Strange Metals in Quantum Materials and Quantum Emulators

802. WE-Heraeus-Seminar

11 – 15 December 2023

at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 802. WE-Heraeus-Seminar:

Strange metals are one of the most prominent frontiers of condensed matter physics. While conventional metals are well described by Landau's Fermi liquid theory – i.e. a quantum liquid of long-lived, local, electron-like quasiparticles – strange metals defy this paradigm. Here, the local low-energy excitations are extremely short lived and the adiabatic connection to free electrons breaks down. As a consequence, strange metals display a multitude of unusual experimental phenomena, including anomalous charge transport (for example linear in temperature and magnetic field scaling of resistance), singular thermodynamics, and characteristic dynamical scaling.

Experimentally, strange metallic behavior has been reported in a variety of experimental systems including high-temperature superconductors and heavy fermion materials. Recent progress in experimental control and device fabrication not only allowed for much more accurate studies of these classic materials, but, in the process, also revealed strikingly new properties such as the unexpectedly simple and yet puzzle scaling of the magnetoresistance. Present-day technology adds novel quantum emulators such as twisted van-der-Waals heterostructures and cold atomic gases to the list of experimental systems displaying strange metallic behavior.

At the same time, most recent theories explaining strange metallic behavior resort – from a healthy variation of perspectives – to such diverse concepts as exotic (beyond-Landau) critical quantum fluctuations, effective dual gravity models, and quantum hydrodynamics. As such, this WE-Heraeus Seminar aims at bringing together key figures in the research on strange metals. A particularly important mission is the fruitful cross-talks between experimentalists working on a variety of platforms, as well as theorists with different perspectives of the problem.

Scientific Organizers:

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Introduction

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Registration:

Mojca Peklaj (WE Heraeus Foundation)
at the Physikzentrum, Reception Office
Sunday (17:00 h - 21:00 h) and Monday morning

Program

Program *(CET)*

Sunday, 10 December 2023

17:00 – 21:00	ARRIVAL and REGISTRATION	
18:00	*BUFFET SUPPER*	

Monday, 11 December 2023

08:00	*BREAKFAST*	
08:45 – 09:00	Organizers	**Welcome**

Emulators: From Cold Atoms to Moire' Materials

09:00 – 09:45	Eugene Demler	**Quantum Simulations of the Fermi Hubbard Model**
09:45 – 10:30	Dmitri Efetov	**Strange Metal and Heavy Fermion Picture in MATBG**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Elena Bascones	**Heavy Quasiparticles and Cascades without Symmetry Breaking in Twisted Bilayer Graphene**
11:45 – 12:30	Shouvik Sur	**Non-Fermi Liquids in Flat-band Systems**
12:30 – 12:45	**Conference Photo (outside at the main entrance)**	
12:45 – 14:00	*LUNCH BREAK*	

Program *(CET)*

Strange Metals: General Experiment

14:00 – 14:45	Girsh Blumberg	**Spectroscopy of Strange Metals**
14:45 – 15:30	Andrew Huxley	**Charge Density Waves and Strange Metals**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	**Poster Flash Presentations**	
from 16:45	**Poster Session**	
18:30	*DINNER*	

Program *(CET)*

Tuesday, 12 December 2023

08:00	*BREAKFAST*	

Topology, Flat Bands and Correlations

09:00 – 09:45	Silke Bühler-Paschen	**Strange Metal Behavior – From Heavy Fermion Metals to Topological Semimetals**
09:45 – 10:30	Ming Yi	**Emergent Phases in Kagome and Pyrochlore Metals**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Emile Pangburn	**Impurity-Bound States and Green's Function Zeros in Olvable Model of Mott Insulator**
	Steffen Bollmann	**Topological Green's Function Zeros**
11:45 – 12:30	Laura Classen	**Quantum Phase Transitions in Moiré Dirac MaterialsQuantum phase transitions in moiré Dirac materials**
12:30 – 14:00	*LUNCH BREAK*	

Discussion Session

14:00 – 14:45	**Discussion**	
14:45	**Excursion**	
18:30	*DINNER*	

Program *(CET)*

Wednesday, 13 December 2023

08:00	*BREAKFAST*	

Heavy Fermions

09:00 – 09:45	Piers Coleman	**New Insights into the Underlying Phenomenology of Strange Metals from Heavy Fermion Materials**
09:45 – 10:30	Haoyu Hu	**Unconventional Superconductivity from Fermi Surface Fluctuations in Strongly Correlated Metals**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Andreas Gleis	**Strange Metallicity and Planckian Dissipation due to a Heavy Fermion Quantum Critical Point**
	Mounica Mahankali	**Quantum Entanglement Characterization of Kondo-destruction Quantum Critical Points**
11:45 – 12:30	Filip Ronning	**Excess Heat Capacity in Ce-based Heavy Fermion Antiferromagnets**
12:30 – 14:00	*LUNCH BREAK*	

Strange Metals: General Theory

14:00 – 14:45	Jörg Schmalian	**Tunable Non-Fermi Liquid Phase from Coupling to Two-level Systems**
14:45 – 15:30	Olivier Parcollet	**Planckian Metal at a Doping-Induced Quantum Critical Point**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Davide Valentinis	**Superconductivity and Magnetotransport in Yukawa-SYK Lattice Theories for Non-Fermi Liquids**
	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**

Program *(CET)*

16:45	**Discussion**
18:30	*HERAEUS DINNER at the Physikzentrum (complimentary drinks)* In Memorian PW Anderson

Program *(CET)*

Thursday, 14 December 2023

08:00	*BREAKFAST*	

Strange Metals Near Quantum Magnets

09:00 – 09:45	Hidenori Takagi	**Highly Mobile Quantum Critical Bose Gas in 2D Limit in the Honeycomb Antiferromagnet YbCl3**
09:45 – 10:30	Stephen Julian	**Resistivity at a Pressure-induced Spin Density Wave Critical Point in Sr3Ru2O7**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Henri Menke	**Superconductivity and Mottness in Organic Charge Transfer Materials**
	David Abergel	**Inside Nature Physics**
12:30 – 14:00	*LUNCH BREAK*	

Cuprates and Nickelates

14:00 – 14:45	Marco Grilli	**Strange Metal Behavior by Overdamped Short-range Fluctuations in Cuprates and Elsewhere**
14:45 – 15:30	Nigel Hussey	**Exploring the Link Between Strange Metallicity and High-Tc Superconductivity in Electron- and Hole-doped Cuprates**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:23	Steffen Bötzel	**Electronic Correlations and Superconducting Instability in La3Ni2O7 Under High Pressure**
16:23 – 17:10	Stephen Hayden	**Spin Fluctuations in the Normal State of Overdoped Cuprate Superconductors**
17:10	**Discussion**	
18:30	*DINNER*	

Program *(CET)*

Friday, 15 December 2023

08:00	*BREAKFAST*	

Hydrodynamics and Transport

09:00 – 09:45	Blaise Goutéraux	**Beyond Drude in Hydrodynamical Metals**
09:45 – 10:30	Gaël Grissonnanche	**Unraveling Electron Scattering in Strange Metals**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Kitinan Pongsangangan	**Transport Properties of Charged Two-dimensional Dirac Systems in Hydrodynamic Regime: the Role of Dynamical Screening and Plasmons**
	Anurag Banerjee	**Strange Metal from Incoherent Bosons**
11:45 – 12:30	**Concluding Discussion**	
12:00	*LUNCH*	

End of Seminar / Departure

Posters

Poster Session, Monday, 11 December, 16:45 h (CET)

1	H. Serhat Alagöz	**Quantum Critical Behavior and Sign Inversion of Magnetoresistance in CaRuO3 Films**
2	Vivek Kumar Anand	**Zero-Field Ambient-Pressure Quantum Criticality in Stoichiometric CeRhBi**
3	Radu Andrei	**Subgap Optical Driving of Mott Insulators: Mechanisms and Applications**
4	Lukas Debbeler	**Non-Fermi Liquid Behavior at Flat Hot Spots at the Onset of Density Wave Order**
5	Bilal Hawashin	**Deconfined Pseudo-criticality from Non-perturbative Renormalization of a Wess-Zumino-Witten Theory**
6	Zheng Liu	**Probing Complex Stacking in a Layered Material via Electron-nuclear Quadrupolar Coupling**
7	Mario Malcolms de Oliveira	**Non-local Correlations and Criticality in the Triangular Lattice Hubbard Model**
8	Raffaele Mazzilli	**Electrical Transport Probes of Quantum Spin Liquids**
9	Bhola Nath Pal	**Observation of Near Room Temperature Thin Film Superconductivity of Atmospherically Stable Ag-Au Mesoscopic Thin Film**
10	Gopal Prakash	**Self Consistent Theory of U Infinity Hubbard Model in Large d**
11	Hadi Rammal	**Transient Localization from Quantum Bosons**
12	Nepomuk Ritz	**Real-frequency Quantum Field Theory Applied to the Single-impurity Anderson Model**

13	Mireia Tolosa Simeón	**Quantum Critical Dirac Semimetals and Finite-temperature Effects**
14	Max Uetrecht	**Absence of SO(4) Quantum Criticality in Dirac Semimetals at Two-loop Order**

Abstracts of Lectures

(in alphabetical order)

Inside Nature Physics

David Abergel[1]

[1] Nature Physics, Berlin, Germany

What happens to your paper after you submit it to a journal is not always clear from the outside, but it's helpful for authors to understand the editorial process so that they can navigate it smoothly. In this talk, we will unpack this process and explain how editors make their decisions. We will introduce Nature Physics (and other journals in the Nature Portfolio) and describe how we see our role in the scientific community and what we are trying to achieve. Building on that, we will discuss how we select papers for peer review based on the likely breadth of interest in the results that they contain, and how we interpret the information in peer review reports in terms of technical and editorial concerns.

Strange metal from incoherent bosons

A.Banerjee[1], **M. Grandadam**[1], **H. Freire**[2] **and C.Pépin**[1]

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[2] *Instituto de Física, Universidade Federal de Goiás, 74001-970 Goiânia, Goiás, Brazil*

The breakdown of the celebrated Fermi liquid theory in the strange metal phase is the central enigma of correlated quantum matter. Motivated by recent experiments reporting short-lived carriers, along with the ubiquitous observations of modulated excitations in the phase diagram of cuprates, we propose a phenomenological boson-fermion model for this phase. Along with the fermions, we consider fluctuating bosons emerging from the remnants of a pair density wave as additional current carriers in the strange metal phase. These bosonic excitations are finite-momentum Cooper pairs and thus carry twice the electronic charge, and their net spin can either be zero or one arising from the two spin-$1/2$ electrons. We show in a perturbative calculation within Kubo formalism that such a model displays a $T \log T$ dependence of the resistivity with temperature and manifests the Drude form of the ac conductivity. Furthermore, such bosons are incoherent and hence do not contribute to the Hall conductivity. Finally, the bosons emerging from finite-momentum pairs of spin-triplet symmetry also reproduce the recently observed linear-in-field magnetoresistance in the optimally doped and overdoped cuprates [1,2].

References

[1] P. Giraldo-Gallo *et al.*, Science **361**, 479 (2018)

[2] J. Ayres *et al.*, Nature **595**, 661 (2021)

Heavy quasiparticles and cascades without symmetry breaking in twisted bilayer graphene

A. Datta[1,2] M.J. Calderón[1], A. Camjayi[3] and E. Bascones[1]

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[3]Universidad de Buenos Aires, Ciclo Básico Común, and CONICET Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina

Among the variety of correlated states found in twisted bilayer graphene (TBG), the cascades happen in a much larger energy, twist angle and temperature range than other effects, pointing to a hierarchy of phenomena [1]. The cascades manifest in different measurements, including the strong reorganization of the density of states, up to tenths of meV, and the oscillations of the remote bands energies in Scanning Tunneling Microscope experiments, the sawtooth peaks in the inverse compressibility and anomalies in the transport properties. Previous proposals to explain the cascades involve in one way or another a symmetry breaking process. Using a combined Dynamical Mean Field Theory + Hartree approach, we have shown [2] that the cascades are a property of the normal state, associated to the formation of local moments and heavy quasiparticles, and not a symmetry breaking process. The phenomena reproduced by our calculations include the cascade flow of spectral weight, the oscillations of the remote band energies, the asymmetric jumps of the inverse compressibility and signatures in the transport and has consequences in other experiments and in the stability of the symmetry breaking phases. Due to the fragile topology of TBG, we predict a strong momentum differentiation in the incoherent spectral weight. In the talk I will also address other measurements which may help distinguishing the phenomenology of the cascades discussed here from proposals involving symmetry breaking.

References

[1] Wong et al, Nature 582, 198 (2020), Zondiner et al, Nature 582, 203 (2020). Polski et al, arXiv:2205.05225

[2] A. Datta, M.J. Calderón, A. Camjayi, and E. Bascones, Nature Communications 14, 5036 (2023)

Topological Green’s function zeros

S. Bollmann[1], C. Setty[2], U. Seifert[3], E. J. König[1]

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[2]*Rice University, Houston, USA*
[3]*University of California, Santa Barbara, USA*

The interplay of topology and strong correlations manifests itself in a plethora of exotic phenomena. Specifically, topological bands of Green's function zeros have recently attracted substantial interest. Here, we present an analytically tractable model displaying such topological bands of zeros in the fermionic Green's function when the system is tuned to a topologically ordered phase. We further demonstrate the existence of "edge states" of zeros and discuss their experimental implications, in particular when proximitized to edge states of non-interacting topological insulators. If time permits, we will also discuss transport signatures

Electronic correlations and superconducting instability in $La_3Ni_2O_7$ under high pressure

F. Lechermann, J. Gondolf, S. Bötzel and I. Eremin

Ruhr-Universität Bochum, Institut für theoretische Physik III, Bochum, Germany

The bilayer nickelate $La_3Ni_2O_7$ displays superconductivity at high pressures (> 10 GPa) with the onset temperature reaching up to 80 Kelvin. Furthermore, the normal state exhibits a linear temperature dependence near the optimal pressure, indicating a strange metal regime.
Here, we examine the interacting electrons in this system. We first derive and analyze a model bilayer Hamiltonian for the Ni-e_g orbitals, which can be decomposed in bonding and anti-bonding combinations. We then examine spin fluctuations within an RPA treatment. The spin susceptibility splits in even and odd parts, which are related to scattering between (anti-)bonding-(anti-)bonding and bonding-antibonding bands, respectively. Spin fluctuations are considered as a possible mechanism for superconductivity. An essential question is the importance of interlayer interaction and the possibility of interlayer pairing.
In addition, using DMFT we analyze how a multi-orbital non-Fermi liquid state resulting from loss of Ni-ligand coherence within a flat-band dominated low-energy landscape evolves. The incoherent low-temperature Fermi surface displays strong mixing between Ni-d_{z^2} and Ni-$d_{x^2-y^2}$ orbital character. We speculate, that the dramatic enhancement of T_C in pressurized $La_3Ni_2O_7$ is due to stronger Ni-d_{z^2} correlations compared to those in the infinite layer nickelates.

Strange metal behavior – From heavy fermion metals to topological semimetals

Silke Paschen

Institute of Solid State Physics, TU Wien, Vienna, Austria

Strange metal behavior is observed in many classes of strongly correlated electron systems [1], and has recently also been evidenced in new flat band platforms, calling for a unified understanding [2]. I will first discuss the key characteristics of $YbRh_2Si_2$ – a particularly well-studied strange metal heavy fermion compound – including dynamical scaling of the optical conductivity [3], superconductivity at ultralow temperatures [4], and strongly suppressed shot noise [5]. Then I will introduce the strange metallicity of the noncentrosymmetric heavy fermion semimetal $CeRu_4Sn_6$ as evidenced by inelastic neutron scattering [6] and our recent observation that a dome of Weyl-Kondo semimetal appears to nucleate out of it [7]. This suggests that the paradigm of strange metal quantum fluctuations stabilizing novel phases may hold also for strongly correlated topological phases.

References

[1] S. Paschen and Q. Si, Nat. Rev. Phys. 3, 9 (2021).
[2] J. G. Checkelsky, B. A. Bernevig, P. Coleman, Q. Si, and S. Paschen, unpublished (2023).
[3] L. Prochaska et al., Science 367, 285 (2020).
[4] D. H. Nguyen et al., Nat. Commun. 12, 4341 (2021).
[5] L. Chen et al., arXiv:2206.00673, to appear in Science (2023).
[6] W. T. Fuhrman et al., Sci. Adv. 7/21, eabf9134 (2021).
[7] D. Kirschbaum et al., unpublished (2023).

Quantum phase transitions in moiré Dirac materials

Laura Classen
Max Planck Institute for Solid State Research, Stuttgart, Germany
Technical University of Munich, Garching, Germany

Moiré materials provide a new opportunity for the investigation of quantum phase transitions in two-dimensional fermionic systems due to unprecedented experimental control. In particular, the relative interaction can be tuned via a twist angle so that it is possible to overcome the critical interaction strength needed to induce a quantum phase transition for Dirac fermions. We study possible patterns for spontaneous symmetry breaking in a Dirac fermion model motivated by twisted bilayer graphene at charge neutrality. These include the spontaneous generation of a gap, but also of a splitting in energy or wave vector of the Dirac points. We employ a renormalisation group treatment and discuss quantum critical behavior for different numbers of fermion flavours such as spin or valley.

New insights into the underlying phenomenology of strange metals from Heavy Fermion Materials.

P. Coleman[1,3] , Premi Chandra[1] and Yashar Komijani[2]

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[3]Hubbard Theory Consortium, Department of Physics, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK.

The tunability and wide variety of heavy fermion materials provides a playground for the study of strange metal behavior. Despite very different microscopic physics, these materials display similar strange metal behavior to cuprate, iron-based and moire-graphene superconductors. We are also presented with various inconvenient truths, such as the conjunction of T-linear Planckian dissipation with a T^2 Hall scattering rate [1,2], strange metal behavior in the absence of antiferromagnetism[3], even at a ferromagnetic QCP[4]. These commonalities suggest a deep universality, but we may need to identify some misconceptions.

I will review strange metal behavior in heavy fermion compounds, discussing the jump in Fermi surface volume, the magneto-transport and an extensive body of spectroscopic measurements of the spin, current and charge fluctuations. I will also present the recent observation of slow charge fluctuations via synchrotron Mossbauer spectroscopy[4]. I will end by discussing the phenomenological constraints on theories and the possibility that longitudinal and transverse currents in the strange metal are governed by different dynamics.

References

[1] T. R. Chien, Z. Z. Wang, N. P. Ong, *Effect of Zn Impurities on the Normal-State Hall Angle in Single-Crystal*, Phys Rev Lett **67**, 2088 (1991).
[2] Y. Nakajima et al., *Normal-state Hall angle & magnetoresistance in quasi-2D heavy fermion $CeCoIn_5$ near a quantum critical point,* J. Phys. Soc. Japan **73**, 5 (2004).
[3] T. Tomita,K. Kuga, Y. Uwatoko, P. Coleman and S. Nakatsuji, *Strange Metal without magnetic criticality*, Science **349**, 506-509 (2015).
[4] Bin Shen et al., *Strange metal behavior in a pure ferromagnetic Kondo lattice,* Nature **579**, 51-55 (2020).
[5] Hisao Kobayashi et al, *Observation of a Critical Charge Mode in a Strange Metal*,Science **379**, 908- 912 (2023).

Quantum simulations of the Fermi Hubbard model

Eugene Demler

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I will discuss recent progress of the optical lattice emulators of the Fermi Hubbard model. The new feature of these experiments is availability of snapshots of many-body states with single particle resolution. I will review new insights from these experiments on the properties of doped Mott insulators in square and triangular lattices, including demonstration of ferromagnetic and antiferromagnetic polarons, crossover between the polaron fluid and Fermi liquid regimes. I will discuss observation of magnetically mediated pairing in a “mixed dimensional” ladder system.

Strange metallicity and Planckian dissipation due to a heavy Fermion quantum critical point

A. Gleis[1], S-S. B. Lee[1,2,3], G. Kotliar[4,5] and J. von Delft[1]

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We present a cellular dynamical mean-field theory (CDMFT) plus Numerical Renormalization Group approach to study quantum criticality in the periodic Anderson model (PAM). The CDMFT phase diagram of the PAM contains a Kondo breakdown (KB) quantum critical point (QCP). At zero temperature, this KB-QCP marks a continuous transition between two Fermi liquid phases, which differ in their Fermi surface volumes. At non-zero temperatures in the vicinity of the QCP, we find a non-Fermi liquid regime which features strange metal like features such as a linear-in-T resistivity or a logarithmic temperature dependence of the Sommerfeld coefficient. We discuss the properties of this non-Fermi liquid regime and in particular also show that the longest lived coherent excitations have an exactly Planckian lifetime.

Beyond Drude in hydrodynamical metals

Blaise Goutéraux,
Ecole Polytechnique, Institut Polytechnique de Paris

In interacting theories, hydrodynamics describes the universal behavior of states close to local thermal equilibrium at late times and long distances in a gradient expansion. In the hydrodynamic regime of metals, momentum relaxes slowly at a rate which formally appears on the right-hand side of the momentum dynamical equation and causes a Drude-like peak in the frequency dependence of the thermoelectric conductivities. Here we study the structure and determine the physical implications of momentum-relaxing gradient corrections beyond Drude, i.e. arising at subleading order in the gradient expansion. We find that they effectively renormalize the weight of the Drude pole in the thermoelectric conductivities, and contribute to the dc conductivities at the same order as previously-known gradient corrections of translation-invariant hydrodynamics. Turning on a magnetic field, extra derivative corrections appear and renormalize the cyclotron frequency and the Hall conductivity. In strongly-coupled metals where quasiparticles are short-lived and which may be close to a hydrodynamic regime, the extra contributions we discuss are essential to interpret experimentally measured magneto-thermoelectric conductivities. They also cause a different dependence on doping in the effective mass deduced from the specific heat and from the cyclotron frequency, which have indeed reported to take different values in the strange metallic regime of cuprate superconductors.

Strange metal behavior by overdamped short-range fluctuations in cuprates and elsewhere

Marco Grilli,[1,2] **S. Caprara[1,2], C. Di Castro[1], G. Mirarchi[1], G. Seibold[3]**

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[2] ISC-CNR, Unità di Roma Sapienza, Roma, Italy.
[3] Institut für Physik, BTU Cottbus-Senftenberg, Cottbus, Germany.

Anomalous metallic properties are often observed in the proximity of quantum critical points, with violation of the Fermi Liquid paradigm. We propose a scenario where, near a quantum critical point, dynamical fluctuations of the order parameter with *finite rather short correlation length* mediate a nearly isotropic scattering among the quasiparticles over the entire Fermi surface [1,2]. This scattering produces a strange metallic behavior, which is extended to the lowest temperatures by an increase of the damping of the fluctuations. We identify one single parameter ruling this increasing damping when the temperature decreases, accounting for both the linear-in-temperature resistivity and the seemingly divergent specific heat [2,3] observed, e.g., in high-temperature superconducting cuprates and some heavy-fermion metals. The challenging issue is also addressed of the mechanisms inducing this seemingly divergent dissipation and local slowing down and its possible relation to a novel type of quantum criticality [4].

References

[1] Götz Seibold, Riccardo Arpaia, Ying Ying Peng, Roberto Fumagalli, Lucio Braicovich, Carlo Di Castro, Marco Grilli, Giacomo Claudio Ghiringhelli, Sergio Caprara, Commun. Phys. 4, 7 (2021)

[2] Sergio Caprara, Carlo Di Castro, Giovanni Mirarchi, Götz Seibold, Marco Grilli, Commun. Phys. 5, 1-7 (2022).

[3] M Grilli, C Di Castro, G Mirarchi, G Seibold, S Caprara, Symmetry 15, 569 (2023).

[4] Riccardo Arpaia, Leonardo Martinelli, M Moretti Sala, Sergio Caprara, Abhishek Nag, Nicholas B Brookes, Pietro Camisa, Qizhi Li, Qiang Gao, Xingjiang Zhou, Mirian Garcia-Fernandez, K-J Zhou, Enrico Schierle, Thilo Bauch, Ying Ying Peng, C Di Castro, M Grilli, Floriana Lombardi, Lucio Braicovich, Giacomo Ghiringhelli, arXiv:2208.13918

Unraveling electron scattering in strange metals

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Strange metals are characterized by a perfectly *T*-linear resistivity observed in various strongly correlated metals close to a quantum critical point [1] and appear tightly connected to the emergence of unconventional superconductivity [2]. The resistivity is dictated by the scattering rate between the electrons, a hard quantity to compute or measure but which holds the mystery to strange metals.

To directly access the temperature dependence of the scattering rate $1/\tau(T)$ of charge carriers in strange metals, we measured the angle-dependent magnetoresistance (ADMR) of Nd-LSCO at p = 0.24: a cuprate that demonstrates *T*-linear resistivity over a wide temperature range. We extract a *T*-linear scattering rate that has the Planckian value [3, 4], $\hbar/\tau = \alpha\ k_B T$, with namely $\alpha = 1.2 \pm 0.4$. Remarkably, this inelastic scattering rate is isotropic.

To directly access the energy dependence of the scattering rate $1/\tau(\varepsilon)$ of charge carriers, we measured the Seebeck coefficient S of Nd-LSCO p = 0.24. We extract an energy-linear scattering rate that reflects the behavior expected from a marginal Fermi liquid and also explains why the sign of the Seebeck effect in cuprates has always been at odds with the theory.

Not only do our findings [6, 7] extend the validity of the semi-classical approach to describe transport measurements, even in the strange-metallic state quantitatively, but they also suggest that *T*-linear resistivity in strange metals is the direct consequence of a *T*-linear scattering rate, that reaches the Planckian bound for all directions of electron motion.

[1] J. Zaanen, *SciPost Phys.* **6**, 061 (2019).
[2] J. Yuan et al., *Nature* **602**, 7897 (2022).
[3] J. A. N. Bruin et al., *Science* **339**, 804 (2013)
[4] A. Legros et al., *Nat. Phys.* **15**, 142 (2019)
[5] G. Grissonnanche et al., *Nature* **595**, 667 (2021)
[6] A. Gourgout et al., *Physical Review X* **12**, 011037 (2022).

Spin fluctuations in the normal state of overdoped cuprate superconductors

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Theories of the origin of superconductivity in cuprates are dependent on an understanding of their normal state which exhibits various competing orders. Transport and thermodynamic measurements on $La_{2-x}Sr_xCuO_4$ show signatures of a quantum critical point, including a peak in the electronic specific heat *C* versus doping p, near the doping *p** where the pseudogap collapses. Here we use inelastic neutron scattering to show [1] that close to T_c and for p=0.22, near p^*, there are very-low-energy collective spin excitations with characteristic energies of about 5 meV. Cooling and applying 8.8 T magnetic field creates a mixed state with a stronger magnetic response below 10 meV. We conclude that the low-energy spin-fluctuations are due to the collapse of the pseudogap combined with an underlying tendency to magnetic order. The latter persists to overdoped compositions. We show that the relatively large specific of overdoped cuprates can be understood in terms of collective spin fluctuations using paramagnon theory.

The spin fluctuations we measure exist across the overdoped part of the cuprate phase diagram. When measured at T=T_c=22 K and p=0.22 they have characteristic energies comparable (with in a factor of 2) with the temperature. Their energy scale also increases rapidly with temperature. Thus, they appear to be intimately connected with the linear or Planckian resistivity observed in cuprates with similar doping.

References

[1] M. Zhu, D. J. Voneshen, S. Raymond, O. J. Lipscombe, C. C. Tam, and S. M. Hayden, Nat. Phys. 19, 99 (2023).

Unconventional Superconductivity from Fermi Surface Fluctuations in Strongly Correlated Metals

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The mechanism for unconventional superconductivity near quantum critical points remains a puzzle in the field of strongly correlated systems. Some of the important issues include how the quantum critical state loses quasiparticles, how it drives superconductivity, and to what extent the strange-metal physics in different classes of correlated systems are connected with each other [1,2,3]. The notion of Kondo destruction quantum critical point has been developed for heavy-Fermi metals [1,2]. At such a quantum critical point, a large-to-small Fermi surface transition takes place, which leads to strong fluctuations in both charge and spin channels. Here [4], using the cluster extended dynamical mean-field theory [5], we demonstrate how these quantum fluctuations near the quantum critical point drive unconventional superconductivity. We find the superconducting transition temperature to be exceptionally high relative to the effective Fermi temperature, reaching several percent of the Kondo temperature scale. We thus provide a natural understanding of the enigmatic superconductivity in the strongly-correlated metals. I will close the talk with a discussion about the connections with the physics in other classes of correlated systems, including the strange metal physics of the cuprates as well as indications of quantum criticality and superconductivity in flat-band systems.

References

1. H. Hu, L. Chen, Q. Si, arXiv:2210.14183; Q. Si et al, Nature 413, 804 (2001); A. Cai, et al, PRL, 124, 027205 (2020).
2. S. Paschen and Q. Si, Nat. Rev. Phys. 3, 9 (2021); S. Kirchner et al, Rev. Mod. Phys. 92, 011002 (2020).
3. L. Chen et al, arXiv:2206.00673 (Science, in press); Y. Wang et al, arXiv:2211.11735; L. Prochaska et al., Science 367, 285 (2020).
4. H. Hu, et al., arXiv:2109.13224 (2021).
5. J. Pixley et al, PRB 91, 125127 (2015).

Exploring the link between strange metallicity and high-T_c superconductivity

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In conventional superconductors, one of the key parameters affecting the robustness of the superconductivity is the electron–phonon coupling strength λ. This in turn is closely related to λ_{tr}, the parameter that defines the transport scattering rate associated with the *T*-linear resistivity found at intermediate temperatures (typically 50–500 K). This link between the coefficient of the *T*-linear resistivity and T_c is enshrined in the old adage; "good metals make bad superconductors". In certain unconventional superconductors, including the high-T_c cuprates, a similar correlation exists, albeit with a *T*-linear resistivity that extends down to anomalously low temperatures indicative of a non-Fermi-liquid ground state. Despite this 'complication', the search for an associated λ has been prolonged and intense. In this presentation, I will highlight a number of other simple yet profound correlations between the normal state (magneto)transport properties of high-T_c cuprates and their corresponding superfluid densities that suggest an altogether different origin for the *T*-linear resistivity (i.e. one that is not related to quasiparticle scattering off a bosonic bath). These correlations compel us to consider an entirely new paradigm for high-temperature superconductivity, one that derives directly from the strange metallic state above T_c.

Charge Density Waves and Strange Metals

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Charge fluctuations observed in high-temperature superconductors provide a possible source of scattering to give strange metal behaviour [1]. The charge fluctuations are linked to nearby charge ordering, while the undoped parent compounds are antiferromagnetic.

In this presentation I will look at charge ordered states in three uranium intermetallic compounds. They all display different properties beyond those expected for simple CDWs.

In the first example, a Peierls-like unit cell doubling is predicted by density functional theory. This indeed occurs at low temperature but is unexpectedly preceded by an incommensurate state, present at higher temperature. One possible explanation is order by disorder, more commonly associated with magnetic transitions.

In the second example, the low temperature state is an incommensurate CDW below 8 K. The material, however, shows unusual behaviour above this transition that is not understood, extending to over 100 K. Neither of these materials show obvious non-fermi-liquid signatures in transport or heat capacity in the limit of low temperature.

The final material to be discussed, UAu_2, shows the growth of CDW order with decreasing temperature within an anti-ferromagnetic state. In this case non-fermi liquid behaviour is seen, including a heat capacity C/T ~ *log(T)* [2,3]. The behaviour in this case does not appear to be associated with a proximity to a quantum critical point.

References

[1] S. Caprera et al, “Strange metal behaviour from charge density fluctuations in cuprates”, Comms Phys **4**:7 (2021)

[2] C. D. O’Neill et al., Non-fermi liquid behaviour below the néel temperature in the frustrated heavy fermion magnet UAu_2. *Proc. Nat. Acc. Sci. U.S.A.* **118**, e2102687118 (2021)

[3] C. D. O’Neill et al., “Multicomponent odd-parity superconductivity in UAu_2 at high pressure”, O Neill et al, *Proc. Nat. Acc. Sci. U.S.A.* **119** e2210235119 (2022)

Resistivity at a pressure-induced spin density wave quantum critical point in $Sr_3Ru_2O_7$

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Measuring the resistivity of high purity single crystals of $Sr_3Ru_2O_7$ under pressure, we find strong evidence that a well-known field-induced spin density wave phase that forms at a metamagnetic transition for $H \parallel c$ is suppressed at a surprisingly low pressure of ~ 3 ± 1 kbar. This offers the possibility of studying a bare quasi-two-dimensional spin-density-wave quantum critical point, testing the $T \rightarrow 0$ K limit of theories of Planckian dissipation and quantum criticality [1]. We indeed find that T-linear resistivity is strongest at the critical field H_c at pressures sufficient to suppress the spin density wave phase. The T-linear resistivity does not, however, extend all the way to base temperature, which could be due to a number of factors: imperfect tuning to the critical pressure, cold regions of the Fermi surface, or a cross-over from quasi-two to three dimensional fluctuations as T goes to 0 K. Building on the succesful fit of specific heat by quantitative spin fluctuation calculations by Lester et al. [2], we make a preliminary attempt to fit ρ(T) with a quantum critical spin fluctuation model. The results, while encouraging, reveal a need for further, complementary measurements.

References

[1] P. Tiwari, L. He, D. Sun, M. Fu, R.S. Perry, A.P. Mackenzie and S.R. Julian, Phys. Rev. B 108 (2023) 115154.

[2] C. Lester, S. Ramos, R.S. Perry, T.P. Croft, M. Laver, R.I. Beasley, T. Guidi, A. Hiess, A. Wildes, E.M. Forgan and S. Hayde, Nature Communications 12 (2021) 1.

Quantum Entanglement Characterization of Kondo-destruction Quantum Critical Points

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Heavy fermion metals are made of a lattice of local moments undergoing Kondo effect. The coherence of Kondo screened local moments expands the Fermi surface and enhances the effective quasiparticle mass. The presence of a lattice, however, also facilitates a competing RKKY interaction promoting magnetic order. A Kondo-destruction Quantum Critical Point (QCP) separates the two phases. The suppression of the Kondo effect is signified by a jump from “large” to “small” Fermi surface across the QCP [1,2]. While the static amplitude for the Kondo singlet vanishes on this side of the QCP, there are non-zero Kondo correlations usually called dynamical Kondo effect[3,4]. Entanglement is one way to probe the local moment dynamics in these strongly-correlated systems[5,6]. We consider Kondo destruction QCP of both the Bose-Fermi Kondo model and the Kondo lattice, and use quantum entanglement means to characterize the competition of the RKKY, Kondo interactions across the QCP and the dynamical Kondo effect.

[1] H. Hu, L. Chen, Q. Si, Quantum critical metals: dynamical Planckian scaling and loss of quasiparticles, arXiv:2210.14183. Q. Si, S. Rabello, K. Ingersent, & J. L. Smith, Locally critical quantum phase transitions in strongly correlated metals, *Nature* **413**, 804–808 (2001).
[2] S. Paschen and Q. Si, Quantum phases driven by strong correlations, Nat. Phys. Rev. 3, 9 (2021). S. Kirchner et al., Heavy-electron quantum criticality and single-particle spectroscopy, Rev. Mod. Phys. 92, 011002 (2020).
[3] A. Cai, Z. Yu, H. Hu, S. Kirchner, & Q. Si, Dynamical Scaling of Charge and Spin Responses at a Kondo Destruction Quantum Critical Point. *Phys. Rev. Lett.* **124**, 027205 (2020).
[4] L. Prochaska *et al.* Singular charge fluctuations at a magnetic quantum critical point. *Science* **367**, 285–288 (2020).
[5] H. Hu, A. Cai, & Q. Si, Quantum Criticality and Dynamical Kondo Effect in an SU(2) Anderson Lattice Model. *arXiv:2004.04679* (2020).
[6] M. Mahankali et al., in preparation.

Superconductivity and Mottness in Organic Charge Transfer Materials

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The phase diagrams of organic superconductors assemble a plethora of fundamental phenomena of strongly correlated systems in two dimensions. The interplay of Mott metal-insulator transitions and magnetic fluctuations with the possibility of unconventional superconductivity and a putative spin-liquid regime make them universal materials for the investigation of the quantum many-body problem. In this manuscript we analyze a minimal model for these compounds, the Hubbard model on an anisotropic triangular lattice, by means of cutting-edge quantum embedding methods, respecting the lattice symmetry. We determine the crossover from a Fermi liquid to a Mott insulator by momentum-selective destruction of the Fermi surface reminiscent of a pseudogap. In the immediate vicinity of the metal-insulator crossover we demonstrate the existence of unconventional superconductivity by directly entering the symmetry-broken phase. Our results are in remarkable agreement with experimental phase diagrams of kappa-organics for which we motivate future spectroscopic studies of hot and cold spots.

Impurity-Bound States and Green's Function Zeros in olvable model of Mott insulator

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The response of insulators to point-like classical impurities has been studied in two-dimensional materials with topologically trivial and non-trivial band structures[1]. We extend these investigations to interacting systems by studying analytical solutions involving models with local momentum space interactions. For example, a recent study [2] revealed that the inclusion of interactions in the topologically non trivial Haldane models leads to the emergence of a quarter-filled state characterized by a non zero Chern number, provided the interactions reach a critical threshold.

In the absence of interactions, the behavior of insulators in response to point-like impurities can be comprehended through symmetries, which can dictate the positions of local Green function zeros. These zeros play a pivotal role in elucidating the emergence of impurity-induced in-gap states. Expanding this approach to interacting insulators, we use the recent concept of Green's function eigenvectors which form a representation of the space group[3, 4]. This framework highlights that Mott poles and zeros, like in the non-interacting scenario, are subject to symmetry constraints, shaping the system's response to point-like impurities.

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[1] S. Michel, A. Fünfhaus, R. Quade, R. Valentí, and M. Potthoff, Bound states and local topological phase diagram of classical impurity spins coupled to a chern insulator, arXiv preprint arXiv:2310.14097 (2023).

[2] P. Mai, B. E. Feldman, and P. W. Phillips, Topological mott insulator at quarter filling in the interacting haldane model, Physical Review Research 5, 013162 (2023).

[3] D. Lessnich, S. M. Winter, M. Iraola, M. G. Vergniory, and R. Valentí, Elementary band representations for the single-particle green's function of interacting topological insulators, Physical Review B 104, 085116 (2021).

[4] C. Setty, S. Sur, L. Chen, F. Xie, H. Hu, S. Paschen, J. Cano, and Q. Si, Symmetry constraints and spectral crossing in a mott insulator with green's function zeros, arXiv preprint arXiv:2301.13870 (2023).

Planckian Metal at a Doping-Induced Quantum Critical Point

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I will present a numerical solution of a model of interacting spin-1/2 electrons with random exchange coupling on a fully connected lattice. This SU(2) model reveals a richer physics than the large-N Sachdev-Ye-Kitaev (SYK), as it hosts a quantum critical point separating two distinct metallic phases as a function of doping: a Fermi-liquid phase with a large Fermi-surface volume and a low-doping phase with local moments ordering into a spin glass. This quantum critical point has non-Fermi-liquid properties characterized by T-linear Planckian behaviour, ω/T scaling, and slow spin dynamics of the Sachdev-Ye-Kitaev type. The ω/T scaling function associated with the electronic self-energy is found to have an intrinsic particle-hole asymmetry, a hallmark of a “skewed” non-Fermi liquid. I will also discuss the quantum spin-glass phase itself, and some aspects of the algorithms used for these studies.

References

[1] Ph. Dumitrescu et al. Phys. Rev B 105 L180404 (2022)
[2] N. Kavokine et al. (in preparation)

Transport properties of charged two-dimensional Dirac systems in hydrodynamic regime: the role of dynamical screening and plasmons

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Clean two-dimensional Dirac systems, for example, graphene, have received a lot of attention for being a prime candidate to observe hydrodynamical transport behaviour of interacting electrons. In this project, we discuss the role of dynamical screening which gives rise to a collective mode, called plasmon, in the thermo-electric transport properties of those systems. We find that the plasmon is an additional low-energy degree of freedom which makes a sizeable contribution to the thermal conductivity and viscosity of graphene. In addition, we find that the form of the hydrodynamic equations as well as the definition of conserved quantities are not only constrained by symmetries of the kinetic energy but also by the interactions of the underlying system. We propose a novel type of hydrodynamics consisting of electrons, holes, and plasmons. Our result suggests that this is a generic feature of ultraclean two-dimensional electronic systems, also applicable to 2DEL, Bernal-stacked and twisted bilayer graphene.

References

[1] K. Pongsangangan, T. Ludwig, H.T.C. Stoof, and L. Fritz, Phys. Rev. B. 106, 205126 (2022)
[2] K. Pongsangangan, T. Ludwig, H.T.C. Stoof, and L. Fritz, Phys. Rev. B. 106, 205127 (2022)
[3] K. Pongsangangan, S. Grubinskas, and L. Fritz, Phys. Rev. Research 4, 043107 (2022)

Excess heat capacity in heavy fermion antiferromagnetic materials

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Filip Ronning

f-electron based materials display a wide variety of exotic phenomena demonstrating many-body quantum entanglement including heavy fermion formation, quantum critical points, topological Hall effects, quantum spin liquids, volume collapse transitions, topological (Kondo) insulators, and unconventional superconductivity, to name a few. The challenge in understanding these prototypical materials is that they possess strong electronic correlations, large bandwidths, and strong spin-orbit coupling, which lead to emergent physics with small energy scales. In this talk I will demonstrate how a first-principles informed multi-orbital (~25 band) periodic Anderson Model can accurately determine the magnetic exchange interactions with three orders of magnitude smaller energy scales. We validate the computed exchange interactions against state-of-the-art inelastic neutron scattering measurements [1]. In doing so, we develop a procedure for deriving a tractable (3 band) Kondo-Heisenberg model, appropriate for the physics of heavy fermion materials, while still capturing materials specific properties. We perform this study on the prototypical Kondo lattice system $CeIn_3$, which under pressure possesses a localized to itinerant Fermi surface transition, as well as unconventional superconductivity on the border of antiferromagnetism. This work reveals an excess low temperature heat capacity that cannot be explained by phonons, electrons, or magnons. We discuss insights discovered along the way concerning typical assumptions made about heavy fermion materials, and the future directions we believe this work enables.

[1] W. Simeth, *et al.* arXiv:2208.02211

Tunable non-Fermi liquid phase from coupling to two-level systems

Jörg Schmalian

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We study a controlled large-N theory of electrons coupled to dynamical two-level systems (TLSs) via spatially-random interactions. Such a physical situation arises when electrons scatter off low-energy excitations in a metallic glass, such as a charge or stripe glass. Our theory is governed by a non-Gaussian saddle point, which maps to the celebrated spin-boson model. By tuning the coupling strength we find that the model crosses over from a Fermi liquid at weak coupling to an extended region of non-Fermi liquid behavior at strong coupling, and realizes a marginal Fermi liquid at the crossover. Beyond a critical coupling strength, the TLSs freeze and Fermi-liquid behavior is restored. Our results are valid for generic space dimensions d>1.
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References

[1] Noga Bashan, Evyatar Tulipman, Jörg Schmalian, Erez Berg arXiv: 2310.07768

Non-Fermi liquids in flat-band systems

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Flat or weakly-dispersive bands arise in a wide variety of material platforms, ranging from twisted heterostructures to line-graph lattices. The low bandwidth encourages correlation effects to play a central role in organizing the phase diagram, thereby realizing new contexts for exploring strongly correlated phenomena. An unconventional aspect of these system is the presence of single and multi-particle topological obstructions, which adds a fascinating new dimension to the study of strongly correlated matter. Here, we investigate the impact of both forms of topological obstructions in compressible matter without electronic quasiparticles. In the first part of the talk, encouraged by recent works on kagome metals [1], I will discuss our works on strongly correlated d-electron-based metals on lattices that realize destructive kinematic interference [2]. In these systems, a topologically non-trivial flat band is present within the active-band subspace, which gives rise to strong correlations at appropriate fillings. Guided by compact localized states, we Wannierize it in terms of molecular orbitals, and obtain an effective Anderson-lattice model to describe the active band subspace. Due to the vastly dissimilar bandwidth between the flat and dispersive bands, orbital-selective Mott correlations develop over a broad range of parameters, driving a quantum phase transition between two strongly correlated metallic states with Fermi surfaces of dissimilar sizes. Non-Fermi liquid behaviors emerge in the associated quantum critical regime. We attribute the lack of localization in the flat band to its single-particle topological obstruction. In the second part, I will present topological non-Fermi liquid states that may be engineered in bilayer twisted transition-metal dichalcogenides [3]. We employ the eigenvectors of the Green's function to diagnose the topological obstructions [4], and explore its consequences on the phase diagram and physical properties.

References

1. L. Ye et al., arXiv:2106.10824; S. A. Ekahana, 2206.13750; L. Liu et al., arXiv:2309.13514.
2. L. Chen et al., arXiv:2307.09431; L. Chen et al., arXiv:2212.08017; H. Hu et al., Sci. Adv. 9, eadg0028 (2023);
3. S. Sur et al., [to appear]
4. H. Hu et al, arXiv:2110.06182; C. Setty et al., arxiv: 2301.13870; C. Setty et al., [to appear]

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Highly mobile quantum critical Bose gas in 2D limit in the honeycomb antiferromagnet $YbCl_3$

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Bose-Einstein condensation (BEC) is a quantum phenomenon, where a macroscopic number of bosons occupy the lowest energy state and acquire coherence at low temperatures. It is realized not only in superfluid ^{4}He and dilute atomic gases, but also in quantum magnets. In three-dimensional (3D) antiferromagnets, an XY-type long-range ordering (LRO) occurs near a magnetic-field-induced transition to a fully polarized state (FP) and has been successfully described as a BEC in the last few decades. An attractive extension of the BEC in 3D magnets is to make their two-dimensional (2D) analogue. For a strictly 2D system, it is known that BEC cannot take place due to the presence of a finite density of states at zero energy, and a Berezinskii-Kosterlitz-Thouless (BKT) transition may instead emerge. In a realistic quasi-2D magnet consisting of stacked 2D magnets, a small but finite interlayer coupling stabilizes marginal LRO and BEC, but such that 2D physics is still expected to dominate. A few systems were reported to show such 2D-limit BEC, but at very high magnetic fields that are difficult to access. The honeycomb S = 1/2 Heisenberg antiferromagnet $YbCl_3$ with an intra-layer coupling J ~ 5 K exhibits a transition to a FP state at a low in-plane magnetic field of H_s = 5.93 T. We demonstrate that the LRO right below H_s is a BEC but close to the 2D-limit, marginally stabilized by an extremely small interlayer coupling $J_\perp$. At the quantum critical point H_s, we clearly capture 2D-limit quantum fluctuations as the formation of a highly mobile, interacting 2D Bose gas in the dilute limit. A much-reduced effective boson-boson interaction U_{eff} as compared with that of prototypical 3D system clearly indicates the presence of a logarithmic renormalization of interaction unique to 2D. The old candidate for a Kitaev quantum spin liquid, $YbCl_3$, is now established as an ideal arena for a quantum critical BEC in the 2D limit.

Superconductivity and magnetotransport in Yukawa-SYK lattice theories for non-Fermi liquids

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Strange-metal phases, found in, e.g., heavy fermions, pnictides, and cuprates, host partially coherent superconducting phases born out of incoherent, non-Fermi liquid (NFL) normal states. The Sachdev-Ye-Kitaev (SYK) approach [1], based on all-to-all interactions among N fermion species ("flavors"), is a promising route for studying strange-metal physics and NFL superconductivity. In this work we construct a lattice of 0-dimensional Yukawa-SYK dots [2], where fermions couple to M bosonic flavors, at once responsible for Cooper pairing and normal-state incoherence, and experience random intersite hopping. 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 Fermi-liquid (FL) to NFL crossovers in the normal and superconducting states [3]. While the critical temperature is maximal in the single-dot NFL limit at given coupling, the phase stiffness, the coherent quasiparticle weight, and the condensation energy all peak precisely at the NFL/FL crossover, in analogy with similar experimental correlations found in superconducting cuprates [4].
Generalizing our model to 2D dispersive fermions and bosons coupled through spatially disordered or translationally invariant random interactions, we study DC and AC strange-metal magnetotransport [5]. We find characteristic signatures of NFL physics in the spectral functions and the magnetoconductivity, including a significant renormalization of the cyclotron mass, as experimentally reported in cuprates [7].

References

[1] D. Chowdhury et al., Rev. Mod. Phys. **94**, 035004 (2022)
[2] I. Esterlis and J. Schmalian, Phys. Rev. B **100**, 115132 (2019)
[3] D. Valentinis, G. A. Inkof, and J. Schmalian, Phys. Rev. Research **5**, 043007 (2023); Phys. Rev. B **108**, L140501 (2023)
[4] D. Feng et al., Science **289**, 277 (2000)
[5] H. Guo, D. Valentinis, J. Schmalian, S. Sachdev, and A. A. Patel, arXiv:2308.01956 (2023)
[6] A. Legros et al., Phys. Rev. B **106**, 195110 (2022)

Emergent phases in kagome and pyrochlore metals

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Electronic correlation effects are manifested in quantum materials when either the onsite Coulomb repulsion is large or the electron kinetic energy is small. The former is the dominant effect in the cuprate superconductors or heavy fermion systems while the latter in twisted bilayer graphene or geometrically frustrated metals. In this talk I would like to present our group's recent work in exploring geometrically frustrated lattice materials where the geometry of particular lattice motifs give rise to quantum destructive interference effects that produce topological flat bands. In particular, I will discuss three examples of such bulk materials. I will first present our work on the kagome magnet FeSn grown by molecular beam epitaxy, where we study the effect of the A-type antiferromagnetism on the electron structure. I will then present our work on the isostructural FeGe, where a charge density wave order has recently been discovered to form deep within an A-type antiferromagnetic order [1-2]. Lastly, I will discuss an example of a pyrochlore lattice—a 3D analog of the 2D kagome lattice, where we observe a 3D flat band pinned at the Fermi level due to the combined effect of quantum destructive interference and moderate electron-electron correlations that work together to give rise to non-Fermi liquid transport behaviors.

References

[1] X. Teng *et al*., Nature **609**, 490 (2022)
[2] X. Teng and J. S. Oh *et al.*, Nat. Phys. **19**, 814 (2023)

Abstracts of Posters

(in alphabetical order)

Quantum Critical Behavior and Sign Inversion of Magnetoresistance in $CaRuO_3$ Films

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$CaRuO_3$ is a perovskite oxide among the Ruddlesden–Popper series with multi-exotic physical properties on the verge of quantum criticality.[1] Unlike the case of the well-known ferromagnetic $SrRuO_3$, the literature on the physical properties of the $CaRuO_3$ system is scarce with no consensus regarding its magnetic and transport ground states.[2] This work provides a detailed study of the magnetotransport properties of 300 nm bulklike $CaRuO_3$ epitaxial films grown on $SrTiO_3$ and $LaAlO_3$ substrates. The magnetic and electronic ground states in tensile strained $CaRuO_3/SrTiO_3$ films and compressively strained $CaRuO_3/LaAlO_3$ films are found to be distinctly different. In a zero magnetic field, the high-temperature resistivity of both films shows a dependence, indicating non-Fermi liquid behavior. Cooling below 30 K, $CaRuO_3/SrTiO_3$ undergoes a metal-insulator transition ascribed to 3D weak localization, with signals of weak ferromagnetic-like domains. By contrast, below 30 K, the transport data of the nonmagnetic $CaRuO_3/LaAlO_3$ film show non-Fermi liquid $T^{3/2}$ type behavior. Magnetoresistance measurements in $CaRuO_3/SrTiO_3$ show a combination of weak antilocalization and weak localization behavior deep in the insulating side, emphasizing the existence of spin-orbit coupling and the strong influence of ferromagnetic impurities. Hall measurements in $CaRuO_3/SrTiO_3$ show nonlinear signals which can be described as an anomalous Hall Effect. Interestingly, below 30 K, magnetoresistance and Hall voltage in $CaRuO_3/LaAlO_3$ change sign, indicating an inversion from hole-like to electron-like behavior. We discuss the possible quantum critical feature observed at 30 K for these films.

References

[1] S. Tripathi, R. Rana, S. Kumar, P. Pandey, R. S. Singh, and D. S. Rana, Scientific Reports **4**, 3877 (2014)

[2] Y. Liu, H. P. Nair, J. P. Ruf, D. G. Schlom, and K. M. Shen, Phys. Rev. B **98**, 041110(R) (2018)

Zero-Field Ambient-Pressure Quantum Criticality in Stoichiometric CeRhBi

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The strange electronic state that appears in the proximity of a quantum critical point (QCP) where the predictions of conventional Fermi-liquid theory of metals are violated remains enigmatic [1,2]. Apart from a QCP this non-Fermi liquid (NFL) behavior can also be induced by disorder which is inherent in off-stoichiometric materials. The NFL behavior has been observed mostly in the chemical composition tuned materials in off-stoichiometric form. However, the presence of disorder in off-stoichiometric material makes it difficult to understand the role of quantum fluctuations in the development of NFL state. A stoichiometric material is thus considered ideal for the study of the role of quantum fluctuations in developing NFL state. There are only a few known stoichiometric materials which display NFL behavior. The NFL behavior in stoichiometric materials can be observed by tuning the ground state by magnetic field or pressure that drives the system to a QCP. The Kondo lattice heavy fermion CeRhBi is an interesting system that presents NFL behavior in stoichiometric form [3]. What makes CeRhBi even more promising is that the NFL behavior of local quantum critical origin is observed in stoichiometric form at zero field and ambient pressure without any tuning. The spin dynamics study provides evidence for an energy-temperature (E/T) scaling in the dynamic response of low-energy inelastic neutron scattering and a time-field (t/H^{η}) scaling of µSR asymmetry function revealing a universal quantum critical scaling in the stoichiometric non-Fermi liquid CeRhBi [3]. The dynamical E/T scaling associated with local quantum criticality is believed to be a manifestation of critical Kondo destruction which has so far been observed only in the field-tuned stoichiometric quantum critical system [4,5]. Untuned quantum criticality makes CeRhBi a model compound for the experimental study of such a critical Kondo destruction at a field-free quantum critical point.

References

[1] G. R. Stewart, Rev. Mod. Phys. **73**, 797 (2001); Rev. Mod. Phys. **78**, 743 (2006)
[2] H. v. Löhneysen *et al.*, Rev. Mod. Phys. **79**, 1015 (2007)
[3] V. K. Anand *et al.*, J. Phys. Soc. Jpn. **87**, 064708 (2018)
[4] Q. Si *et al.*, Nature (London) **413**, 804 (2001)
[5] Q. Si *et al.*, J. Phys. Soc. Jpn. **83**, 061005 (2014)

Subgap optical driving of Mott insulators: mechanisms and applications

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Advances in IR laser technology have enabled increasingly stronger ultrafast driving of correlated insulators at frequencies below their charge excitation gap. Experimental access to new pump-probe regimes challenges the conventional understanding of such materials' nonequilibrium behavior under subgap driving, and motivates further theoretical study of the carrier photoexcitation mechanisms. Here, we employ a time-dependent Gaussian approach to study the behavior of a 2D repulsive Hubbard model at half filling, under driving by strong ac electric fields. We discuss how carrier scattering and suppression of the Mott gap give rise to a rich landscape of photoexcitation regimes. Taking electron-phonon coupling into consideration, we arrive at a microscopic model for the coherent excitation of acoustic phonons on timescales much longer than the pump duration.

Non-Fermi liquid behavior at flat hot spots at the onset of density wave order

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We analyze quantum fluctuation effects at the onset of charge or spin density wave order with a $2k_F$ wave vector **Q** in two-dimensional metals -- for the special case where **Q** connects a pair of hot spots situated at high symmetry points of the Fermi surface with a vanishing Fermi surface curvature. We compute the order parameter susceptibility and the fermion self-energy in one-loop approximation. The susceptibility has a pronounced peak at **Q**, and the self-energy displays non-Fermi liquid behavior at the hot spots, with a linear frequency dependence of its imaginary part. The real part of the one-loop self-energy exhibits logarithmic divergences with universal prefactors as a function of both frequency and momentum, which may be interpreted as perturbative signatures of power laws with universal anomalous dimensions. As a result, one obtains a non-Fermi liquid metal with a vanishing quasiparticle weight at the hot spots, and a renormalized dispersion relation with anomalous algebraic momentum dependencies near the hot spots.

References

[1] L. Debbeler and W. Metzner, Physical Review B **107**, 165152 (2023)
[2] J. Sýkora et al. Physical Review B **97,** 155159 (2018)
[3] J. Halbinger et al. Physical Review B **99**, 195102 (2019)

Theory of deconfined SO(5) pseudocriticality from non-standard renormalization of a Wess-Zumino-Witten theory

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Not all possible phase transitions occurring in nature are captured by the Landau-Ginzburg-Wilson-Fisher paradigm. An exciting class of such non-Landau transitions are deconfined quantum critical points (DQCP) which exhibit emergent fractional excitations and gauge fields at criticality. The primary example in the study of DQCPs has been a system of half-integer spins on a square lattice with competing interactions. Whether or not this system shows true criticality, however, is a major open question in the field. In fact, numerical simulations for this model either indicate weak-first order behavior or at least a severely anomalous continuous transition between Néel and valence bond solid order.

It has been established early on that the effective field theory describing the putative critical behaviour between those orders is a 3D Wess-Zumino-Witten theory with target manifold S^4, which is notoriously difficult to access with field-theoretical methods. I will discuss a first study of this model using the non-perturbative functional renormalization group to include the effects of the topological Wess-Zumino-Witten term on the coupling of the non-linear sigma model within a leading-order truncation of the effective action. To that end, we take an unconventional approach by including higher-order regulator insertions. We find evidence for a fixed-point annihilation mechanism, leading to a pair of complex conformal field theories. We discuss two possible mechanisms leading to pseudo-criticality and drifting exponents, which can be induced by the Wess-Zumino-Witten term. Moreover, we provide an estimate for several (complex) scaling dimensions from which we derive predictions for effective thermodynamic critical exponents and their drifts as a function of system size.

Probing complex stacking in a layered material via electron-nuclear quadrupolar coupling

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For layered materials, the interlayer stacking is a critical degree of freedom tuning electronic properties, while its microscopic characterization faces great challenges. The transition-metal dichalcogenide 1T -TaS2 represents a novel example, in which the stacking pattern is not only enriched by the spontaneous occurrence of the intralayer charge density wave, but also recognized as a key to understand the nature of the low-temperature insulating phase. We exploit the ^{33}S nuclei in a 1T -TaS2 single crystal as sensitive probes of the local stacking pattern via quadrupolar coupling to the electron density distribution nearby, by combining nuclear magnetic resonance (NMR) measurements with the state-of-the-art first-principles electric-field gradient calculations. The applicability of our proposal is analyzed through temperature, magnetic-field, and angle-dependent NMR spectra. Systematic simulations of a single 1T -TaS2 layer, bilayers with different stacking patterns, and typical stacking orders in three-dimensional (3D) structures unravel distinct NMR characteristics. Particularly, one 3D structure achieves a quantitative agreement with the experimental spectrum, which clearly rationalizes the coexistence of two types of interfacial environments. Our method may find general applications in the studies of layered materials

References

[1] Cheng et al., Physical Review Materials 7, L091001 (2003) (Editors' Suggestion and Featured in Physics)

Non-local correlations and criticality in the triangular lattice Hubbard model

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We investigate the role of non-local electronic correlations at finite temperatures in the half-filled triangular lattice Hubbard model using the dynamical vertex approximation (DΓA), a diagrammatic extension [1] of the dynamical mean-field theory (DMFT). We analyze the impact of (quantum) phase transitions on finite temperature properties at the one- and two-particle level. We discuss the absence of magnetic ordering at finite temperatures due to the fulfilment of the Mermin-Wagner theorem and the (Mott) metal-insulator crossover. In addition we compare the results of this method to the ones obtained by other cutting-edge techniques like DMFT, its real-space cluster extension cellular dynamical mean-field theory (CDMFT) and diagrammatic Monte Carlo (DiagMC) [2].

References

[1] G. Rohringer, H. Hafermann, A. Toschi, A. A. Katanin, A. E. Antipov, M. I. Katsnelson, A. I.Lichtenstein, A. N. Rubtsov, and K. Held, Rev. Mod. Phys. 90, 025003 (2018).

[2] Alexander Wietek, Riccardo Rossi, Fedor Šimkovic IV, Marcel Klett, Philipp Hansmann, Michel Ferrero, E. Miles Stoudenmire, Thomas Schäfer, Antoine Georges, Phys. Rev. X 11, 041013 (2021).

Electrical transport probes of quantum spin liquids

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Quantum spin liquids are an exotic phase of matter characterized by the presence of fractionalized excitation(spinons) and emergent gauge fields. One of the difficulties in probing experimentally a QSL phase comes from the fact that the spinons do not carry an electric charge, ruling out the possibility of using conventional electrical probes. Going beyond conventional transport, we propose two setups of electric probes to characterize a QSL phase. First, we analyze a setup in which a QSL layer is interposed between two metallic layers. In this setup, we apply a current in the first metallic layer and measure the induced voltage on the second one. The momentum transfer is affected by the non-trivial behavior of momentum-carrying spinons and results in a response that will potentially be helpful for the future characterization of candidate QSL materials. The second probe we propose is an STM experiment on a Kondo lattice in which the local moments have non-trivial dynamics (hence forming a QSL phase). We provide the STM response in each of the phase configurations of this system allowing also for the possibility for the conduction electrons and for the spinons to form a superconducting phase. This last setup might find a concrete realization in materials such as TaS2, TaSe2 and NbSe2 in the 1T, 2H and in the 4Hb crystallographic phases.

Observation of near room temperature thin film superconductivity of atmospherically stable Ag-Au mesoscopic thin film

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Abstract: An environmentally stable mesoscopic thin film of Au of certain thickness has been deposited thermally on top of a Ag^+ implanted oxide substrate to develop a close to room temperature superconductor. This thin film has been deposited in two different stages. Initially, a sol-gel derived ion conducting metal oxide (ICMO) thin film has been deposited by spin coating method followed by an annealing process. Afterward, Ag^+ has been introduced inside ICMO thin film by a chemical method. Following this, a thin layer of Au has been deposited on top of that Ag ion-implanted oxide via thermal evaporation. The temperature dependent resistivity (R-T) has been studied by four probe method. During high-to-low temperature sweep, around 240 K this thin film sample shows a sudden drop of resistance from 0.7 Ω to 0.1 μΩ which is the noise floor of the measuring instrument. This 6-7 orders drop of resistance has been observed instantly within <0.1 K temperature variation of the sample. This transition temperature (T_C) has been shifted toward the higher temperature by 5-6 degrees when temperature has been increased from low to the higher side (transition from low resistance-to-high resistance). During 2nd and 3rd temperature cycling, both these transitions (forward and backward) have been shifted by ~10 K towards room temperature w.r.t the earlier. However, after three successive temperature cycles, T_C becomes stable and transitions occur close to 0 °C repeatedly which has been tested even after several months by storing the thin film under open atmospheric conditions. At the low resistance phase, current level has been varied from +100 mA to -100 mA which shows a random fluctuation of voltage drop within ±10 nV range, indicating resistance under such circumstance is too low to measure by Delta mode electrical measurement (≤0.1μΩ). Besides, transition temperature reduces to lower temperature by 4 K, after applying 1 tesla magnetic field perpendicular to the thin film. Few YouTube video links of temperature dependent electrical characterization of such a thin film is given next to the acknowledgement section of reference.

References

[1] Sobhan Hazra, Sandip Chatterjee and Bhola Nath Pal*, Observation of near room temperature thin film superconductivity of atmospherically stable Ag-Au mesoscopic thin film", arXiv:2302.09974, 2023

Self consistent theory of U infinity Hubbard model in large d

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We propose and implement here an approximate, nonperturbative, self consistent equation of motion approach to the strong correlation problem for the case of an extremely strongly correlated Fermi liquid (ECFL; $U = \infty$ in the single orbital lattice model of Hubbard) for large spatial dimension d. We obtain an equation of motion for the single particle Green's function G and for the associated self energy Σ; the latter involves the (number) density correlation function D_N and the spin correlation function D_S. We obtain coupled closed form equations for G, D_N, D_S and solve them self consistently. The imaginary part $-\operatorname{Im}\Sigma(0,T)$ has a low temperature coherent Fermi liquid regime with well defined low energy quasiparticle excitations crossing over smoothly into the high temperature incoherent Fermi liquid regime with no quasiparticles; these two limiting regimes are characterized by $-\operatorname{Im}\Sigma(0,T)$ going as T^2 and T respectively. We also obtain results for dc resistivity $\rho(T)$, which also is seen to cross over from a T^2 behaviour at low temperatures to being linear in T at high temperatures.

Transient localization from quantum bosons

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We study the electron-boson scattering problem on a lattice using the Finite Temperature Lanczos Method (FTLM). By providing exact results beyond early treatments based on classical bosons and perturbation expansions, we demonstrate numerically the emergence of Anderson localization in the absence of extrinsic disorder: the localization phenomenon is caused here by the randomness resulting from a large thermal population of the bosons at temperatures larger than the Debye scale, which is effective at transient times before diffusion can set in. We identify the fingerprint of the relevant quantum localization corrections through the appearance of a distinctive displaced Drude peak (DDP). Such transient localization phenomenon accompanied by a marked suppression of the conductivity, identifying a route for bad metal behavior in interacting electron systems.

References

[1] Displaced Drude peak and bad metal from the interaction with slow fluctuations. S Fratini, S Ciuchi - SciPost Physics, 2021
[2] The transient localization scenario for charge transport in crystalline organic materials. S Fratini, D Mayou, S Ciuchi - Advanced Functional Materials, 2016

Real-frequency quantum field theory applied to the single-impurity Anderson model

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A major challenge in the field of correlated electrons is the computation of dynamical correlation functions. For comparisons with experiment, one is interested in their real-frequency dependence. This is difficult to compute, as imaginary-frequency data from the Matsubara formalism require analytic continuation, a numerically ill-posed problem. Here, we apply quantum field theory to the single-impurity Anderson model (AM), using the Keldysh instead of the Matsubara formalism with direct access to the self-energy and dynamical susceptibilities on the real-frequency axis. We present results from the functional renormalization group (fRG) at one-loop level and from solving the self-consistent parquet equations in the parquet approximation. In contrast to previous Keldysh fRG works, we employ a parametrization of the four-point vertex which captures its full dependence on three real-frequency arguments. We compare our results to benchmark data obtained with the numerical renormalization group and to second-order perturbation theory. We find that capturing the full frequency dependence of the four-point vertex significantly improves the fRG results compared to previous implementations, and that solving the parquet equations yields the best agreement with the NRG benchmark data, but is only feasible up to moderate interaction strengths. Our methodical advances pave the way for treating more complicated models in the future.

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Quantum critical Dirac semimetals and finite-temperature effects

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The chiral Ising-, XY-, and Heisenberg models serve as effective descriptions of Dirac semimetals undergoing a quantum phase transition into a symmetry-broken ordered state. Interestingly, their quantum critical points govern the physical behavior of the system in the vicinity of the transition even at finite temperatures. In this contribution, we explore the chiral models at zero and finite temperature, both in the Dirac phase as well as in the symmetry-broken phases. To that end, we set up a functional renormalization group approach, which allows us to systematically track (1) the phenomenon of pre-condensation, (2) the manifestation of the Mermin-Wagner-Hohenberg theorem due to pseudo-Goldstone fluctuations at finite temperatures, and (3) the quantitative behavior of the system in the quantum critical fan, e.g., by calculating the quasiparticle weight. Our work aims at a more holistic understanding of chiral models near their quantum critical point, including, e.g., the description of non-Dirac-liquid behavior, in analogy to the non-Fermi-liquid behavior in metallic quantum critical points.

Absence of SO(4) quantum criticality in Dirac semimetals at two-loop order

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Evidence for relativistic quantum criticality of antiferromagnetism and superconductivity in two-dimensional Dirac fermion systems has been found in large-scale quantum Monte Carlo simulations [1]. However, the corresponding (2+1)-dimensional Gross—Neveu—Yukawa field theory with N_f = 2 four-component Dirac fermions coupled to two triplets of order parameters does not exhibit a renormalization group fixed point at one-loop order [2]. Instead, the theory only features a critical point for a large or very small fractional number of fermion flavors N_f, which disappears for a broad range of flavor numbers around the physical case, N_f = 2, due to fixed-point annihilation. This raises the question on how to explain the observed scaling collapse in the quantum Monte Carlo data. In our work [3], we extend previous renormalization-group analyses by studying a generalized model at two-loop order in $4-\epsilon$ spacetime dimensions. We determine the ϵ correction to the upper and lower critical flavor numbers for the fixed-point annihilation and find that they both go towards the physical case N_f = 2. However, this only happens very slowly, such that an extrapolation to $\epsilon = 1$ still suggests the absence of criticality in 2+1 dimensions. Thereby, we consolidate the finding that the continuum field theory does not feature a stable renormalization-group fixed point and no true quantum criticality would be expected for the considered system. We briefly discuss a possible reconciliation in terms of a complex conformal field theory. Further, we also explore the fixed-point structure in an enlarged theory space and identify a candidate stable fixed-point solution.

References

[1] H. Liu, E. Huffman, S. Chandrasekharan, and R. K. Kaul, Phys. Rev. Lett. 128, 117202 (2022)
[2] I. F. Herbut and M. M. Scherer, Phys. Rev. B 106, 115136 (2022)
[3] M. Uetrecht, I. F. Herbut, E. Stamou and M. M. Scherer, arXiv:2308.12464 (2023, preprint)