid, is found for large values of the flux. In the regime of hardcore bosons, we show that the extension of the bond order insulator beyond the case of the fully frustrated ladder exhibits Meissner-type chiral currents. We discuss the consequences of our findings for experiments in cold atomic systems.

[1] C.-M. Halati and T. Giamarchi, Phys. Rev. Research **5**, 013126 (2023).

Poster 7

Solving models of high-T_c and dynamically induced superconductivity from the microscopic models

Gunnar Bollmark,[1] Thomas Köhler,[2] Lorenzo Pizzino,[3] Svenja Marten,[4] Yiqi Yang,[5] Johannes S. Hofmann,[6] Hao Shi,[7] Shiwei Zhang,[8] Salvatore R. Manmana,[4] Thierry Giamarchi,[3] and Adrian Kantian[1]

[1] *Heriot-Watt University*
[2] *Uppsala Universitet*
[3] *Geneva University*
[4] *Göttingen University*
[5] *College of William and Mary*
[6] *Weizmann Institute of Science*
[7] *University of Delaware*
[8] *Flatiron Institute*

Computing the properties of even basic systems of repulsively mediated high-T_c or dynamically induced superconductivity from the microscopic model is a highly challenging endeavour. We have recently developed a powerful new framework, combining matrix product states and mean field theory (MPS+MF), that can treat such systems, even in 3D, for unprecedented lattice-sizes, temperatures and time scales for the quasi-one-dimensional (Q1D) class of models [1,2]. This framework can also treat one of the most difficult aspects of many high-T_c models, the close competition between superconducting and insulating states, in an unbiased manner [3].

[1] Gunnar Bollmark, Thomas Köhler, Lorenzo Pizzino, Yiqi Yang, Johannes S. Hofmann, Hao Shi, Shiwei Zhang, Thierry Giamarchi, and Adrian Kantian, Phys. Rev. X **13**, 011039, (2023).

[2] Svenja Marten, Gunnar Bollmark, Thomas Köhler, Salvatore R. Manmana, and Adrian Kantian, arXiv:2207.09841 (2022).

[3] Gunnar Bollmark, Thomas Köhler, and Adrian Kantian, arXiv:2301.08116 (2023).

Poster 9

Depinning free of the elastic approximation

Alejandro Kolton,[1] Ezequiel Ferrero,[2] and Alberto Rosso[3]

[1] *Centro Atomico Bariloche, CNEA, CONICET, Bariloche, Argentina. Instituto Balseiro, Universidad Nacional de Cuyo, Bariloche, Argentina*

[2] *Instituto de Nanociencia y Nanotecnologia, CNEA-CONICET. Centro Atomico Bariloche, R8402AGP S. C. de Bariloche, Rio Negro, Argentina. Departament de Fisica de la Materia Condensada, Universitat de Barcelona, Marti i Franques 1, 08028 Barcelona, Spain. 5 Institute of Complex Systems (UBICS), Universitat de Barcelona, Barcelona, Spain*

[3] *Universite Paris-Saclay, LPTMS, CNRS, 91405 Orsay, France*

We model the isotropic depinning transition of a domain-wall using a two dimensional Ginzburg-Landau scalar field instead of a directed elastic string in a random media. An exact algorithm accurately targets both the critical depinning field and the critical configuration for each sample. For random bond disorder of weak strength Δ, the critical field scales as $\Delta^{4/3}$ in agreement with the predictions for the quenched Edwards-Wilkinson elastic model. However, critical configurations display overhangs beyond a characteristic length $l_0 \sim \Delta^{-\alpha}$, with $\alpha \approx 2.2$, indicating a finite-size crossover. At the large scales, overhangs recover the orientational symmetry which is broken by directed elastic interfaces. We obtain quenched Edwards-Wilkinson exponents below l_0 and invasion percolation depinning exponents above l_0. A full picture of domain wall isotropic depinning in two dimensions is hence proposed.

Poster 10

Signatures of a charge-density wave quantum-critical point in superconducting 2H-TaS$_{2-x}$ induced by disorder

Huanlong Liu and Andreas Schilling

University of Zurich

Many superconductors exist in close proximity to various forms of electronic order, particularly in unconventional superconductors and transition-metal dichalcogenides, where charge-density-waves (CDWs) and superconductivity can coexist and compete. Anomalous electrical transport behaviour is often exhibited when such superconductors are tuned to a quantum critical point where superconductivity is optimized. Despite extensive research efforts, the origin of such strange-metal behaviour remains a mystery. Here we report the evolution of long-range CDW and superconductivity in 2H-TaS$_{2-x}$ with various levels of disorder induced by sulfur vacancies. Measurements of complementary magnetization, electronic and thermal transport properties show that the long-range CDW is continuously suppressed, leading to strange-metal behaviour with linear resistivity at the endpoint of the long-range CDW, which is accompanied by the emergence of a short-range CDW phase. The superconductivity shows at first a two-step-like behaviour but reaches a maximum at the endpoint of long-range CDW with a single homogeneous phase, suggesting an interplay between superconductivity and CDW order. Moreover, our results suggest that the strange-metal behaviour, which could arise from the short-range charge density fluctuations, is a signature of quantum criticality with Planckian dissipation.

Poster 11

Effects of (non)-magnetic disorder in quasi-1D singlet superconductors

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DQMP, University of Geneva

We investigate the effects of the combination of interactions and disorder in a quasi 1D system. In this case, the critical temperature of superconductivity is an interesting observable for this purpose. Anderson's theorem indeed states that BCS-type superconductivity is resistant to non-magnetic disorder because time-reversal invariance is still preserved [1–3]. In quasi-1D systems, since there the effect of disorder and interactions is more important than in higher dimensional systems (Anderson localization), the Anderson theorem is not respected [4].

We here study the competition between disorder and interactions in such systems by considering forward scattering disorder, both for magnetic and non-magnetic impurities. Using a field theory representation and renormalization, we show that non magnetic disorder preserves T_c in agreement with Anderson theorem. However, for the magnetic disorder, we find a reduction of the spin-gap and compute the reduction of T_c. We investigate the consequences for systems made of fermionic tubes with attractive interactions.

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Poster 12

Hidden orbital order in copper monolayer at a cuprate/manganite interface uncovered by RIXS studies

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Resonant inelastic x-ray scattering (RIXS) allows one to exploit tiny differences in the electronic states of copper ions at the interface from the bulk in the cuprate/manganites heterostructures. Using this feature, our RIXS measurement uncovers a new magnetic excitation at the interfacial layer of $YBa_2Cu_3O_7$ with energy and intensity behavior distinctly different from the bulk magnons. Using theoretical modeling, we demonstrate that all observed features can be explained by a hidden orbital order specific for the interface layer that couples with the checkerboard-type antiferromagnetic order. The most remarkable manifestation of the hidden orbital order is the scattering intensity increase under lowering momentum transfer instead expected decrease for the usual single orbital antiferromagnetic order.

Poster 13

Dimensional crossover in strongly-interacting weakly-coupled chains

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We study the dimensional crossover that occurs in systems made of weakly-coupled one dimensional chains in presence of interactions U. We separately consider hard-core bosons (repulsive interaction) and spinful fermions (attractive interaction). We show that the excitation gap, due to the transverse coupling, scales as the critical temperature, therefore the ratio is constant and completely controlled by the only Luttinger parameter K [1]:

$$\frac{\Delta(T=0)}{k_b T_c} = f(K) \tag{1}$$

The results are in very good agreement with numerical simulations which combine numerical matrix product state (MPS) methods with mean-field (MF) theory.

Furthermore, we show how the results are also in good agreement with QMC data [2] which well simulate an experimental realisation of ultracold atoms undergoing a dimensional crossover [3].

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Poster 14

Effect of A-site substitution on the magnetic properties of a high entropy oxide

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Here we report the growth, characterization and magnetic properties of $Nd(Fe_{0.2}Mn_{0.2}Co_{0.2}Cr_{0.2}Ni_{0.2})O_3$ (HEO-1). Using synchrotron-based x-ray absorption spectroscopy, employing x-ray magnetic circular dichroism (XMCD), we performed an element-sensitive study of an epitaxial thin film of HEO-1 grown on $LaAlO_3$ (001) substrate to understand the specific contributions of the ions in the total magnetism. We have further analyzed the change in these properties after doping the A-site (Nd) with Ca, which shows a significant difference in the total XMCD as well as the lineshape of the spectra.

Poster 15

Quantum spin liquid in a langbeinite family member $K_2Ni_2(SO_4)_3$

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Quantum spin liquids (QSL) are interesting phases of matter, possessing highly entangled quantum states which are, at the same time, disordered. The states possesses fractional excitations, detectable using inelastic neutron scattering, giving rise to dispersionless excitations, which is a hallmark of QSLs. Ordered magnetic states being ubiquitous, their counterpart disordered QSL states of matter have been elusive and their detection has been a difficult course of matter over of the decades. All the materials which have been proposed to display QSL states have eventually been shown to order at low enough temperature. $K_2Ni_2(SO_4)_3$ is a member of langbeinite family and a candidate material for QSL. The material has a two-trillium lattice structure, which is highly frustrated, which plays a role in stabilizing the QSL state. Previous [1] experiments (specific heat, magnetic susceptibility, muSR, etc.) have shown a quantum spin liquid state exists in the material. In the recent work in our group [2], single crystal inelastic neutron scattering data compared with PFFRG and finite temperature classical Monte Carlo shows a remarkable conformity further establishing the existence of QSL state inside the material.

[1] Ivica Živković *et al.*, *Magnetic Field Induced Quantum Spin Liquid in the Two Coupled Trillium Lattices of $K_2Ni_2(SO_4)_3$*, Physical Review Letters **127** 157204 (2021).
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Poster 16

Flat bands in a kagome ferromagnet

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The kagome (woven bamboo mat) lattice, a triangular network with one quarter of its nodes removed, is a particularly simple venue for seeing classical and quantum effects of frustration. Theoretical approaches have yielded many interesting conjectures (including for example the possibilities of quantum spin liquids and a fractional quantum Hall effect at zero applied field for ferromagnets), but experiments on real materials containing kagome layers have not validated even relatively straightforward predictions, such as flat bands, especially for metals. This follows because of the three-dimensionality and large unit cells of the materials. We describe recent progress exploiting both density functional theory [1] and various spectroscopic tools [2, 3] towards identifying flat bands in a kagome system, Fe_3Sn_2.

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Poster 18

Dynamical conductivity in disordered quantum chains

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We study the spectra of dynamical conductivity for interacting fermionic chains with disorder [1]. The dynamical conductivity is calculated numerically by using the Chebyshev matrix product state (CheMPS) method. As a benchmark, we first investigate the noninteracting case and compare the numerics with a known analytical expression, which shows a good agreement. We then calculate the dynamical conductivity spectra of the interacting system with random chemical potential. The spectra shows a power law decay in the high-frequency regime and the power depends on the strength of interaction, which is consistent with the prediction from the bosonized field theory. We also evaluate the characteristic pinning frequency, which is characterized as a peak in the spectra and confirm that it is related to the inverse of the localization length. It is shown that the localization length behaves in a power law of the disorder strength with an exponent that depends on the interaction. In the low-frequency regime, we find that the dynamical conductivity is described by a function $\omega^2(\ln\omega)^2$ independently of the interaction strength. We also discuss the relevance of our finding to the experiments in cold atomic gases.

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Poster 19

Fermi-liquid to non-Fermi liquid crossovers in the superconducting Yukawa-SYK model on a lattice

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Strange-metal phases, found in, e.g., heavy fermions, pnictides, and cuprates, host partially coherent superconducting states, born out of incoherent, non-Fermi liquid (NFL) normal-state spectra [1–4]. The Sachdev-Ye-Kitaev (SYK) approach [5–7], based on all-to-all interactions among N fermion species ("flavors") in 0-dimensional dots, is a promising route for building toy models of NFL physics. A superconducting instability emerges by coupling fermions to M bosonic flavors (the Yukawa-SYK model), responsible for Cooper pairing and for normal-state incoherence [8,9]. In this work, we generalize the Yukawa-SYK model to a lattice with random hopping parameters. We exactly solve the model in the spin-singlet large-N limit, at $N = M$ and at particle-hole symmetry, we construct the phase diagram, and we characterize the FL to NFL crossovers in the normal and superconducting states [10,11]. Hopping exponentially decreases the critical temperature in FL regime, which is maximal in the single-dot NFL limit at given coupling. However, the phase stiffness and the condensation energy are maximal precisely at the NFL/FL crossover. Such correlation is reminiscent of an analogous experimental evidence found in superconducting cuprates [11]. We then generalize the theory to 2D dispersive fermions and bosons, and apply this model to DC and AC strange-metal magnetotransport [12].

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Poster 20

Phenomenological XXZ model of the competition between superconductivity and charge order

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Filamentary superconductivity is naturally emerging as a new rich field. The highly inhomogeneous nature of the superconducting condensate has been reported in several families of low-dimensional superconductors. The mechanisms behind the fragmentation of the electronic condensate can be diverse, depending on the specific material and conditions, leading to unusual trends in transport measurements [1] and masking the hallmarks of a Berezinskii-Kosterlitz-Thouless (BKT) transition [2].

In the present contribution we focus on cuprates. We argue that there is a special doping point in their phase diagram, hereafter the $p_{O(3)}$ point, where the condensation of holes into a charge-ordered and into a superconducting phase are degenerate in energy but with an energy barrier in between [3]. We present Monte Carlo simulations of a phenomenological two-dimensional XXZ model of the problem without and with quenched disorder.

In the clean case, the presence of a barrier potential, that we introduced to lift the accidental $O(3)$ symmetry of the system, results in a first-order phase transition separating charge order and superconductivity and in the emergence of metastable regions. Such a first-order line is not completely temperature independent. Rather than exactly vertical, it shows a positive slope indicating that entropy slightly favours superconductivity over charge order. We predict that in a very clean system close to the $p_{O(3)}$ point the phenomenon of superconductivity stabilized by temperature could be seen.

In the presence of quenched disorder, filamentary superconductivity spontaneously emerges in the charge order phase as domain walls between different charge-ordered realizations. This phenomenon is reminiscent of the supersolid behaviour in ^{4}He. Contextually, when superconductivity gets suppressed near the charge order phase, BKT signatures get smeared out until they disappear. Finally, assuming weak interlayer couplings, the resulting phase diagram of the three-dimensional system is in good agreement with the typical cuprates phase diagrams.

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Poster 22

Superconductivity of high-entropy-alloy-type compounds

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Since the discovery of superconductivity in a high-entropy alloy Ti-Zr-Hf-Nb-Ta [1], exploration of new HEA superconductors has been a growing topic in the field of superconductivity [2]. The common strategy to design HEA is alloying five or more elements with a range of 5–35% in concentration of each element. Our focus has been material development of new compound superconductors having a HEA-type site; the examples are shown in Fig. 1(b-e), where one of crystallographic sites is high-entropy-alloyed with different five elements [3–5]. Since the introduction of a HEA-type site in compounds result in highly disordered chemical bonds and electronic states. To find out new pathway to designing novel unconventional superconductors or high-performance practical-use materials, clarification of the effects of the HEA-site on superconductivity should be understood. We have investigated the effects of the presence of HEA-type site on superconducting properties for various compounds [3–7]. Through the reserch, we found that the HEA effects on superconducting properties are depending on dimensionality of crystal structure. For some cases, positive effects, such as an increase in critical current density and an improvement of bulk nature of superconductivity. In addition, unexpected modification of supercondcuting states were found in specific heat experiments in $TrZr_2$. In this presentation, we will show an overview on superocnducting properties of HEA-type compound superconductors and recent results on superconducting properties in highly disordered systems.

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Poster 23

Strongly-interacting ultracold bosons at dimensional crossover: single-particle correlation and anomalous cooling

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Dimensionality plays an essential role in determining the nature and properties of quantum gases. Fruitful physics may appear at the crossover between dimensions. In the current generation of cold atom experiments, the dimensionality of the system can be controlled by optical lattices. In this poster, I will firstly present our recent study of strongly-interacting bosons at 2D-1D dimensional crossover [1]. We find, using Cesium atoms in optical lattices, that the single-particle correlation function of the system evolves from a Berezinskii-Kosterlitz-Thouless (BKT) form to a Tomonaga-Luttinger liquid (TLL) type. At the crossover, a two regime structure is captured. These results are consistent with our theoretical prediction [2] obtained via ab-initio quantum Monte Carlo (QMC) calculations. In addition, the comparison of the experimentally measured correlation function with the QMC calculation, allows us to perform thermometry on the low dimensional bosons with 1 nK sensitivity [3]. Strikingly, during the dimensional reduction process, we find that the temperature for the 1D case can be much lower than the initial temperature in 3D. Our findings show that this decrease results from the interplay of dimensional reduction and strong interactions.

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Poster 24

Bath induced localisation in interacting one dimensional systems

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We study an XXZ spin chain, where each spin is coupled to an independent bath of harmonic oscillators at zero temperature. By varying the strength of the coupling to the bath the chain undergoes a quantum phase transition between a Luttinger liquid phase and a spin density wave (SDW). The SDW emerges in the absence of the opening of a gap, due to the spontaneous symmetry breaking of a continuous symmetry. We also show, by computing the DC conductivity, that the dissipative phase is insulating in the presence of a subohmic bath. Our results highlight that in a many-body system slow baths can induce “localisation” à la Caldeira and Leggett due to annealed dynamical disorder, to be compared with the effect of quenched impurities.

Poster 25

Subgap states and quantum phase transitions in one-dimensional superconductor-ferromagnetic insulator heterostructures

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We theoretically study the spectral properties of a one dimensional semiconductor-superconductor-ferromagnetic insulator (SE-SU-FMI) hybrid nanostructure, motivated by recents experiments where such devices have been fabricated using epitaxial growing techniques. We model the hybrid structure as a one-dimensional single-channel semiconductor nanowire under the simultaneous effect of two proximity-induced interactions: superconducting pairing and a (spatially inhomogeneous) Zeeman exchange field. The coexistence of these competing mechanisms generates a rich quantum phase diagram and a complex subgap Andreev bound state (ABS) spectrum. By exploiting the symmetries of the problem, we classify the solutions of the Bogoliubov-de Gennes equations into even and odd ABS with respect to the spatial inversion symmetry $x \to -x$. We find the ABS spectrum of the device as a function of the different parameters of the model: the length L of the coexisting SU-FMI region, the induced Zeeman exchange field h_0, and the induced superconducting coherence length ξ. In particular we analyze the evolution of the subgap spectrum as a function of the length L. Interestingly, we generically find spin-polarized ABS emerging in the subgap region which, depending on the ratio h_0/Δ, can eventually cross below the Fermi energy at certain critical values L_c, and induce spin- and fermion parity-changing quantum phase transitions. We argue that this type of device constitute a promising highly-tunable platform to engineer subgap ABS.

List of

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The Magic of Disorder and Correlations

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