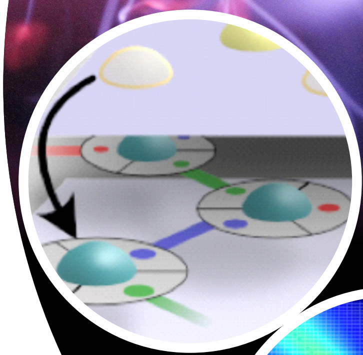
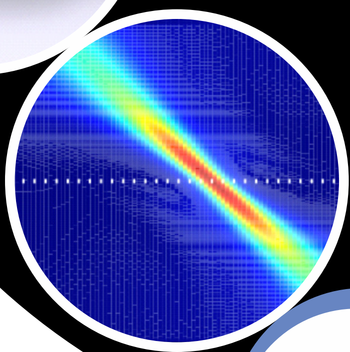
Workshop on the theory of condensed quantum matter

Correlations in Novel Quantum Materials

June 20–23, 2022 • Stuttgart, Germany

Max Planck Institute for Solid State Research





Program Details

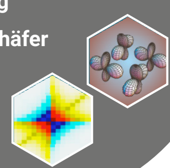
Further information at

www.fkf.mpg.de/cnqm2022

Public interdisciplinary panel discussion

Emergence 2.0:
Philosophy,
Quantum Materials,
and Artificial Intelligence

Organizing Committee
MPI for Solid State Research
Elio J. König
Thomas Schäfer

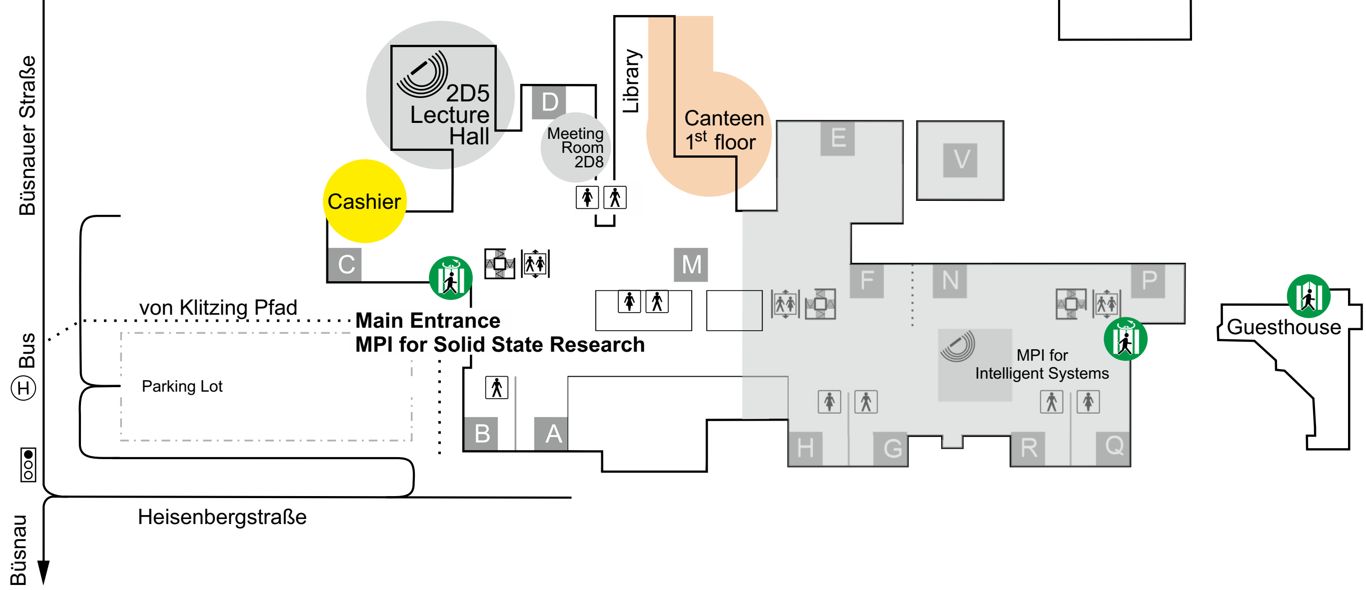


Max Planck Institute for Solid State Research

Site Map

Floor 3 Room A4 and Room B3

Changing Table
Floor 2 Room M2 and Room M4



Scope

Materials with strongly correlated quantum particles are at the forefront of present solid state research. Understanding the experimental properties of novel quantum materials crucially relies on the application of cutting-edge analytical and numerical tools.

This workshop aims at bringing together world-leading experts in both analytical and numerical theory to advance the current perspective on important questions of the field: What are the signatures of quantum order in newly synthesized experimental setups? Which aspects of quantum materials can be described on the model level? What are the computational and algorithmic boundaries hindering the solution of the many-body problem? What is the nature of phase transitions between these novel states of matter?

Program

Monday, June 20, 2022

Lecture Hall 2D5

CEDT AM 08:00	**Registration**
08:45	**Thomas Schäfer and Elio König** Max Planck Institute for Solid State Research, Stuttgart **Welcome**
	Session 1 — Quantum Criticality and Superconductivity
09:00	**Andrey Chubukov** University of Minnesota **Interplay Between Superconductivity and Non-Fermi Liquid at a QCP in a Metal**
09:45	**Premala Chandra** Rutgers University **Superconductivity in Dilute Quantum Critical Polar Metals**
10:15	Coffee Break
10:45	**Annica Black-Schaffer** Uppsala University **Nematic d-wave superconductivity in magic-angle twisted bilayer graphene from atomistic modeling**
11:15	**Jörg Schmalian** Karlsruhe Institute of Technology **Superconductivity without quasiparticles: Quantum critical Eliashberg theory and its holographic dual**
11:45	Lunch Break
CEDT PM 01:15	**Discussion**
	Session 2 — Dynamical Response Functions and Vertices
02:00	**Jan von Delft** Ludwig-Maximilians-Universität, Munich **Computing Local Multipoint Correlators Using the Numerical Renormalization Group**
02:45	**Fabian Kugler** Rutgers University **Spectral Representations for Multipoint Correlators and the Real- Frequency Four-Point Vertex**
03:15	Coffee Break
03:45	**Alessandro Toschi** TU Wien **Fluctuation diagnostics in broken-symmetry phases: Identification of the pairing glue in d-wave superconductors**
04:15	**Georg Rohringer** University of Hamburg **Two-particle self-consistency in diagrammatic extensions of the dynamical mean field theory**
04:45	**Poster Ads**
05:30	**Poster Session**

Program

Lecture Hall 2D5

Tuesday, June 21, 2022

	Session 3 — **Frustrated magnetism and local moment formation**
CEDT AM 09:00	**Natalia Perkins** University of Minnesota **Disorder in the Kitaev spin liquid**
09:45	**Lukas Janssen** TU Dresden **Quantum criticality in frustrated magnets**
10:15	Coffee Break
10:45	**Massimo Capone** International School for Advanced Studies, Trieste **Hund, phonons, Hubbard U: Friends or foes?**
11:15	**Alexei Tsvelik** Brookhaven National Laboratory **A solvable 3D Kondo lattice exhibiting odd-frequency pairing and order fractionalization**
11:45	Lunch Break
CEDT PM 01:15	**Discussion**
	Session 4 — **Transport in Correlated Quantum Materials**
02:00	**Sean Hartnoll** University of Cambridge **Joule Heating in Bad Metals**
02:45	**Alex Levchenko** University of Wisconsin-Madison **Thermoelectric anomaly and hydrodynamic paradox in viscous electronics**
03:15	Coffee Break
03:45	**Achim Rosch** University of Cologne **Dynamics of visons in perturbed Kitaev models**
04:15	**Jedediah Pixley** Rutgers University **Twisting nodal superconductors**
04:45	**Discussion**
06:00	**Public interdisciplinary panel discussion** **Emergence 2.0: Philosophy, Quantum Materials, and Artificial Intelligence** **Prof. Dr. Marco Huber • Prof. Dr. Patricia Palacios • Prof. Dr. Jörg Schmalian**

Program

Lecture Hall 2D5

Wednesday June 22, 2022

	Session 5 Numerical Approaches to Quantum Materials
CEDT AM 09:00	**Karsten Held** TU Wien **New developments in nickelate superconductors**
09:45	**Philipp Hansmann** Friedrich-Alexander-Universität Erlangen-Nürnberg **From three to one band models for high T_c cuprates: A closer look at single- and two particle observables**
10:15	Coffee Break
10:45	**Massimo Capone** International School for Advanced Studies, Trieste **Hund, phonons, Hubbard U: Friends or foes?**
11:15	**Michel Ferrero** École Polytechnique, Paris **Spin and charge response and pseudogap in the 2D Hubbard model**
11:45	Lunch Break
CEDT PM 01:30	**Poster Discussion**
03:00	**Departure to Excursion and Conference Dinner** — **Meeting point in front of the main entrance**
06:00	**Discussion on the 'Future of Novel Quantum Materials'**
07:00	**Conference Dinner**
09:00	**Discussion**

Program

Lecture Hall 2D5

Thursday, June 23, 2022

	Session 6	**(Un)Conventional Superconductivity**
CEDT AM 09:00		**Piers Coleman** Rutgers University **Order Fractionalization and Neutral Fermi Surfaces**
09:45		**Lilia Boeri** University of Rome **In-silico Synthesis of new high-T_c conventional Superconductors**
10:15		Coffee Break
10:45		**Michael Scherer** Ruhr Universität Bochum **Chiral superconductivity with enhanced quantized Hall responses in moiré transition metal dichalcogenides**
11:15		**Ilya Eremin** Ruhr-Universität Bochum **Non-local nematicity, collective modes and non-linear dynamics in nematic unconventional superconductors**
11:45		Lunch Break
CEDT PM 01:15		**Discussion**
	Session 7	**Strong Correlations in Low Dimensions**
02:00		**Alexander Lichtenstein** University of Hamburg **Local Plaquette Physics as Key Ingredient of High-Temperature Superconductivity in Cuprates**
02:45		**James LeBlanc** Memorial University of Newfoundland **Single- and two-particle properties of the weakly interacting two- dimensional Hubbard model in proximity to the van Hove singularity**
03:15		Coffee Break
03:45		**Giorgio Sangiovanni** University of Würzburg **Mott insulators with boundary zeros**
04:15		**Friedrich Krien** TU Wien **Bosons lost in translation**
04:45		**Elio König and Thomas Schäfer** Max Planck Institute for Solid State Research, Stuttgart **Closing remarks and farewell**

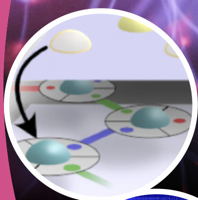
Workshop on Correlations in Novel Quantum Materials, CNQM 2022

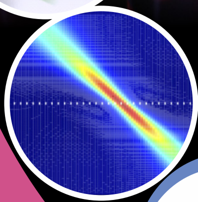
Public interdisciplinary panel discussion

Tuesday, June 21, 2022 • 6 pm

Max Planck Institute for Solid State Research
Heisenbergstraße 1, 70569 Stuttgart

Lecture Hall 2D5





Refreshments will be served.

The 2021 Nobel Prize in physics was awarded **"for groundbreaking contributions to our understanding of complex systems".** But what are complex systems and what makes them special?

"Emergence 2.0: Philosophy, Quantum Materials, and Artificial Intelligence".

The concept of emergence is central to the collective behavior of complex systems in a variety of research fields ranging from quantum materials and statistical physics to biological micro-organisms, machine learning, and, in its strongest form, even to the notion of consciousness. This panel discussion will bring together experts from philosophy, quantum physics, and computer science to discuss the phenomena of complexity with the general public.

Panelists:

Prof. Dr. Patricia Palacios
(Philosopher, University Salzburg/Ludwig-Maximilian-University Munich)

Prof. Dr. Jörg Schmalian
(Physicist, Karlsruhe Institute for Technology)

Prof. Dr. Marco Huber
(Computer Scientist, University of Stuttgart)

"MORE IS DIFFERENT." P.W. Anderson (Physics Nobel Laureate 1977)

Organizing Committee

MPI for Solid State Research

Elio J. König

Thomas Schäfer

Contact
CNQM2022@fkf.mpg.de

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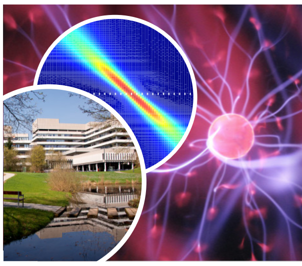
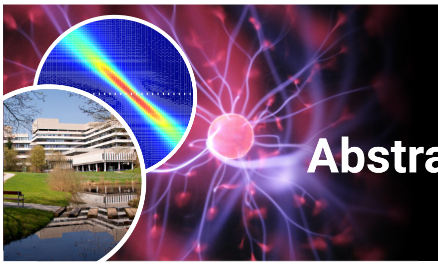


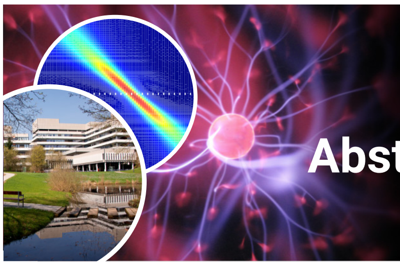
Abstracts: Oral Presentations

T-1	**Black-Schaffer,** Annica Uppsala University	Nematic d-wave superconductivity in magic-angle twisted bilayer graphene from atomistic modeling
T-2	**Boeri,** Lilia University of Rome	In-silico Synthesis of new high-T_c conventional Superconductors
T-3	**Capone,** Massimo Int. School for Adv. Studies, Trieste	Hund, phonons, Hubbard U: Friends or foes?
T-4	**Chandra,** Premala Rutgers University	Superconductivity in Dilute Quantum Critical Polar Metals
T-5	**Chubukov,** Andrey University of Minnesota	Interplay Between Superconductivity and Non-Fermi Liquid at a QCP in a Metal
T-6	**Coleman,** Piers Rutgers University	Order Fractionalization and Neutral Fermi Surfaces
T-7	**Eremin,** Ilya Ruhr-Universität Bochum	Non-local nematicity, collective modes and non-linear dynamics in nematic unconventional superconductors
T-8	**Ferrero,** Michel École Polytechnique, Paris	Spin and charge response and pseudogap in the 2D Hubbard model
T-9	**Hansmann,** Philipp FAU Erlangen-Nürnberg	From three to one band models for high T_c cuprates: A closer look at single- and two particle observables
T-10	**Hartnoll,** Sean University of Cambridge	Joule Heating in Bad Metals
T-11	**Held,** Karsten TU Wien	New developments in nickelate superconductors
T-12	**Janssen,** Lukas TU Dresden	Quantum criticality in frustrated magnets
T-13	**Krien,** Friedrich TU Wien	Bosons lost in translation
T-14	**Kugler,** Fabian Rutgers University	Spectral Representations for Multipoint Correlators and the Real-Frequency Four-Point Vertex
T-15	**LeBlanc,** James Memorial Univ. of Newfoundland	Single- and two-particle properties of the weakly interacting two- dimensional Hubbard model in proximity to the van Hove singularity
T-16	**Levchenko,** Alex University of Wisconsin-Madison	Thermoelectric anomaly and hydrodynamic paradox in viscous electronics
T-17	**Lichtenstein,** Alexander University of Hamburg	Local Plaquette Physics as Key Ingredient of High-Temperature Superconductivity in Cuprates
T-18	**Perkins,** Natalia University of Minnesota	Disorder in the Kitaev spin liquid
T-19	**Pixley,** Jedediah Rutgers University	Twisting nodal superconductors
T-20	**Rohringer,** Georg University of Hamburg	Two-particle self-consistency in diagrammatic extensions of the dynamical mean field theory
T-21	**Rosch, Achim** University of Cologne	Dynamics of visons in perturbed Kitaev models
T-22	**Sangiovanni,** Giorgio University of Würzburg	Mott insulators with boundary zeros
T-23	**Scherer,** Michael Ruhr-Universität Bochum	Chiral superconductivity with enhanced quantized Hall responses in moiré transition metal dichalcogenides
T-24	**Schmalian,** Jörg Karlsruhe Institute of Technology	Superconductivity without quasiparticles: Quantum critical Eliashberg theory and its holographic dual
T-25	**Thomale,** Ronny University of Würzburg	Kagome metals
T-26	**Toschi,** Alessandro TU Wien	Fluctuation diagnostics in broken-symmetry phases: Identification of the pairing glue in d-wave superconductors
T-27	**Tsvelik,** Alexei Brookhaven National Laboratory	A solvable 3D Kondo lattice exhibiting odd-frequency pairing and order fractionalization
T-28	**von Delft,** Jan Ludwig-Maximilians-Univ., Munich	Computing Local Multipoint Correlators Using the Numerical Renormalization Group



Abstracts: Poster Presentations

P-1	**Afrose,** Ramal National University of Singapore	Modelling viscous hydrodynamic electron flow in graphene with a two fluid model
P-2	**Al-Eryani,** Aiman University of Tübingen	Multiloop fRG Analysis of the Attractive Hubbard Model
P-3	**Bollmann,** Steffen MPI for Solid State Research, Stuttgart	Groundstate Phase Diagrams of Variants of the Two-Leg *t-J* Lad- der at Low Fillings
P-4	**Bonetti**, Pietro Maria MPI for Solid State Research, Stuttgart	Spin stiffness, spectral weight, and Landau damping of magnons in metallic spiral magnets
P-5	**Braun,** Hannes MPI for Solid State Research, Stuttgart	SU(N)xSU(M) symmetries realised by AB stacked twisted multilayer TMDs: A fRG study
P-6	**Chakraborty,** Debmalya Uppsala University	Disorder-robust phase crystal in high-temperature superconductors from topology and strong correlations
P-7	**Chalupa-Gantner,** Patrick TU Wien	Fulfillment of sum rules and Ward identities in the multiloop functional renormalization group solution of the Anderson impurity model
P-8	**Datta,** Anushree Instituto de Ciencia de Materiales de Madrid	Accuracy of moiré Wannier function models for twist bilayer graphene
P-9	**Foo,** Darryl Centre for Advanced 2D Materials, National University of Singapore	A stabilisation mechanism for many body localisation in 2D
P-10	**Fraboulet,** Kilian University of Tübingen	Single-boson exchange fRG application to the two-dimensional Hubbard model at weak coupling
P-11	**Gleis,** Andreas Ludwig-Maximilians Universität, Munich	Heavy-fermion quantum criticality via two-stage screening
P-12	**Gonçalves,** Miguel CeFEMA, Instituto Superior Técnico, Universidade de Lisboa	Renormalization-group theory of localization for 1D quasiperiodic lattice models
P-13	**Grandadam,** Maxence Memorial University of Newfoundland	Optical conductivity and Force-Force correlation function in the Hubbard model
P-14	**Greco,** Andrés Facultad de Ciencias Exactas, Ingeniería y Agrimensura Univ. Nacional de Rosario	Emergent bands induced by plasmon excitations in cuprate superconductors
P-15	**Heinzelmann,** Sarah University of Tübingen	Single boson exchange implementation of the multiloop functional renormalization group for the 2D Hubbard model
P-16	**Hirschmann,** Moritz MPI for Solid State Research, Stuttgart	Topology in magnetic phases of SmB_6
P-17	**Katukuri,** Vamshi MPI for Solid State Research, Stuttgart	Many body wavefunctions of hole-doped nickelate and cuprate superconductors
P-18	**Klett,** Marcel MPI for Solid State Research, Stuttgart	Magnetism and Mottness in the unfrustrated triangular lattice Hubbard model: a cellular dynamical mean-field study
P-19	**Malcolms de Oliveira**, Mário MPI for Solid State Research, Stuttgart	The role of non-local correlations in the triangular lattice Hubbard model



Abstracts: Poster Presentations

P-20	**Mazzilli,** Raffaele MPI for Solid State Research, Stuttgart	Spinon induced drag in quantum spin liquid heterostructures
P-21	**Meixner,** Michael MPI for Solid State Research, Stuttgart	The Mott metal-insulator transition in the two-dimensional Hubbard model - a cellular dynamical mean-field study on large clusters
P-22	**Menke,** Henri Friedrich-Alexander-Universität Erlangen-Nürnberg	Bogoliubov Fermi surfaces stabilized by spin-orbit coupling
P-23	**Mirsadegh,** Pouria Memorial University of Newfoundland	Quantifying Entanglement in Heisenberg Spin Chains
P-24	**Mitscherling,** Johannes MPI for Solid State Research, Stuttgart	Quantum metric, resistivity bound, and flat bands - Electrical conductivity in multiband systems
P-25	**Muñoz-Segovia,** Daniel Donostia International Physics Center	Superconducting collective Leggett modes in single-layer 1H-$NbSe_2$
P-26	**Parthenios,** Nikolaos MPI for Solid State Research, Stuttgart	SU(4) symmetry in Dirac materials - Application to twisted bilayer graphene
P-27	**Ritter,** Marc Ludwig-Maximilians-Universität, Munich	Multiloop pseudofermion functional renormalization for quantum spin systems: Application to the spin-1/2 kagome Heisenberg model
P-28	**Sarkar,** Saheli Karlsruhe Institute of Technology	Quantum criticality on a compressible lattice
P-29	**Sbierski,** Björn Ludwig-Maximilians-Universität, Munich	Spins, pseudo-Majoranas and the functional RG
P-30	**Scheurer,** Mathias University of Innsbruck	Zero-field superconducting diode effect in twisted trilayer graphene
P-31	**Starkov,** Grigorii Ruhr-Universität Bochum	Investigations of Instanton Crystal Phase
P-32	**Thunström,** Patrick Uppsala University	The generalized DMFT susceptibility from linear response
P-33	**Tolosa-Simeón,** Mireia University of Cologne	Curved FLRW universes in Bose-Einstein condensates
P-34	**van Loon,** Erik Lund University	How to get U? On the applicability of the constrained Random Phase Approximation
P-35	**Vilardi,** Demetrio MPI for Solid State Research, Stuttgart	Antiferromagnetic and pairing critical temperatures in the 2D Hubbard model
P-36	**Wallerberger,** Markus TU Wien	Pushing the envelope: sparse modelling of two-particle diagrammatics
P-37	**Weber,** Manuel MPI for the Physics of Complex Systems, Dresden	SU(2)-symmetric spin-boson model: Quantum criticality, fixed-point annihilation, and duality

Abstracts: Oral Presentations

Nematic d-wave superconductivity in magic-angle twisted bilayer graphene from atomistic modeling

Annica Black-Schaffer

Uppsala University

Bilayer graphene at certain small internal twist angles develops large scale moiré patterns with flat energy bands hosting correlated insulating states and superconductivity. The large system size and intricate band structure have however hampered investigations into the properties of the superconducting state. By using full-scale atomistic modeling with local electronic interactions, mimicking closely those of the high-temperature cuprate superconductors, and solving fully self-consistently for the superconducting order, we find a highly inhomogeneous superconducting state with nematic ordering on both the atomic and moiré lattice length scales. More specifically, we obtain locally anisotropic real-valued d-wave pairing with a nematic vector winding throughout the moiré pattern and a three-fold degenerate ground state. Despite the d-wave nature, the superconducting state has a full energy gap, which we show is tied to a π-phase interlayer coupling. We further show that the superconducting nematicity is easily detected through signatures in the local density of states. These results show both that atomistic modeling is essential for superconductivity in twisted bilayer graphene and that the superconducting state is distinctly different from that of the cuprate superconductors. in twisted bilayer graphene and that the superconducting state is distinctly different from that of the high-temperature cuprate superconductors, even if their electronic interactions may be the same.

In-silico Synthesis of new high-T_c conventional Superconductors

Lilia Boeri

University of Rome

The discovery of near-Room-Temperature Superconductivity in High-Pressure Super-hydrides has revolutionized the landscape of superconducting material research, establishing ab-initio calculations as the tool of choice for predicting superconducting properties and synthesis conditions of new superconductors. [1]

In this talk, I will give an overview of our recent efforts to design high-Tc conventional superconductors that can operate at ambient pressure [2] and to explore metastable phases of multinary phase diagrams and assess the kinetic stability of promising metastable phases [3].

References

[1] 1. J. A. Flores-Livas, L. Boeri, A. Sanna, G. Profeta, R. Arita, M. Eremets, Physics Reports 856, 1-78 (2020).

[2] 1. S. Di Cataldo, W. Von der Linden, L. Boeri, NPJ Computational Materials, 8, 2 (2022). S. Di Cataldo, C. Heil, W. von der Linden, and L. Boeri, Phys. Rev. B 104, L020511 (2021); S. Di Cataldo, S. Qulaghasi, G. B. Bachelet, L. Boeri, , Phys. Rev. B 105, 064516 (2022);

[3] S. Saha, S. Di Cataldo, M. Amsler, W. von der Linden, and L. Boeri, Phys. Rev. B 102 024519 (2020); R. Lucrezi, S. Di Cataldo, W. von der Linden, L. Boeri, C. Heil, NPJ Comp. Mat. In press (2022) - arxiv:2112.02131.

Hund, phonons, Hubbard U: Friends or foes?

Massimo Capone

International School for Advanced Studies, Trieste

I will present some results showing that the Hubbard repulsion and other interactions like the Hund's coupling and electron-phonon interaction can either compete or cooperate, leading to different strongly correlated phases.

First I will review the interplay between Hubbard U and Hund's coupling emphasizing how different fillings are characterized by different scenarios. Namely at half-filling the two interactions cooperate to localize the electrons in a high-spin Mott state, while for other integer fillings they compete, leading to a Hund's metal region bridging two strongly correlated insulators [1].

I will then address how an electron-phonon coupling changes the picture. In a two-orbital model we witness a cooperation between the Hubbard U and Jahn-Teller phonons, while the latter compete with the Hund's coupling. Also in this case we deal with the competition between two Mott insulators bridged by a hybrid insulator with mixed properties [2].

References

[1] A. Isidori, M Berovic, L. Fanfarillo, L. de' Medici, M. Fabrizio and M. Capone, Phys. Rev. Lett. 122, 186401 (2019).

[2] A. Scazzola, A. Amaricci and M. Capone, arXiv:2111.14663.

Superconductivity in Dilute Quantum Critical Polar Metals

Premala Chandra

Rutgers University

Superconductivity in low carrier density metals challenges the conventional electron-phonon theory due to the absence of retardation required to overcome Coulomb repulsion. Here I will discuss how pairing mediated by energy fluctuations, ubiquitously present close to continuous phase transitions, occurs in dilute quantum critical polar metals and results in a dome-like dependence of the superconducting Tc on carrier density, characteristic of non-BCS superconductors. In quantum critical polar metals, the Coulomb repulsion is heavily screened, while the critical transverse optic phonons decouple from the electron charge. In the resulting vacuum, long-range attractive interactions emerge from the energy fluctuations of the critical phonons, resembling the gravitational interactions of a charge-neutral dark matter universe. Our estimates show that this mechanism may explain the critical temperatures observed in doped $SrTiO_3$ in the appropriate density regime. Predictions for the enhancement of superconductivity near polar quantum criticality in two- and three-dimensional materials that can be used to test our theory are provided.

Work based on “Superconductivity from Energy Fluctuations in Dilute Quantum Critical Polar Metals,” P.A. Volkov, P. Chandra and P. Coleman, arXiv:2106.11295.

Interplay Between Superconductivity and Non-Fermi Liquid at a QCP in a Metal

Andrey Chubukov

University of Minnesota

I discuss the interplay between non-Fermi liquid behavior and pairing near a quantum-critical point (QCP) in a metal. These tendencies are intertwined in the sense that both originate from the same interaction mediated by gapless fluctuations of a critical order parameter. The two tendencies compete because fermionic incoherence destroys the Cooper logarithm, while the pairing eliminates scattering at low energies and restores fermionic coherence. I discuss this physics for a class of models with an effective dynamical interaction V (W) ~1/|W|^g (the g-model). This model describes, in particular, the pairing at a 2D Ising-nematic critical point (g=1/3), a 2D antiferromagnetic critical point (g=1/2) and the pairing by an Einstein phonon with vanishing dressed Debye frequency (g=2). I argue the pairing wins, unless the pairing component of the interaction is artificially reduced, but because of fermionic incoherence in the normal state, the system develops pseudogap behavior in the temperature range between the onset of the pairing at Tp and the onset of phase coherence at the actual superconducting Tc. The ratio Tc/Tp decreases with g and vanishes at g=2. I present two complementary arguments of why this happens. One is the softening of longitudinal gap fluctuations, which become gapless at g=2. Another is the emergence of a 1D array of dynamical vortices, whose number diverges at g=2. I argue that a fundamentally novel superconducting ground state emerges at g>2.

Order Fractionalization and Neutral Fermi Surfaces

Piers Coleman

Rutgers University

Over the past two decades, research into quantum materials has reverberated under the impact of new concepts, particularly those of topology and fractionalization. This talk will discuss the merger of these ideas. When a spin fractionalizes into a fermion, we argue that the resulting particle can hybridize or pair with mobile electrons to develop fractionalized order. This concept enables us to extend the concept of off-diagonal order to encompass the formation of order parameters with fractional quantum numbers [1], and it opens the way to new kinds of ordered state with novel gapless excitations.

A controlled illustration of this phenomenon is provided by a model which incorporates a solvable, gapless, Z2 spin liquid – the "Yao-Lee-Kitaev model" into a Kondo lattice [2]. This model explicitly exhibits order fractionalization, and in its three dimensional formulation, undergoes a transition into an order-fractionalized phase with a Majorana Fermi surface, and a charge *e*, *S* = 1/2 order parameter at at arbitrarily weak Kondo coupling [3]. The broader implications of these considerations for Quantum Materials with neutral Fermis surfaces will be discussed.

Work done in collaboration with Alexei M. Tsvelik, Brookhaven National Laboratories, supported by US department of energy grants DE- SC0012704 (AMT) and DE-FG02-99ER45790 (PC).

References

[1] Order Fractionalization, Yashar Komijani, Anna Toth, Premala Chandra, Piers Coleman, (2018).
[2] Order Fractionalization in a Kitaev Kondo model, Alexei Tsvelik and Piers Coleman, arXiv:2112.07781, (2021).
[3] A solvable 3D Kondo lattice with a neutral Fermi surface, Piers Coleman, Aaditya Panighri and Alexei Tsvelik, arXiv:2203.04104, (2022).

Non-local nematicity, collective modes and non-linear dynamics in nematic unconventional superconductors

Ilya Eremin

Ruhr-Universität Bochum

The recent technological development of THz spectroscopy makes it possible to probe properties of quantum matter, which cannot be observed in equilibrium. This is of considerable interest in the field of nematic unconventional superconductors, where controlled probing of the non-equilibrium dynamics yields access to understanding ground state properties of the underlying system.

In the first part of my talk I will discuss the electronic structure of the nematic order in FeSe and discuss the particular role of the non-local d_{xy} orbital nematicity. In addition to a pure d_{xz} /d_{yz} nematic order, known previously, provides a natural explanation for the unusual Fermi surface reconstruction and correctly reproduces the strongly anisotropic momentum dependence of the superconducting gap. We predict a Lifshitz transition of an electron pocket mediated by temperature and sulphur doping, whose feedback on various properties I will discuss by analysing available experimental data.

In the second part of my talk I will discuss the short-time dynamics in such a nematic superconductor with multiple attractive superconducting channels. I will analyze the signatures of collective excitations of the pairing symmetries (known as Bardasis-Schrieffer modes) its interaction with nematic order/fluctuations as well as the order parameter amplitude (Higgs mode) in the short-time dynamics of the spectral gap and quasiparticle distribution after an excitation by a pump pulse. I show that the polarization and intensity of the pulse can be used to control the symmetry of the non-equilibrium state as well as frequencies and relative intensities of the contributions of different collective modes

References

[1] Luke C. Rhodes, Jakob Böker, Marvin A. Müller, Matthias Eschrig and Ilya M. Eremin, npj Quantum Mater. 6, 45 (2021).
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[3] Marvin A. Müller, Pavel A. Volkov, Indranil Paul, Ilya M. Eremin, Phys. Rev. B 100, 140501(R) (2019).
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Spin and charge response and pseudogap in the 2D Hubbard model

Michel Ferrero

École Polytechnique, Paris

I will present recent numerically exact finite-temperature results for the two-dimensional Hubbard model obtained by diagrammatic Monte Carlo. I will show that there are several correlation regimes characterized by different magnetic correlation lengths and interaction strengths. I will discuss the connection between these regimes and the onset of a pseudogap. Finally, I will try to shake hands with ground state results and discuss how a stripe-ordered ground state can eventually be recovered at low doping and how it is connected to the fate of the pseudogap at zero temperature.

From three to one band models for high T_c cuprates: A closer look at single- and two particle observables

Philipp Hansmann

Friedrich-Alexander-Universität Erlangen-Nürnberg

The different low energy effective Hamiltonians for cuprate high-T_c superconductors [1] can be considered as steps in a Wilsonian renormalization procedure from large- to small energy windows around the Fermi level. High energy models include bare interactions and all spin-, orbital-, and lattice degrees of freedom explicitly. However, at low energies many researchers consider the single band Hubbard model with a screened interaction to be adequate for capturing ground state and "near-ground state properties" like the magnetic susceptibility. Occasionally, this viewpoint is still challenged. Recent measurements [2] of the doping dependence in the NMR Knight shift were claimed to be in contradiction with an effective single band description calling for explicit inclusion of oxygen degrees of freedom.
In our ongoing work we revisit the single- and three band Hubbard models for cuprates on the one- and two particle level within dynamical mean-field theory. We study the temperature/doping phase diagram using material-realistic parameters [3] and account also for possibly incommensurate order by solving the Bethe-Salpeter equation. At lower doping levels our preliminary results seem to support the idea of a single band description for single and two particle observables in small energy windows at low temperatures (at least qualitatively). At the same time, however, excitations beyond a couple of 100meV as well as the high doping regime seem to be problematic for a static single band picture.

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Joule Heating in Bad Metals

Sean Hartnoll

University of Cambridge

I will first review why it is important to disentangle the effects of electronic interactions and electron-lattice interactions in unconventional metals. I will then describe an observable process that depends crucially on electron-lattice interactions: the transfer of energy from hot electrons to a cooler lattice. Textbook discussion of this effect build upon weakly interacting electronic quasiparticles and may well not be applicable in bad metals. I will present a formula for rate at which this energy transfer occurs in the absence of quasiparticles. I will illustrate the use of this formula using recent EELS data as well as Monte-Carlo simulations of the Hubbard model.

New developments in nickelate superconductors

Karsten Held

TU Wien

Recent experimental progress has brought about better, defect-free infinite-layer nickelates [1] and the first finite-layer nickelate superconductor [2]. The measured superconducting dome is in exceedingly good agreement with our theoretical prediction [3] based on single Ni-$d_{x^2y^2}$-band Hubbard model plus a decoupled electron reservoir for the pockets around the A momentum and at low doping Γ momentum [4]. These pockets are essential for the obtaining the correct filling of the Ni-$d_{x^2y^2}$-band for the infinite layer compound. In contrast, there are no such pockets for the pen- talayer nickelate superconductor if electronic correlations included [5]; its T_c not only well agrees with theory but also with that of the new infinite-layer films at the same $d_{x^2y^2}$- doping. The ab- sence and presence of pockets also explains the very different Hall coefficient in the infinite and finite-layer nickelates, respectively.

Nickelates are not optimal for superconductivity. In particular they have a too large Coulomb interaction, i.e., are too strongly correlated. For this reason, pressure, strain or replacing 3d nickelates by 4d palladates are viable alternatives for obtaining higher T_c's [3]. This prediction has been spectacularly confirmed in a first experiment [6], showing an increase to a record high $T_c > 30K$ at 12 GPa in infinite-layer nickelates, and no indication yet of a saturation.

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Quantum criticality in frustrated magnets

Lukas Janssen

TU Dresden

In frustrated magnets, novel phases characterized by fractionalized excitations and emergent gauge fields can occur. A paradigmatic example is given by the Kitaev model of localized spins 1/2 on the honeycomb lattice, which realizes an exactly solvable quantum spin liquid ground state with Majorana fermions as low-energy excitations. I will demonstrate that the Kitaev solution can be generalized to systems with spin and orbital degrees of freedom. The phase diagrams of these Kitaev-Kugel-Khomskii spin-orbital magnets feature a variety of novel phases, including different types of quantum liquids, as well as conventional and unconventional long-range-ordered phases, and interesting phase transitions in between. In particular, I will discuss the example of a transition between a Kitaev spin-orbital liquid and a symmetry-broken phase. This transition can be understood as a realization of a fractionalized fermionic quantum critical point.

Bosons lost in translation

Friedrich Krien

TU Wien

Using appropriate terminology, we say more with fewer words. A useful terminology to describe two-particle electronic correlations was introduced by Hedin [1] and in the context of the spin- fermion model [2,3]. In this spirit, we show that re-expressing two-particle correlations through exchange bosons [4,5] greatly enhances the computational power of algorithms and, at the same time, gives us deeper insights into their output. Using exchange bosons, we formulate approxima- tions that remain valid at strong coupling [6], where perturbation theory breaks down. We solve the Hubbard model on a large lattice using the parquet approach [7,8]. Finally, breaking down self-energy diagrams into bosons and their coupling to fermions provides us with an appealing ex- planation of the pseudogap phenomenon in cuprates [9]. The bosons, so to say, are no longer lost in translation.

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Spectral Representations for Multipoint Correlators and the Real- Frequency Four-Point Vertex

Fabian Kugler

Rutgers University

The many-body problem is usually approached from one of two perspectives: the first originates from an action and is based on Feynman diagrams, the second is centered around a Hamiltonian and deals with quantum states and operators. The connection between results obtained in either way is made through spectral (or Lehmann) representations, well known for two-point correlators. We have derived generalized spectral representations for multipoint correlators that complete this picture and apply in the imaginary-frequency Matsubara, the real-frequency zero-temperature, and the real-frequency Keldysh formalisms. Our spectral representations consist of partial spectral functions, containing the system-specific information, and convolution kernels, encoding the formalism-dependent time-ordering prescription, and thereby elucidate the relation between the different many-body formalisms.

In this talk, I will first describe how we derive the generalized spectral representations and what they tell us about analytic properties of multipoint correlators. Then, I will present numerical results for the four-point vertex of the Anderson impurity model and the DMFT solution of the Hubbard model, discussing imaginary-frequency Matsubara and real-frequency Keldysh data. The numerical results are obtained using our numerical renormalization group (NRG) scheme explained in the opening talk by Jan von Delft.

Single- and two-particle properties of the weakly interacting two- dimensional Hubbard model in proximity to the van Hove singularity

James LeBlanc

Memorial University of Newfoundland

Leveraging the power of algorithmic Matsubara integration (AMI) we can generate pseudo-analytic results for virtually any diagrammatic expansion. Here we generate the longitudinal spin and charge susceptibilities for the 2D Hubbard model and employ our AMI toolset to obtain expressions that are explicit functions of chemical potential, temperature, interaction strength and frequency (both real and Matsubara).

We study the weak coupling limit for finite next-nearest neighbour hopping where we resolve features in real frequency spectra that appear to be missed in numerical analytic continuation of Matsubara axis data. We track these features throughout the phase diagram and find that their existence has a simple explanation made clear when considering the $\chi_{\uparrow\uparrow}$ and $\chi_{\uparrow\downarrow}$ susceptibilities. We further find that incompressibility in the model at weak coupling originates from vector nesting near the van Hove point and present evidence that this may be distinct from Mott insulating behaviour.

Thermoelectric anomaly and hydrodynamic paradox in viscous electronics

Alex Levchenko

University of Wisconsin-Madison

We study hydrodynamic electron transport in Corbino and Hall bar graphene devices. In Corbino geometry due to the irrotational character of the flow, the forces exerted on the electron liquid are expelled from the bulk. We show that in the absence of Galilean invariance, force expulsion produces qualitatively new features in thermoelectric transport: (i) it results in drops of both voltage and temperature at the system boundaries and (ii) in conductance measurements in pristine systems, the electric field is not expelled from the bulk. We obtain thermoelectric coefficients of the system in the entire crossover region between charge neutrality and high electron density regime. The thermal conductance exhibits a sensitive Lorentzian dependence on the electron density. The width of the Lorentzian is determined by the fluid viscosity. This enables determination of the viscosity of electron liquid near charge neutrality from purely thermal transport measurements. In general, the thermoelectric response is anomalous: it violates the Matthiessen's rule, the Wiedemann-Franz law, and the Mott relation. For Hall bar devices subject to long-range inhomogeneities we show that the effective electrical conductivity of the system may significantly exceed the intrinsic conductivity of the electron liquid.

Local Plaquette Physics as Key Ingredient of High-Temperature Superconductivity in Cuprates

Alexander Lichtenstein

University of Hamburg

We introduce a strong coupling dual super-perturbation scheme starting from the general reference system optimised for a given many-body problem. We discuss the physics of high-temperature cuprate superconductors starting from the highly degenerate four-site plaquette of the Hubbard model as a reference system. The degeneracy causes strong fluctuations when a lattice of plaquettes is constructed. We show that there is a large binding energy between holes when a set of four plaquettes is considered. The next-nearest-neighbour hopping plays a crucial role in the formation of these strongly bound electronic bipolarons whose coherence at lower temperature could be the explanation for superconductivity. We also use a cluster dual fermion starting from a single degenerate plaquette, which contains the relevant short-ranged fluctuations from the beginning. It gives d-wave superconductivity as the leading instability under a reasonably broad range of parameters. The origin of the pseudogap is discussed in terms of the coupling of degenerate plaquettes. Generalisations of the present approach to the lattice Quantum Monte-Carlo scheme is presented.

Disorder in the Kitaev spin liquid

Natalia Perkins

University of Minnesota

Quantum spin liquid (QSL), an exotic magnetic phase with fractionalized spin excitations and intricate entanglement structure, has been pursued both theoretically and experimentally since its first proposal by Anderson in 1973. Theoretical models and candidate materials with strong geometrical or exchange frustration are expected to greatly reduce the ordering temperature and reveal the quantum fluctuations. However, the presence of residual interactions in real systems usually leads to magnetic ordering and shatters the hope for finding QSL. Nevertheless, various compounds were discovered with no magnetic ordering even down to the lowest measurable temperature, and commonly the quenched randomness was found to serve as a potential cause of the sustaining disordered phase and intriguing dynamics of low-energy degrees of freedom. Therefore, the competition between quantum fluctuations and randomness raises a critical question about the true nature of the low-energy phase in those materials. In some Kitaev materials, the so-called second-generation Kitaev materials, experimentally observed peculiar low-energy excitations may be ascribable to spin fractionalization in weakly disordered QSL, but it may also relate to the random singlet (RS) phase in strongly disordered magnets. In my talk, I will discuss these possible scenarios by considering disorder in the exactly solvable Kitaev spin liquid.

Twisting nodal superconductors

Jedediah Pixley

Rutgers University

The realization of correlated insulators and superconductivity in twisted van der Waals heterostructures has brought forth twisting as a new control knob in condensed matter laboratories. In this talk we will show how twisting can be used to control the low energy physics of bilayers of nodal superconductors. Focusing in the vicinity of the Dirac nodes in their Bogolioubov de Gennes (BdG) spectrum we derive an effective model, which is surprisingly simpler then in twisted bilayer graphene. As a result, we demonstrate that in the limit of small twists the BdG velocity vanishes at a magic-angle, which we estimate for a few nodal superconductors that are available in monolayer form. At the magic-angle the effects of the interactions between the BdG quasiparticles are greatly enhanced leading to a secondary, time reversal breaking, superconducting instability. In addition, we demonstrate quite generally that applying an interlayer current to twisted nodal superconductors at any (small) twist angle induces a topological superconducting state. Preliminary results on the interlayer tunneling of $Bi_2Sr_2CaCu_2O(8+y)$ (BSCCO) to more precisely estimate the magic-angle at low twist angles will be discussed. Last, recent experiments have successfully twisted thin slabs of BSCCO while maintaining the high temperature superconducting state. The results on the critical current and related Josephson effects for a wide range of twist angles will be presented in conjunction with our theoretical analysis that demonstrates an observation of the second harmonic in the current phase relationship for a twist of 45 degrees.

Two-particle self-consistency in diagrammatic extensions of the dynamical mean field theory

Georg Rohringer

University of Hamburg

In the last 30 years, the dynamical mean field theory (DMFT) has developed to a standard tool for the theoretical description of strongly correlated electron systems. It self-consistently maps a lattice Hamiltonian onto an impurity problem which can be solved exactly via exact diagonalization or Quantum Monte Carlo methods. In this way, all purely local correlation effects in the system are captured. However, often non-local correlations play an equally important role for correlated electron systems. In the last decade, diagrammatic extension of DMFT have emerged which take into account such spatial fluctuations by means of a Feynman diagrammatic expansion around the DMFT starting point. Unfortunately, their predictive power is limited due to intrinsic inconsistencies which lead to a violation of either the Pauli principle and/or the conservation laws of the system. In my talk, I will discuss these two problems highlighting their important implications for the predictive power of the diagrammatic extensions of DMFT. Moreover, I will discuss ideas to overcome these difficulties for the example of the dynamical vertex approximation and demonstrate their applicability for the description of antiferromagnetic fluctuations in the half-filled three dimensional Hubbard model on a simple cubic lattice.

Dynamics of visons in perturbed Kitaev models

Achim Rosch

University of Cologne

A vison is an excitation of the Kitaev spin liquid which carries a Z_2 gauge flux. While immobile in the pure Kitaev model, it becomes a dynamical degree of freedom in the presence of perturbations. We [1] study an isolated vison in the isotropic Kitaev model perturbed by a small external magnetic field h, an offdiagonal exchange interactions Γ and a Heisenberg coupling J. In the ferro- magnetic Kitaev model, the dressed vison obtains a dispersion linear in Γ and h and a fully universal low-T mobility, $= 6v^2_m/T^2$, where v_m is the velocity of Majorana fermions. In contrast, in the an- tiferromagnetic Kitaev model interference effects preclude coherent propagation and an incoherent Majorana-assisted hopping leads to a T-independent mobility. The motion of a single vison due to Heisenberg interactions is strongly suppressed for both signs of the Kitaev coupling. Vison bands induced by can be topological and may lead to signatures in the thermal Hall effect.

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Mott insulators with boundary zeros

Giorgio Sangiovanni

University of Würzburg

In the recent literature, the concept of topological Mott insulator has been spelled out in quite different ways. Most of the proposed realizations rely either on Hartree-Fock approximations or on appropriately defined auxiliary degrees of freedom. I will discuss a novel, remarkably simple way of describing a topological Mott insulator without long-range order based on the topological properties of their Green's function zeros in momentum space. After discussing the fate of the bulk-boundary correspondence in these systems, I will show how the zeros can be seen as a form of "topological antimatter" with distinctive features associated to the annihilation with conventional topologically protected edge modes.

Chiral superconductivity with enhanced quantized Hall responses in moiré transition metal dichalcogenides

Michael Scherer

Ruhr-Universität Bochum

Experimental demonstrations of tunable correlation effects in magic-angle twisted bilayer graphene have put two-dimensional moiré quantum materials at the forefront of condensed-matter research. In particular, bilayers of transition metal dichalcogenides (TMDs) have further enriched the opportunities for analysis and utilization of correlations in such systems. Recently, within the latter material class, the relevance of many-body interactions with an extended range has been demonstrated. Interestingly, the interaction, its range, and the filling can be tuned experimentally by twist angle, substrate engineering and gating.

Moiré hetero-bilayer TMDs can be accurately modelled by an effective extended Hubbard model on the triangular superlattice, which defines a starting point for quantum many-body approaches. In my presentation, I will discuss the Fermi surface instabilities and resulting correlated phases of hetero-bilayer TMDs employing a functional renormalization group approach with high momentum resolution. The results from this approach suggest that hetero-bilayer TMDs are unique platforms to realize topological superconductivity with high winding number which reflects in pronounced experimental signatures such as enhanced quantum Hall features.

Superconductivity without quasiparticles: Quantum critical Eliashberg theory and its holographic dual

Jörg Schmalian

Karlsruhe Institute of Technology

Superconductivity is abundant near quantum-critical points, where fluctuations suppress the formation of Fermi liquid quasiparticles and the Bardeen-Cooper-Schrieffer theory no longer applies. Two very distinct approaches have been developed to address this issue: quantum-critical Eliashberg theory and holographic superconductivity. The former includes a strongly retarded pairing interaction of ill-defined fermions, the latter is rooted in the duality of quantum field theory and gravity theory. We demonstrate that both are different perspectives of the same theory. We derive holographic superconductivity in form of a gravity theory with emergent space-time from a quantum many-body Hamiltonian - the Yukawa SYK model and finite-dimensional generalizations thereof - where the Eliashberg formalism is exact. Exploiting the power of holography, we then determine the dynamic pairing susceptibility of the model. Our holographic map comes with the potential to use quantum gravity corrections to go beyond the Eliashberg regime.

Kagome metals

Ronny Thomale

University of Würzburg

The recent discovery of AV_3Sb_5 (A=K,Rb,Cs) has uncovered an intriguing arena for exotic Fermi surface instabilities in kagome metals. Aside from charge density wave order, a multi-dome superconducting phase is found, with strong indications to be of unconventional origin including features such as time reversal symmetry breaking. We find that the sublattice interference mechanism is necessary and sufficient to uncover the nature of unconventional particle-hole and particle-particle pairing in the V net kagome metals. We predict a Peierls-type charge density wave with finite relative angular momentum and orbital current formation. With regard to the possible nature of unconventional pairing, we find a rich phase diagram depending on the range of the screened electronic interactions, the multi-orbital content, and the location of multiple van Hove singularities with respect to the Fermi level. Combined, kagome metals open a new domain of unconventional electronic order, unfolding a plethora of fascinating experimental and theoretical investigations.

Fluctuation diagnostics in broken-symmetry phases: Identification of the pairing glue in d-wave superconductors

Alessandro Toschi

TU Wien

In recent years, reliable approaches have been developed [1,2] to unambiguously identify the dominant fluctuations driving the multifaceted phenomena of many-electron physics. Among those, the *"fluctuation diagnostics"* [3] relies on the possibility of expressing the physical quantity of interest in complementary representations. Hitherto, this scheme has been only applied to normal, paramagnetic phases, allowing to pinpoint the spin-fluctuation nature of the pseudogap features in the Hubbard model. After extending the formulation of the fluctuation diagnostics to the *superconducting ordered phase*, we have applied it [4] to identify the fluctuations responsible for pairing in the d-wave superconducting state of the two-dimensional Hubbard model, solved at intermediate coupling via the dynamical cluster approximation. This way, we could identify antiferromagnetic fluctuations as the "pairing glue" of the observed superconductivity both in the underdoped and the overdoped regime. However, at the intermediate values of coupling considered, the predominant magnetic fluctuations might significantly differ from those described by conventional spin-fluctuation theory.

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A solvable 3D Kondo lattice exhibiting 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. The solution describes 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.

Computing Local Multipoint Correlators Using the Numerical Renormalization Group

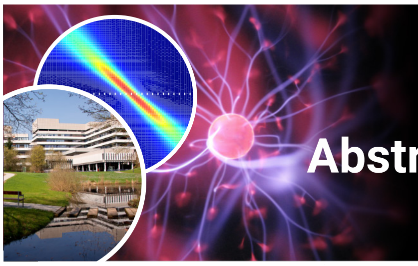
Jan von Delft

Ludwig-Maximilians-Universität, Munich

Local three- and four-point correlators yield important insight into strongly correlated systems and have many applications. However, the nonperturbative, accurate computation of dynamical multipoint correlators is challenging, particularly in the real-frequency domain for systems at low temperatures. We have developed generalized spectral representations for multipoint correlators, and a numerical renormalization group (NRG) approach for computing local three- and four-point correla- tors of quantum impurity models. The key ingredients in our scheme are partial spectral functions, encoding the system's dynamical information. Their computation via NRG allows us to simultaneously resolve various multiparticle excitations down to the lowest energies. By subsequently convolving the partial spectral functions with appropriate kernels, we obtain multipoint correlators in the imaginary-frequency Matsubara, the real-frequency zero-temperature, and the real-frequency Keldysh formalisms.

In this talk, I will begin with a review of the NRG computation of real-frequency two-point spectral functions and correlators and discuss some examples involving DMFT+NRG applications. I will then describe how the NRG methodology can be generalized from two-point to three- and four-point spectral functions, and present exemplary results for the connected four-point correlators of the Anderson impurity model.

In a subsequent talk, Fabian Kugler will discuss the generalized spectral representations for multipoint correlators in detail and show additional numerical results for the four-point vertex obtained using our scheme.



Abstracts: Poster Presentations

Modelling viscous hydrodynamic electron flow in graphene with a two fluid model

Ramal Afrose

National University of Singapore

Current in conventional conductors is characterized by electron-impurity and electron-phonon scattering. However, recent breakthroughs in fabrication of 2D materials with very low impurity has led to the realization of a new regime of transport, namely, the hydrodynamic regime, where electron-electron Coulomb interaction dominates. A lot of work has been done recently on hydrodynamic transport but they mainly focus on high carrier densities where electrons can be described by a Fermi liquid. In graphene near charge neutrality, the situation is different as both electrons and holes contribute to the current. Some recent work (e.g, G. Wagner, D. X. Nguyen, S. H. Simon, Phys. Rev. Lett. 124, 026601 (2020)) approach this problem by considering a two fluid model with interactions between electrons and holes. However, their analysis is restricted to uniform currents where viscous effects do not arise.

In this talk, I will discuss non-uniform two carrier flow in graphene near charge neutrality. Specifically, we derive a two fluid model with appropriate interactions between electrons and holes that can model this type of flow. Our work is of importance when explaining magneto-resistance in geometries like the Corbino where a simple non-viscous transport theory breaks down.

Multiloop fRG Analysis of the Attractive Hubbard Model

Aiman Al-Eryani

University of Tübingen

We analyse the effect of multiloop corrections in the 2D Attractive Hubbard Model. In a TU-fRG scheme where the conventional multi-loop self-energy flow equations are replaced with a Schwinger-Dyson flow, we demonstrate the importance of self-energy iteration in the convergence to reference Parquet results. Furthermore, we study the feedback of the s-wave pairing fluctuations on the charge density wave order.

Groundstate Phase Diagrams of Variants of the Two-Leg *t-J* Lad- der at Low Fillings

Steffen Bollmann

MPI for Solid State Research, Stuttgart

We study variants of the two-leg t-J ladder at low fillings using matrix product states (MPS) and analytical methods. While the groundstate phase diagram for the usual t-J ladder with spatially isotropic couplings at fillings $n > 0.5$ has been studied in detail, relatively little is known at low fillings. We address the phase diagram at low fillings and investigate the influence of nearest-neighbor Coulomb interactions V and asymmetries in the spin-exchange $J_z = J_x = J$ on the size and nature of superconducting phases. For $V = 0$ the superconducting phase is enhanced, and we find a crossover within this phase from s-wave pairing to d-wave pairing when increasing the filling. For $J_z=0$, the size of the superconducting region is reduced. In this talk, I will present the phase diagrams, discuss the physics, briefly introduce the methods used to classify the different phases, and give an outlook towards 2D systems and possible realizations in experiments.

Spin stiffness, spectral weight, and Landau damping of magnons in metallic spiral magnets

Pietro Maria Bonetti

MPI for Solid State Research, Stuttgart

We analyze the properties of magnons in metallic electron systems with spiral magnetic order. Our analysis is based on the random phase approximation for the susceptibilities of tight binding electrons with a local Hubbard interaction in two or three dimensions. We identify three magnon branches from poles in the susceptibilities, one associated with in-plane, the other two associated with out-of-plane fluctuations of the spiral order parameter. We derive general expressions for the spin stiffnesses and the spectral weights of the magnon modes, from which also the magnon velocities can be obtained. Moreover, we determine the size of the decay rates of the magnons due to Landau damping. While the decay rate of the in-plane mode is of the order of its excitation energy, the decay rate of the out-of-plane mode is smaller so that these modes are asymptotically stable excitations even in the presence of Landau damping. We finally prove that the spin stiffnesses and spectral weights can be alternatively computed from the response to a SU(2) gauge field. Ward identities guarantee the equivalence of both approaches.

SU(N)xSU(M) symmetries realised by AB stacked twisted multilayer TMDs: A fRG study

Hannes Braun

MPI for Solid State Research, Stuttgart

The development of twisted bilayer TMDs established a new field for the investigation of correlated electron phases in 2D materials on triangular lattices. Compared to TBG, twisted bilayer TMDs allow the access to quantitative different layer orientations with respect to the twisting angle. This results in the case of AB stacking to a suppressed interlayer tunneling from the bottom to the top layer valence band. Recent studies connected this to an SU(4) symmetry, which perturbations can break down to SU(2)xSU(2). Continuing this idea, we enhance this ansatz to twisted multilayer systems concluding in a theoretical SU(N)xSU(M) symmetry. The idea is also motivated by recent realisations of SU(2)xSU(6) systems in cold atomic gases. To analyse the correlated phases of the resulting Hubbard models, we generalise the functional renormalization group approach for correlated fermion systems to efficiently incorporate the high symmetries.

Disorder-robust phase crystal in high-temperature superconductors from topology and strong correlations

Debmalya Chakraborty

Uppsala University

Today there exists a strong research focus on topological effects in condensed matter. Initial studies were only focused on non-interacting electronic systems, but attention is now shifting towards the influence of electron-electron interactions and also the broken symmetry states they can generate. Real-world materials bring disorder as a third important component, as many symmetry broken states are sensitive to disorder. Hence, to understand many materials we need to keep a combined focus on topology, electronic correlations, and disorder. Copper oxide high-temperature superconductors (cuprates) with pair breaking edges host a flat band of topological zero-energy states, making them an ideal playground where strong correlations, topology, and disorder are strongly intertwined. Here, we show that the three way interplay in cuprates generates a new phase of matter: a fully gapped "phase crystal" state that breaks both translational and time reversal invariance, characterized by a modulation of the d-wave superconducting phase co-existing with a modulating extended s-wave superconducting order. In contrast to conventional wisdom, this phase crystal state is remarkably robust to omnipresent disorder, but only in the presence of strong correlations, thus giving a clear route to its experimental realization.

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Fulfillment of sum rules and Ward identities in the multiloop functional renormalization group solution of the Anderson impurity model

Patrick Chalupa-Gantner

TU Wien

We showcase several fundamental characteristics of the multiloop functional renormalization group (mfRG) flow by hands of its application to a prototypical many-electron system: the Anderson impurity model (AIM). On the one hand, we analyze the convergence of the algorithm in the different parameter regions of the AIM. On the other hand, by exploiting the converged results, we inspect the fulfillment of (i) sum rules associated to the Pauli principle and (ii) Ward identities related to conservation laws. For the Pauli principle, we observe a systematic improvement by increasing the loop order and including the multiloop corrections to the self-energy. For the Ward identities, we numerically confirm a visible improvement by means of the Katanin substitution. At weak coupling, violations of the Ward identity are further reduced by increasing the loop order in mfRG. For larger interaction values, the overall behavior becomes more complex, and the benefits of the higher-loop terms are mostly present in the contributions at large frequencies.

Accuracy of moiré Wannier function models for twist bilayer graphene

Anushree Datta

Instituto de Ciencia de Materiales de Madrid

Recent experimental observations of correlated phases in magic-angle twisted bilayer graphene (MATBG) strongly indicate the enhanced importance of electronic correlations in this flat band system. Twist in graphene layers in MATBG results in the formation of moiré patterns with length scales much larger than the atomic distance between carbon atoms in individual layers. It is often believed that most of the crucial physical properties occur at the moiré length scale. Thus a natural first step towards treating correlations is to construct a tight-binding model based on Wannier functions localized on the effective moiré lattice. However, the construction of such a model for twisted bilayer graphene is under debate due to the topological character of the energy bands. We discuss the accuracy of such Wannier descriptions for the widely-used Bistritzer and MacDonald model for a range of twist-angles and values of relaxations. Our study provides a starting point for investigating interaction effects in MATBG.

A stabilisation mechanism for many body localisation in 2D

Darryl Foo

Centre for Advanced 2D Materials, National University of Singapore

Experiments in cold atom systems see identical signatures of many body localisation (MBL) in both one-dimensional (d=1) and two-dimensional (d=2) systems despite the thermal avalanche hypothesis showing that the MBL phase is unstable for d>1. Underpinning the thermal avalanche argument is the assumption of exponential localisation of local integrals of motion (LIOMs), a result taken from the Furstenberg theorem. In this work we show that the Furstenberg theorem assumptions break down for real experimental systems, resulting in super-exponential localisation of LIOMs. A more careful analysis of the quantum avalanche argument for such realistic systems shows that the critical dimension changes from d=1 to d=2, thereby bridging the divide between the experimental demonstrations of MBL in these systems and existing theoretical arguments that claim that such demonstrations are impossible.

Single-boson exchange fRG application to the two-dimensional Hubbard model at weak coupling

Kilian Fraboulet

University of Tübingen

We illustrate the computational advantages of the recently introduced single-boson exchange (SBE) formulation for the one-loop functional renormalization group (fRG) applied to the two-dimensional Hubbard model. We present a detailed analysis of the screened interactions and Yukawa couplings and their evolution with temperature and interaction strength, both at half filling and finite doping. We find that the rest functions describing the corrections beyond the SBE contributions play a negligible role in the weak coupling regime, except for the vicinity of a pseudo-critical transition. However, even in this situation the impact on the resulting self-energy and physical susceptibilities is of marginal importance. The SBE formulation of the one-loop flow hence allows for a substantial reduction of the numerical effort in the treatment of the two-particle vertex function, paving a promising route for future multiboson and multiloop extensions.

Heavy-fermion quantum criticality via two-stage screening

Andreas Gleis

Ludwig-Maximilians Universität, Munich

Heavy-fermion systems [1] have triggered a tremendous amount of experimental and theoretical research since the discovery of quantum criticality and pronounced non-Fermi-liquid behavior in these materials more than two decades ago. The properties of these compounds are largely derived from localized f orbitals hybridized with broad conduction bands, resulting in a lattice of local moments coupled to an electronic bath via the Kondo interaction.

A vast number of these heavy-fermion compounds, examples including $YbRh_2Si_2$ [2], $CeCoIn_5$ [3] or $CeRhIn_5$ [4], show a so-called Kondo breakdown (KB) quantum critical point (QCP). Hallmarks of such a KB-QCP are a sudden reconstruction of the Fermi-surface when crossing the QCP at zero temperature and strange metallic behavior at finite temperatures close to the QCP, featuring a linear in temperature resistivity, a log T dependence of the Sommerfeld coefficient and ω/T scaling of various dynamical susceptibilities.

I present a model study of a KB-QCP in the periodic Anderson model using two-site Cellular Dynamical Mean-field Theory [5,6] using the Numerical Renormalization Group [7] to solve the self-consistent impurity model. We show that the low temperature phases on both sides of the QCP are Fermi-liquids, which differ in their Fermi-surface volumes. Close to the QCP, these Fermi-liquid fixed points are reached via a two-stage screening process, leading to non-Fermi-liquid behavior at intermediate temperatures. Evidence for a linear in temperature resistivity beyond self-energy effects and a log T dependence of the Sommerfeld coefficient in the non-Fermi-liquid are provided. Special emphasis is put on ω/T scaling of the optical conductivity, where we find good qualitative agreement with recent results on $YbRh_2Si_2$ [8].

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Renormalization-group theory of localization for 1D quasiperiodic lattice models

Miguel Gonçalves

CeFEMA, Instituto Superior Técnico, Universidade de Lisboa

Building on the results in arxiv:2103.03895, we develop a renormalization group theory to understand the localization phase diagrams of 1D quasiperiodic lattice models, using commensurate approximants. We define renormalized couplings that measure the dependence of single-particle energies on phase twists/Bloch momenta and real-space shifts for increasing unit cell size.

We show that for widely different models, the phase twist (real-space shift) coupling becomes irrelevant in the localized (extended) phase as the unit cell size is increased: the original model flows to an effective model with no hopping (potential) term. At a critical point/phase, both couplings are relevant at any scale. We identify a special class of models for which the renormalized couplings may be computed analytically, which enables the exact analytical determination of the phase diagram. We also show that approximate analytical predictions can also be made if we add perturbations to such models respecting their original symmetries under shifting and twisting. To demonstrate the wide applicability of our description, we apply it to a number of known models and also to new models that we introduce.

We finally show preliminary results supporting the possibility to generalize this theory to describe ground-state localization phase diagrams of 1D interacting many-body systems. Our findings provide a deep and simple understanding of localization for generic 1D quasiperiodic systems; a way to fully characterize the localization phase diagram, including extended, localized and critical phases and the transitions between them; and clear insights on how to create models with analytically trackable phase diagrams.

Optical conductivity and Force-Force correlation function in the Hubbard model

Maxence Grandadam

Memorial University of Newfoundland

The computation of the frequency-dependent conductivity in interacting systems is still an open problem while being one of the most widely used experimental techniques. Even restricting the question to the zero-frequency limit, there remain unsolved questions such as the nature of the linear dependence of the dc resistivity in multiple strongly-correlated materials ranging from cuprates to magic-angle graphene [1].

The problem of computing the optical conductivity in systems with electron-electron interactions is made difficult due to the importance of vertex corrections [2] which include strong momentum and frequency dependence of scattering events and thus require additional care when evaluating the conductivity through numerical methods. One example of such vertex correction appears when performing a perturbative expansion for the current-current correlation in the Kubo formula for the conductivity.

We present here an alternative way of obtaining the current-current correlation function, and thus the optical conductivity, through the computation of the force-force correlation function [3]. These two quantities are linked but have different perturbative expansions with different convergence properties, especially regarding the analytical continuation parameter when performing the computation for real frequencies. Moreover, the lowest order term in the perturbative series for the force-force correlation function encompasses all terms up to second order, thus taking into account the first vertex correction of the current-current correlation function. We present here the computation of the force-force correlation function in the Hubbard model using the Algorithmic Matsubara Integration [4] technique. These results are compared to the corresponding current-current correlation and we discussed the optical conductivity obtained in both cases.

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Emergent bands induced by plasmon excitations in cuprate superconductors

Andrés Greco

Facultad de Ciencias Exactas, Ingeniería y Agrimensura Univ. Nacional de Rosario

The study of charge excitations in cuprate superconductors is an active topic in present days. Recent resonant inelastic x-ray scattering (RIXS) experiments detected low-energy plasmons in electron-doped (e-cuprates) and hole-doped (h-cuprates) cuprates. These plasmon excitations are, in leading order of a $1/N$ approximation, satisfactorily described in the context of the layered t-J model with long-range Coulomb interaction. On the basis of this model, and beyond the leading order in $1/N$, the role of plasmons in the electron self-energy and the spectral functions is discussed. As a salient feature, it was found an emergent band (a sharp side band) which was interpreted as the combined effect of correlations and plasmons. The possible role of these findings in ARPES experiments on h- and e-cuprates is also discussed.

Single boson exchange implementation of the multiloop functional renormalization group for the 2D Hubbard model

Sarah Heinzelmann

University of Tübingen

We present a multiloop implementation of the functional renormalization group (fRG) based on the single boson exchange (SBE) decomposition applied to the two dimensional Hubbard model.

In the SBE diagrams of the two particle vertex are classified accoring to their reducibility in the bare interaction compared to the two-particle reducibility of the widely-used parquet decomposition. This allows for a substantial reduction of numerical effort by isolating divergences in the screened interactions and reducing the importance of the most cost intensive element, the rest function, to such a degree that it may be neglected in many cases.

In the multiloop fRG the Parquet approximation is recovered through an iterative procedure. We analyze the Yukawa couplings and screened interactions and rest functions with increasing loop order and the influence the rest function has on observables such as the self energy and susceptibilities.

Topology in magnetic phases of SmB_6

Moritz Hirschmann

MPI for Solid State Research, Stuttgart

SmB_6 is a mixed valence compound and a well known candidate material for topological Kondo insulators. With the application of pressure the valence of Sm atoms increases and as a consequence antiferromagnetism emerges in experiments.

We have constructed a tight-binding model to describe the system after the spin exciton mode has condensed into one out of two possible antiferromagnetic orders: A-type and G-type. Interestingly, the magnetic orders lead to different topological properties. The A-type state exhibits nodal lines and gapped Dirac surface states, whereas the G-type state retains Dirac surface states, although time-reversal symmetry that protects them in the paramagnetic phase is broken. To distinguish the magnetic phases and to characterize the topological properties we study all band crossings, propose suitable crystalline topological invariants, and calculate the resulting surface states. Furthermore, we also consider the band topology in the high-field limit with a ferromagnetic order.

Many body wavefunctions of hole-doped nickelate and cuprate superconductors

Vamshi Katukuri

MPI for Solid State Research, Stuttgart

The discovery of superconductivity in hole-doped infinite-layer $NdNiO_2$ — a transition metal oxide that is both isostructural and isoelectronic to cuprate superconductors — has lead to renewed enthusiasm in the hope of understanding the origin of unconventional superconductivity. In this talk, we present the many body wavefunction analysis of electron-removal (which mimics hole-doping) states in infinite-layered $NdNiO_2$ and $CaCuO_2$ obtained from the state-of-the-art many-body multireference quantum chemistry calculations. We find that the hole-doped ground state of $NdNiO_2$ is very different from the isostructural cuprate analog $CaCuO_2$ [1], although the ground states of the parent undoped compounds are for the most part identical [2]. The doped hole in $NdNiO_2$ is mainly localized on the Ni $3d_{x^2-y^2}$ orbital to form a closed-shell singlet, and this singlet configuration contributes to ~40% of the wavefunction. In contrast, in $CaCuO_2$ the Zhang-Rice singlet configurations contribute to ~65% of the wavefunction. The dynamic radial-type correlations within the Ni *d*-manifold are significantly stronger in $NdNiO_2$ compared to the cuprate, as a result, the multiplet effects become crucial. Further, the additional hole foot-print is more three dimensional in $NdNiO_2$. We conclude that the most commonly used three-band Hubbard model employed to express the doped scenario in cuprates represents ~90% of the wavefunction for $CaCuO_2$, but such a model grossly approximates the wavefunction for $NdNiO_2$ as it only stands for ~60% of the wavefunction.

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Magnetism and Mottness in the unfrustrated triangular lattice Hubbard model: a cellular dynamical mean-field study

Marcel Klett

MPI for Solid State Research, Stuttgart

We investigate the phase diagram of the unfrustrated triangular lattice Hubbard model in a center-focused cellular dynamical mean-field theory (CDMFT) approach using impurity clusters of 4, 7 and 19 sites. We investigate the Mott metal-to-insulator transition and crossover region in terms of these cluster sizes. Using a magnetic symmetry-broken approach of the CDMFT, allowing for a rotations of spins on the Bloch sphere, we are able to investigate the magnetic ordering of the different cluster schemes.

The role of non-local correlations in the triangular lattice Hubbard model

Mário Malcolms de Oliveira

MPI for Solid State Research, Stuttgart

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].

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Spinon induced drag in quantum spin liquid heterostructures

Raffaele Mazzilli

MPI for Solid State Research, Stuttgart

Several quantum spin liquid candidate materials, such as αgRuCl3 and 1T-$TaSe_2$, are exfoliable, so that it is possible to investigate 2D samples which avoid the manifestation of bulk properties that might disrupt the quantum spin liquid phase. In this phase the material is a Mott insulator impenetrable to direct electric probes such as charge currents.

Despite this, we propose an experimental setup that will allow to use non-local electrical probes to gain information on the transport properties of gapless quantum spin liquids. The proposed setup is a spinon induced drag experiment, that consists in interfacing two metallic films separated by a layer of quantum spin liquid. A current is injected in one of the two layers (active layer) and a voltage is measured on the second (passive) metallic film. The electrons of both layers interact with the spinons via Kondo interaction, thus allowing momentum transfer from the active to the passive layer. We calculate, both for a U(1) and a Z_2 spin liquids, the drag resistivity in the framework of the linearized quantum Boltzmann equation derived from the Keldysh formalism. In this framework the three layers are out of thermodynamic equilibrium. We further confront the results obtained with the equilibrium case and with the results of standard Coulomb drag.

The Mott metal-insulator transition in the two-dimensional Hubbard model - a cellular dynamical mean-field study on large clusters

Michael Meixner

MPI for Solid State Research, Stuttgart

We study the half-filled two-dimensional Hubbard model on a square lattice in cellular dynamical mean-field theory (CDMFT), a real-space cluster extension [1] of the dynamical mean-field theory. By increasing the number of cluster sites up to 6x6 we observe a progressive reduction of the onset interaction U* of a metal-insulator crossover. In particular, in the case of 4x4 sites, we observe a site-dependent U, which is lower at the center sites than at the corner sites. In addition to this real-space analysis we investigate different periodization schemes for the one-particle spectral function and argue that a center-focused [2] cumulant scheme is well-suited in the intermediate coupling regime of U due to its locality.

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Bogoliubov Fermi surfaces stabilized by spin-orbit coupling

Henri Menke

Friedrich-Alexander-Universität Erlangen-Nürnberg

The presence of multiple bands qualitatively changes the nodal structure of an inversion-symmetric time-reversal symmetry-breaking superconductor. Instead of point or line nodes, the gap exhibits extended nodal pockets, called Bogoliubov Fermi surfaces [1-4]. These surfaces originate from the "inflation" of point and line nodes in the absence of time-reversal symmetry breaking. In this work we study a paradigmatic model for Bogoliubov-Fermi surfaces, the Luttinger-Kohn Hamiltonian of spin $j = 3/2$ fermions for the cubic point group, and investigate the thermodynamic stability of a time-reversal symmetry-breaking superconducting state with Bogoliubov-Fermi surfaces compared to a time-reversal symmetry-preserving one without as a function of the multiband character of the electronic band structure. We formulate a mean-field theory and minimize the free energy to find the self-consistent superconducting gap as a function of band parameters. The multiband nature gives rise to a rich phase diagram. We also study some basic spectroscopic properties and the influence of cubic anisotropy.

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Quantifying Entanglement in Heisenberg Spin Chains

Pouria Mirsadegh

Memorial University of Newfoundland

In this work we probe and contrast different measures of entanglement for quantum systems, the most well-known of which is the von Neumann entropy. The entropy, however, is only a good measure of entanglement when a system is in a pure state. For mixed states other measures exist such as the concurrence, the Entanglement of Formation, and Negativity. We choose to study a model Hamiltonian representing a Heisenberg spin chain in a magnetic field which provides a testbed for studying the fundamentals of entanglement.

Using QuTiP, a library for quantum computations and simulations in python, we can generate the Hamiltonian and density matrix and eventually calculate the concurrence as the primary measure of the degree of the entanglement between pairs of spins. We probe the concurrence for variations in a magnetic field, temperature, coupling constants as well as system size and boundary properties.

Quantum metric, resistivity bound, and flat bands - Electrical conductivity in multiband systems

Johannes Mitscherling

MPI for Solid State Research, Stuttgart

Geometric concepts provide a very fruitful language for quantum (interband) contributions to the dc electrical conductivity of multiband systems. A well-known example is the intrinsic anomalous Hall conductivity, which is based on the Berry curvature. The quantum metric is a second central quantity of band theory but has so far not been related to many response coefficients due to its nonclassical origin. In this talk, I show that the electrical conductivity yields an interband contribution based on the quantum metric. I discuss the implications of this observation in several examples, which range from spiral magnetism in the context of cuprate superconductors to flat-band models. In the former case, the interband contribution due to the quantum metric is crucial for a consistent theoretical description of the Hall number close to the onset of order. In the latter case, interband effects due to the quantum metric can be significantly enhanced and even dominate the conductivity. This is true in particular for topological flat-band materials with nonzero Chern number, where an upper bound exists for the resistivity due to the common geometrical origin of the quantum metric and the Berry curvature. I close by proposing a conductivity minimum due to the quantum metric in low-mobility rhombohedral trilayer graphene.

Superconducting collective Leggett modes in single-layer 1H-$NbSe_2$

Daniel Muñoz-Segovia

Donostia International Physics Center

While bulk 2H-$NbSe_2$ is generally accepted to be a conventional superconductor, several unconventional features of the superconducting state have been reported in the monolayer limit, including the breaking of threefold symmetry in magnetotransport [1,2] and anomalously large in-plane critical fields [3]. In this work, I will first present another unconventional feature measured by our collaborators [4]: the existence of satellite peaks in the STM spectra of 1H-$NbSe_2$ monolayers which exist only in the superconducting state and show a clear anticorrelation with the superconducting gap. After briefly discussing other potential candidate explanations, I will propose a scenario of compet- ing pairing between s-wave and subleading f-wave triplet channels that leads to a superconducting Leggett collective mode. In particular, I will present a calculation of the Leggett mode energy using a simplified continuum model for $NbSe_2$, and show that this particle-particle collective mode gives rise to resonances in the tunneling spectrum. I will discuss how our model compares with the experimental data, discuss the origin of the anticorrelation, and argue that it provides support to the competing pairing scenario, with a sizable attraction in the subleading triplet channel.

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SU(4) symmetry in Dirac materials - Application to twisted bilayer graphene

Nikolaos Parthenios

MPI for Solid State Research, Stuttgart

A multitude of novel phases have been proposed for twisted bilayer graphene (TBG) at charge neutrality such as a nematic insulator which breaks C3 lattice symmetry or as inter-valley coherent order (IVC) which breaks U(1) valley symmetry. We show that the Dirac fermion model of TBG is invariant under an SU(4) group composed of combined spin, valley and sublattice transformations. We determine all symmetry-allowed four-fermion interactions and employ a renormalization group treatment to derive the flow equations for each of the six allowed couplings. We identify the critical points that describe transitions into the different ordered phases and discuss the corresponding critical behavior of the system.

Multiloop pseudofermion functional renormalization for quantum spin systems: Application to the spin-1/2 kagome Heisenberg model

Marc Ritter

Ludwig-Maximilians-Universität, Munich

We present a multiloop pseudofermion functional renormalization group (pffRG) approach to quantum spin systems and its application to the spin-1/2 Heisenberg model on the kagome lattice. At pure nearest-neighbor coupling, the system shows indications for an algebraic spin liquid through slower-than-exponential decay with distance for the static spin susceptibility, while the pseudofermion self-energy develops a pronounced low-energy power law. Methodologically, the pseudofermion representation of spin models inherently yields a strongly interacting system, and the quantitative reliability of a truncated fRG flow is a priori unclear. We demonstrate convergence in loop order, which provides further evidence for the internal consistency of the approach through correspondence with the self-consistent parquet equations. In the spin-liquid phase, the multiloop flow remains stable as the infrared cutoff Λ is reduced down to below 1% of the microscopic exchange interaction J. We also scrutinize the pseudofermion constraint of single occupation per site, which is only fulfilled on average in pffRG. Although fluctuations in the occupation number are not entirely suppressed, we find that they do not affect the qualitative conclusions drawn from the spin susceptibility.

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Quantum criticality on a compressible lattice

Saheli Sarkar

Karlsruhe Institute of Technology

As an example of quantum criticality on a compressible lattice we study the Lorentz invariant φ^4 theory with an N-component field φ, where strain couples to the square of the order parameter. In three spatial dimensions this coupling as well as the self-interaction of the φ field are both marginal on the tree-level. We compute the one-loop renormalization group equations treating the φ field as well as the phonons on the same footing. We find that the velocities of the φ field as well as of the phonons are renormalized yielding an effective dynamical exponent $z > 1$. The renormalization group flow is found to depend on the number of components N. Whereas we find run-away flow for $N < 4$ a new fixed-point emerges for $N >= 4$. We discuss the relation to known results for classical criticality. Our findings are directly relevant to insulating quantum critical antiferromagnets.

Spins, pseudo-Majoranas and the functional RG

Björn Sbierski

Ludwig-Maximilians-Universität, Munich

Frustrated three-dimensional quantum magnets bear a rich phenomenology but are notoriously hard to treat theoretically. We show how a SO(3) Majorana representation of spin operators, in combination with the functional renormalization group allows for quantitative simulations at finite temperatures. Focusing on Heisenberg magnets, we establish a finite-size scaling approach and extract critical temperatures and -exponents. For the Pyrochlore lattice, we discuss the improvements introduced by two-loop contributions in the flow equations. We also extend the formalism towards the Kitaev spin representation which is instrumental for the simulation of Rydberg atom arrays.

Zero-field superconducting diode effect in twisted trilayer graphene

Mathias Scheurer

University of Innsbruck

The semiconducting diode, which is characterized by a highly asymmetric current-voltage relation, is central to modern-day electronics. In the last few years, its superconducting analogue – a system that behaves like a superconductor for current flow in one direction but exhibits finite resistance when the current direction is reversed – has attracted attention in the physics community, due to its potential for future quantum-electronics applications. So far, this behavior has only been realized in the presence of a magnetic field, magnetic junction or magnetic proximity, and is typically rather weak in the sense that it exhibits the superconducting diode effect only for a small range of applied current.
In this talk, I will present experimental evidence and a microscopic theory for a strong superconducting diode effect at zero external magnetic in twisted trilayer graphene [1-3]. After a brief introduction to the rich physics of twisted trilayer graphene close to the magic angle, I will discuss why this is a natural system to realize this exotic superconducting behavior as an intrinsic property and illustrate the intricate underlying microscopic physics.

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Investigations of Instanton Crystal Phase

Grigorii Starkov

Ruhr-Universität Bochum

Instanton Crystal is a fascinating phase which is encountered when the minimum of the free energy corresponds to a configuration with an imaginary-time-dependent order parameter in the form of a chain of alternating instantons and anti-instantons. An important feature of this phase is that the average of the order parameter over the imaginary time vanishes [1].

We propose a model that hosts the Instanton Crystal phase. The stability of the phase is proved both numerically and analytically in the certain region of parameters [1].

After that, we present the results of the investigation of the real-time correlation functions of the order parameter in the Instanton Crystal Phase [2]. In order to obtain the correlation functions in real-time, we formulate an original method of analytic continuation from imaginary times, which is easily adapted into an efficient numerical scheme for the computations. The resulting correlation functions exhibit non-trivial oscillations in real-time.

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The generalized DMFT susceptibility from linear response

Patrick Thunström

Uppsala University

The generalized Dynamical Mean Field Theory (DMFT) susceptibility is (formally) derived from the response of the physical system to a small perturbation of the lattice Hamiltonian. The perturbation couples the lattice to an external environment, which allows for the transfer of both momentum and energy. In this setting, the eigenvectors of the generalized susceptibility can be interpreted as a basis in which the perturbations can be expressed. Since the presented construction follows the standard DMFT self-consistency cycle, it is also possible to study the impact of technical approximations, such as the discretization of the hybridization function.

Curved FLRW universes in Bose-Einstein condensates

Mireia Tolosa-Simeón

University of Cologne

Analog models provide another point of view to approach problems. They play a very important role in physics and mathematics, since they allow us to study and observe phenomena that are not directly accessible. In this talk, we will address the problem of cosmological particle production in curved and expanding universes, specifically, in expanding Friedmann-Lemaître-Robertson-Walker (FLRW) cosmologies, using such analogies. It is common, although not strictly necessary, to use condensed matter systems to obtain information on these phenomena, since they can be realized experimentally and are well-controlled systems. In this case, we choose Bose-Einstein condensates (BECs) to mimic their dynamical aspects. In particular, we study low-momentum excitations of BECs (phonons), which have a linear dispersion relation as massless relativistic particles. Their dynamics is described by an acoustic metric and we investigate the mapping between this metric and that of a spatially curved FLRW universe. In essence, we show that cosmological particle production and many other quantum phenomena can be studied by simulating them in a condensate and can be confirmed experimentally.

How to get U? On the applicability of the constrained Random Phase Approximation

Erik van Loon

Lund University

Electronic correlations are often discussed in terms of effective low-energy models, with the Hubbard model as the most prominent example. To simulate real materials, the Coulomb interaction U needs to be determined, taking into account the screening by high-energy electronic states. The constrained Random Phase Approximation (cRPA) is frequently used for this purpose, but its applicability has been questioned. Here I show that cRPA approximation can be justified when the electronic states responsible for the screening are energetically far away from the Fermi level. In that case, the electronic propagation length is exponentially short and provides a way to identify leading diagrams, similar to the analysis in diagrammatic extensions of dynamical mean-field theory. Nonlocal corrections to cRPA vanish. Local (excitonic) vertex corrections to cRPA exist, but are compensated by the underestimation of the band gap in density functional theory.

Antiferromagnetic and pairing critical temperatures in the 2D Hubbard model

Demetrio Vilardi

MPI for Solid State Research, Stuttgart

We analyse the competition of antiferromagnetism and superconductivity in the two -dimensional Hubbard model at moderate coupling. By using the functional renormalization group in its fully dynamical implementation, we compute the flow of the vertex function and of the magnetic and superconducting order parameters. In spite of strong frequency dependences of the effective interactions and the pairing gap, we confirm important physical results from previous static functional renormalization group calculations. The magnetic critical temperature is interpreted as the onset of pseudogap behavior. Computing the Kosterlitz-Thouless temperature from the superfluid phase stiffness, we obtain a superconducting dome in the Temperature-doping phase diagram centered around 15 percent hole doping.

Pushing the envelope: sparse modelling of two-particle diagrammatics

Markus Wallerberger

TU Wien

Propagators and associated diagrammatic equations are the bedrock upon which a large portion of qunatum many-body theory is built. For one-particle physics, the imaginary-time axis combined with recently developed, maximally compact intermediate representation (IR) allows fast and stable computations. However, in capturing fluctuations and phase transitions, the two-particle propagator takes center stage. It not only encodes more information, but due to the Pauli principle, it is non-trivial to store compactly.

With the recent advent of the overcomplete IR for two-particle quantities and the associated sparse frequency grid for the storage, we are now frequently able to compress the complete three-frequency dependence of two-particle quantities into less than one megabyte of data. In this contribution, we show that sparse time IR grids can also be used to reduce the computational effort of exact diagonalization. We also show that data from numerical renormalization group calculations can similarly be compressed.

Diagrammatic equations at the two-particle level are particularly challenging, as they involve convolutions, which converge slowly. We recently extended the IR approach to we construct small convolution grids that allow for exponentially converging solutions to the Bethe-Salpeter equation.

SU(2)-symmetric spin-boson model: Quantum criticality, fixed-point annihilation, and duality

Manuel Weber

MPI for the Physics of Complex Systems, Dresden

Dissipative quantum impurity models represent conceptually simple yet non-trivial settings for quantum criticality. Here we consider the SU(2)-symmetric spin-boson (or Bose-Kondo) model with a power-law bath spectrum $\alpha\, \omega^s$, relevant to diverse problems such as cavity quantum electrodynamics, magnetic moments in quantum critical magnets, and Kondo-breakdown transitions in heavy-fermion metals. Using a recently developed wormhole quantum Monte Carlo method, we present high-accuracy results for the phase diagram and find, in addition to a critical phase predicted by perturbative renormalization group (RG), a stable strong-coupling phase present for all values of $0 < s < 1$. The critical phase ceases to exist for $s < s^* = 0.6540(2)$, rendering the perturbative prediction invalid. We provide direct numerical evidence for the collision and annihilation of two intermediate-coupling RG fixed points at s^* responsible for that – a scenario that is of interest in diverse fields from statistical mechanics to high-energy physics. We uncover a surprising dual- ity between the two fixed points, corresponding to a reflection symmetry of the RG beta function. We then utilize this duality to make analytical predictions for critical properties at strong coupling which are in excellent agreement with the numerical results. We comment on the consequences for impurity moments in critical magnets.

Bus shedule

Max Planck Institutes → University

Mon. – Fr. 2022

5	27
6	0, 25, 35, 43, 46, 53
7	0, 5, 16, 23, 25, 35, 46
8	0, 5, 6, 15, 23, 25, 35, 46, 46, 54
9	0, 15, 23, 25, 35, 46
10	46, 46
11	30, 35, 46
12	25, 35, 46
13	25, 30, 35, 46
14	35, 46
15	25, 35, 46, 53
16	16, 23, 35, 40, 46, 53
17	16, 23, 35, 40, 46, 53
18	5, 16, 23, 35, 40, 46, 53
19	16, 46
20	16
21	

Linie 84 | 91 | 92 | X74 | 747 | 748

University → Max Planck Institutes

Mon. – Fr. 2022

5	24, 38
6	8, 13, 21, 31, 38, 43
7	8, 12, 20, 21, 31, 38, 42, 50, 55
8	8, 12, 21, 31, 38, 42, 50
9	8, 12, 21, 31, 42
10	21, 38
11	21, 38, 50
12	21, 31, 38, 50
13	21, 31, 38, 50
14	21, 31, 38, 50
15	8, 12, 21, 25, 38, 42, 46, 50
16	8, 12, 20, 21, 23, 38, 42, 46, 50
17	8, 12, 21, 23, 38, 42, 46, 50
18	8, 12, 21, 23, 38, 42, 46, 50
19	8, 21, 23, 38
20	
21	

Linie 84 | 91 | 92 | X74 | 747 | 748

Max Planck Institutes → Vaihingen ZOB 2022

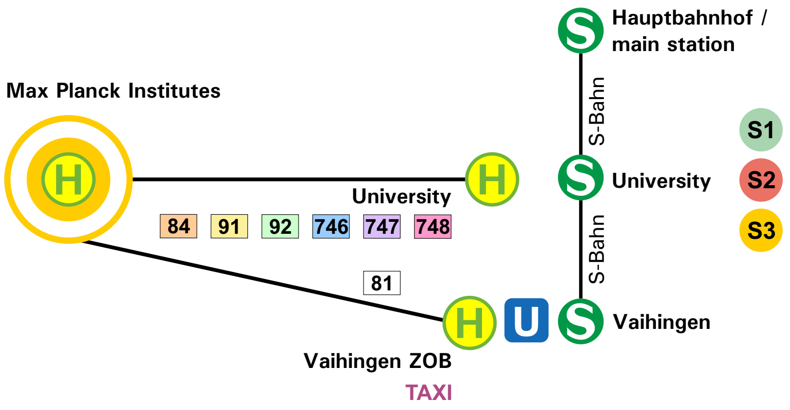
4	29	59	Mon. – Fr.					
5	14	29	44	59				
6	14	25	35	45	55			
7	05	10	15	20	25	35	45	55
8	05	15	25	35	45	55		
9	05	every 10 Min.				55		
10	05					55		
11	05					55		
12	05					55		
13	05					55		
14	05					55		
15	05					55		
16	05					55		
17	05					55		
18	05	15	25	35	45	55		
19	05	15	30	45	55			
20	12	27	42	57				
21	12	27	52					
22	22	52						
23	22	52						
0	22	52						

Linie 81

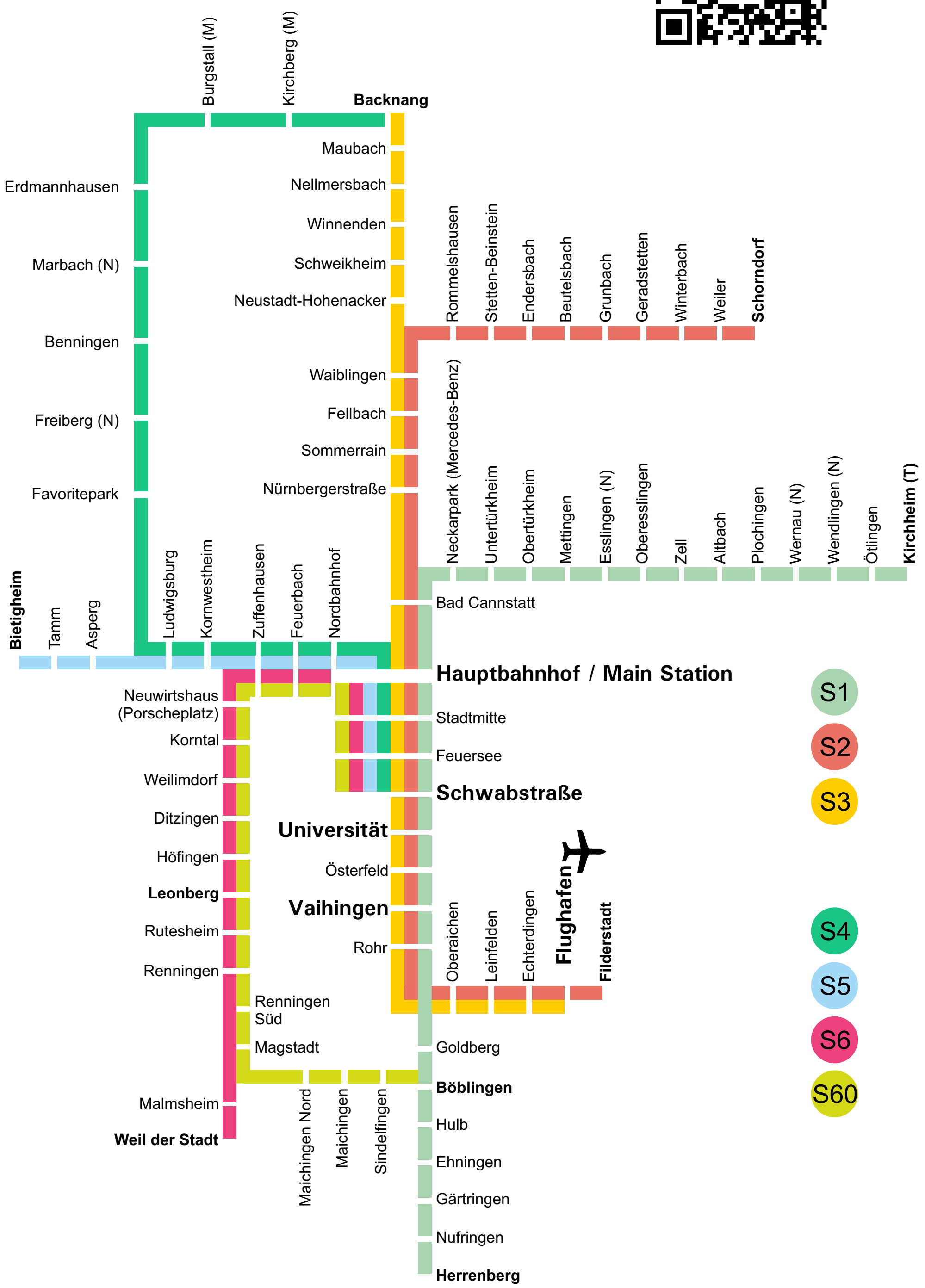
Vaihingen ZOB → Max Planck Institutes 2022

4	38	53	Mon. – Fr.				
5	08	23	38	53			
6	08	24	39	49	59		
7	09	19	29	39	49	59	
8	09	every 10 Min.				59	
9	09					59	
10	09					59	
11	09					59	
12	09					59	
13	09					59	
14	09					59	
15	09					59	
16	09					59	
17	09					59	
18	09	19	29	39	49	59	
19	09	19	29	39	52		
20	07	22	37	52			
21	07	24	52				
22	23	53					
23	23	53					
0	23	53					

Linie 81



S-Bahn Map



1

Motel One Stuttgart-Mitte

Lautenschlagerstraße 14
70173 Stuttgart
Phone: +49/711/300 209 0
stuttgart-mitte@motel-one.com

Bus Nr. 84, 91, 92, 746, 747, 748 to University or Bus 81 to Vaihingen ZOB than take S1 (direction Kirchheim/Teck), S2 (direction Schorndorf) or S3 (direction Backnang)

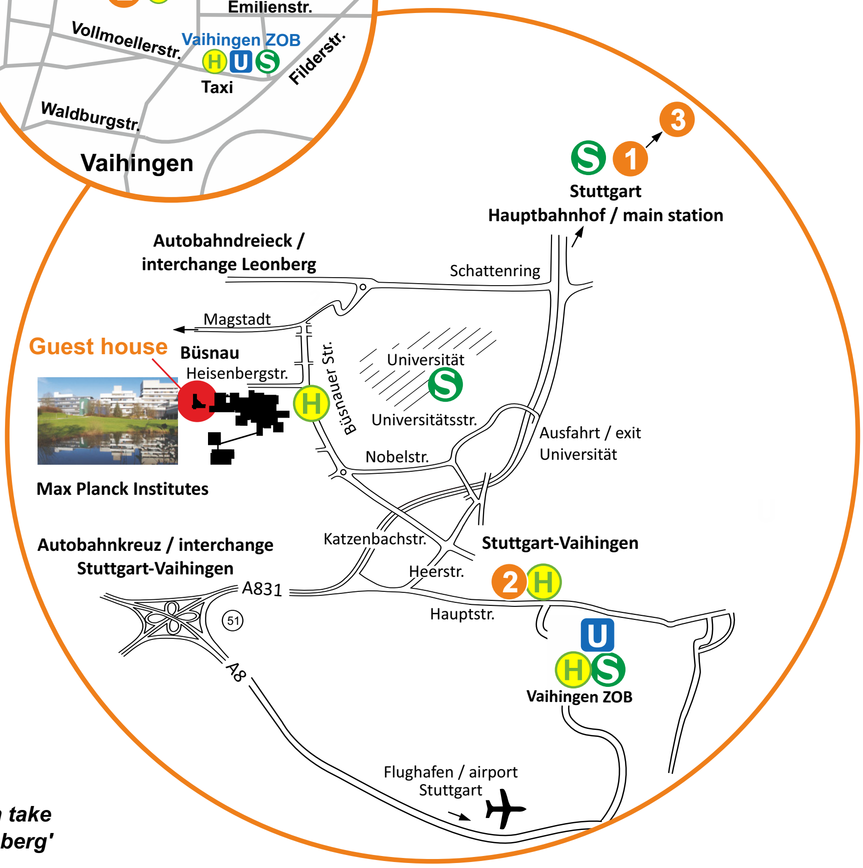
2

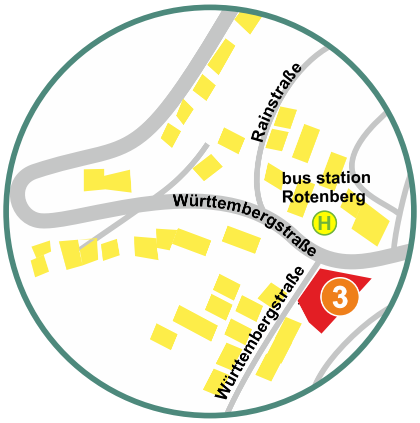
Vienna House Easy MO.

Hauptstraße 26
70563 Stuttgart
Phone: +49/711/280 560
info.easy-stuttgart@viennahouse.com

Bus Nr. 81

Hotels & Restaurants





3

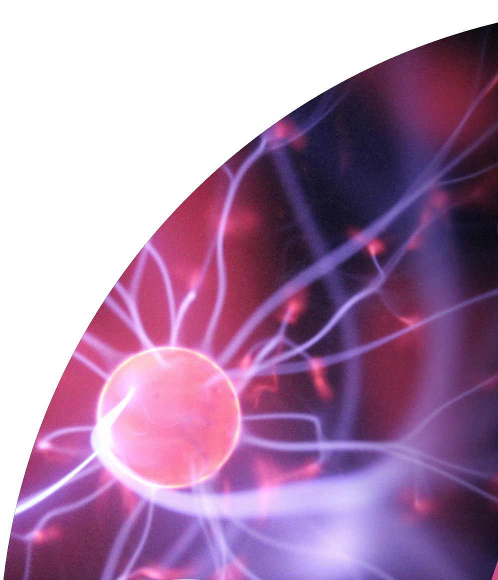
Rotenberger Weingärtle

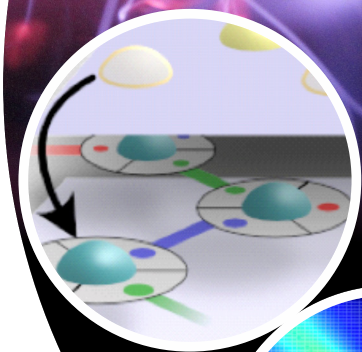
Württembergstraße 317
70327 Stuttgart
Phone: +49/711/334 015

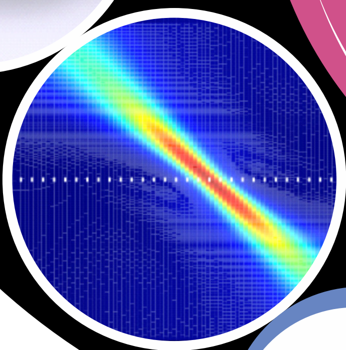
S-Bahn to Untertürkheim than take Bus Nr. 61, bus station 'Rotenberg'

Restaurants

Near MPI Büsnau:	Trattoria **Da Franco** (Italian) Adolf-Engster-Weg 10, 70569 Stuttgart, ✆ +49/711/681 704 **Katzenbacher Hof** (large beer garden), Katzenbacher Hof 1, 70569 Stuttgart
Near S-Bahn Schwabstraße:	Ristorante **Goldoni** (Italian), Reinsburgstraße 151, 70197 Stuttgart, ✆ +49/711/659 988 9 **Italo Disco** (Italian), Augustenstraße 70, 70178 Stuttgart, ✆ +49/711/414 927 91 **TAVERNA** (Greek), Reinsburgstraße 102, 70197 Stuttgart, ✆ +49/711/504 818 88 **Taverna Yol** (Turkish), Spittastraße 2, 70193 Stuttgart, ✆ +49/711/636 325 6
Near S-Bahn Feuersee:	**Trollinger** (large beer garden), Rotebühlstraße 50, 70178 Stuttgart, ✆ +49/711/621 441
Downtown:	**Carls Brauhaus**, Schlossplatz, Stuttgart Mitte, ✆ +49/711/259 746 11 **KICHO** (Japanese), Jakobstraße 19, 70182 Stuttgart, ✆ +49/711/247 687 **Ochs'n Willi**, Kleiner Schlossplatz / am Königsbau, Stuttgart Mitte, ✆ +49/711/226 519 1 **Tschechen & Söhne** (large beer garden), Humboldtstraße 44, 70178 Stuttgart **Markthalle:** Near the Königsbau, direction Rathaus, you 'll find the Market Hall, Dorotheenstraße 4, one of the most beautiful market halls in Germany. Built 1912 – 1924, renovated in 1993. Restaurant **Marktstüble** provides typical German specialities, there is also an Italien restaurant inside, **the Empore** and a **Tapas Bar**. Near the Market Hall direction to the Rathaus, you will find a lot of good small restaurants.



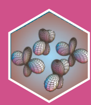




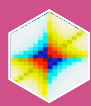
Organizing Committee

Max Planck Institute for Solid State Research

Elio J. König
E.Koenig@fkf.mpg.de



Thomas Schäfer
T.Schaefer@fkf.mpg.de



CNQM2022@fkf.mpg.de

ICAM-I2CAM
Institute for Complex Adaptive Matter

MAX PLANCK INSTITUTE FOR
SOLID STATE RESEARCH

Heisenbergstraße 1
70569 Stuttgart, Germany

www.fkf.mpg.de