Online Workshop on Zoom, 23-25 May 2022

Zoom Links: Day 1, Day 2, Day 3

Strange metals: from the Hubbard model to AdS/CFT

Hosted by:
Institute of Physics Belgrade (IPB), Serbia
Key2SM project, funded by the *Science fund of the Republic of Serbia*

Organizers:

Dr Jakša Vučičević, Associate Research Professor (IPB)
Dr Mihailo Čubrović, Assistant Research Professor (IPB)

We aim to bring together the top experts approaching the same outstanding physical problem in two greatly different ways. The main subject will be the strange metallic behavior, as viewed from the perspective of the holographic theories and the microscopic theories based on interacting lattice models. Particular focus will be given to the direct comparison between the two general approaches. The workshop will also cover the specific realizations of the ubiquitous strange metal regime: in the cuprates and other strongly correlated materials, moire systems and cold atom simulators. The goal of the workshop is to provide a wider perspective on the theoretical work focusing on the strange metals, a better overview of the established phenomenology, and a connection of the strange metal to other phenomena in strongly correlated electronic systems.

Speakers:

Antoine Georges	Wéi Wú	Jie Ren
Michel Ferrero	Jake Ayres	Richard Davison
Waseem Bakr	Jan Zaanen	Aristomenis Donos
Rok Žitko	Koenraad Schalm	Mark Golden
Darko Tanasković	Blaise Goutéraux	Mihailo Čubrović
Thomas Schäfer	Alexander Krikun	

Schedule:

GMT+01 (Belgrade)	Day 1 (23/05/2022)	Day 2 (24/05/2022)	Day 3 (25/05/2022)
14h			
	14:45-15:00 | Intro by the organizers		
15h	15:00-15:45 | Antoine Georges	15:15-15:45 | Waseem Bakr	
	15:45-16:15 | Wéi Wú	15:45-16:15 | Michel Ferrero	15:45-16:15 | Rok Žitko
16h	16:15-16:45 | Thomas Schäfer	16:15-16:45 | Darko Tanasković	16:15-16:45 | Jake Ayres
	16:45-17:15 | Break, general discussion	16:45-17:15 | Break, general discussion	16:45-17:15 | Break, general discussion
17h	17:15-18:00 | Jan Zaanen	17:15-18:00 | Blaise Goutéraux	17:15-18:00 | Koenraad Schalm
18h	18:00-18:45 | Mark Golden	18:00-18:30 | Richard Davison	18:00-18:30 | Jie Ren
	18:45-19:15 | Mihailo Čubrović	18:30-19:00 | Aristomenis Donos	18:30-19:00 | Alexander Krikun
19h	19:15-19:45 | General discussion	19:00-19:30 | General discussion	19:00-19:30 | Break, general discussion
			19:30-19:45 | Outro by the organizers

Full program:

Day 1

15:00-15:45

Antoine Georges

CCQ, Flatiron Institute, New York, USA & Collège de France, Paris, France

Doped SYK Models, Quantum Criticality and Strange Metal Behavior

15:45-16:15

Wéi Wú

Sun Yat-sen University, Guangzhou, China

Linear-in-temperature scattering rate in overdoped two dimensional Hubbard model

In this talk, we will discuss a recent numerical study on the overdoped Hubbard Model at low temperatures. We show that in the Hubbard model, the electron scattering rate γ(T) can display linear T- dependence as temperature T goes to zero. The T-dependent scattering rate is found in general isotropic on the Fermi surface, in agreement with recent experiments. We identify the antiferromagnetic fluctuations as the physical origin of the T-linear scattering rate in this system. Finally, we will also discuss briefly the T-linear electron scattering rate that shows up in the two dimensional periodic Anderson model.

16:15-16:45

Thomas Schäfer
Max-Planck-Institute for Solid State Research, Stuttgart, Germany

Multimethod, multimessenger approaches to models of strong correlations

The Hubbard model is the paradigmatic model for electronic correlations. In this talk I present a general framework for the reliable calculation of its properties, which we coined 'multi-method, multi-messenger' approach. I will illustrate the power of this approach with three recent studies: (i) an extensive synopsis of arguably all available finite-temperature methods for the half-filled Hubbard model on a simple square lattice in its weak-coupling regime [1] and (ii) a complementary subset of those applied to the Hubbard model on a triangular geometry [2]. While the former example fully clarifies the impact of spin fluctuations and tracks it footprints on the one- and two-particle level, the latter exhibits the intriguing interplay of geometric frustration (magnetism) and strong correlations (Mottness). As a last example (iii) I will show the application to a model system for the magnetic properties of an actual material, the infinite layer nickelate compound LaNiO2, whose magnetic susceptibility exhibits non-Curie-Weiss behavior at low temperatures [3,4]. These examples may work as a blueprint for similar future studies of strongly correlated systems.

[1] Thomas Schäfer, Nils Wentzell, Fedor Šimkovic IV, Yuan-Yao He, Cornelia Hille, Marcel Klett, Christian J. Eckhardt, Behnam Arzhang, Viktor Harkov, François-Marie Le Régent, Alfred Kirsch, Yan Wang, Aaram J. Kim, Evgeny Kozik, Evgeny A. Stepanov, Anna Kauch, Sabine Andergassen, Philipp Hansmann, Daniel Rohe, Yuri M. Vilk, James P. F. LeBlanc, Shiwei Zhang, A.-M. S. Tremblay, Michel Ferrero, Olivier Parcollet, and Antoine Georges, Phys. Rev. X 11, 011058 (2021).
[2] Alexander Wietek, Riccardo Rossi, Fedor Šimkovic IV, Marcel Klett, Philipp Hansmann, Michel Ferrero, E. Miles Stoudenmire, Thomas Schäfer, and Antoine Georges, Phys. Rev. X 11, 041013 (2021).
[3] R. A. Ortiz, P. Puphal, M. Klett, F. Hotz, R. K. Kremer, H. Trepka, M. Hemmida, H.-A. Krug von Nidda, M. Isobe, R. Khasanov, H. Luetkens, P. Hansmann, B. Keimer, T. Schäfer, and M. Hepting, arXiv:2111.13668 (2021), to be published in Phys. Rev. Research 2022.
[4] Marcel Klett, Philipp Hansmann, and Thomas Schäfer, Frontiers in Physics 10, 834682 (2022).

17:15-18:00

Jan Zaanen
Instituut-Lorentz for Theoretical Physics, Leiden University, Netherlands

Quantum supreme matter and the strange metals

Quantum supreme matter refers to forms of matter that are densely many-body entangled with the ramification that the quantum supremacy of the quantum computer is required to enumerate the way it works. Prime candidates are the strange metals, in particular those observed in cuprates. I will present the case that holography yields a mathematical view on generic properties of such states of matter. In particular, it gives away a generalization of the universality principle associated with strongly interacting "stoquastic" quantum critical states to the realms of finite density fermion matter. This revolves around a "covariant" renormalization group flow revealed by holography showing how the Fermi-liquid generalizes into a densely many-body entangled affair [1], revealing the finite temperature physics through a "first principle" treatment of quantum thermalization. Guided by these insights, substantial progress has been made in recognizing various of these traits in experiments on the strange metal states of the high Tc superconductors.

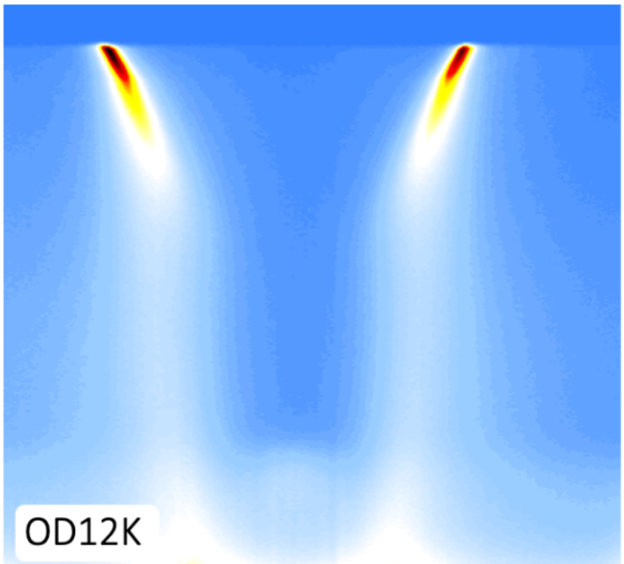
[1]. J. Zaanen, arXiv:2110.00961 (2021).

18:00-18:45

Mark Golden
Van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam, Netherlands

Momentum-dependent scaling exponents of cuprate strange metal self-energies: ARPES meets semiholography

ARPES enables the precise experimental determination of the electronic self-energy from data like these shown here from the cuprate $(Pb,Bi)_2 Sr_{2-x} La_x CuO_{6+\delta}$. Constant energy cuts through the spectral function have a non-Lorentzian lineshape, meaning the nodal self-energy is k dependent. This provides a new test for aspiring theories. We show that the experimental data are captured remarkably well by a power law with a k-dependent scaling exponent, smoothly evolving with doping, a description that emerges naturally from AdS/CFT-based semi-holography, putting a spotlight on holographic methods for the quantitative modelling of strongly interacting quantum materials like the cuprate strange metals.



See arXiv:2112.06576 .
This research was carried out by: S. Smit, E. Mauri, L. Bawden, F. Heringa, F. Gerritsen, E. van Heumen, Y. K. Huang, T. Kondo, T. Takeuchi, N. E. Hussey, T. K. Kim, C. Cacho, A. Krikun, K. Schalm, H.T.C. Stoof, M. S. Golden

18:45-19:15

Mihailo Čubrović
Institute of Physics Belgrade, Serbia

Spectral functions in holographic lattices and the Hubbard model

We compare the spectral functions of probe fermions on holographic square lattices to the Hubbard model spectra obtained from Quantum Monte Carlo CTINT simulations. We find that a minimal AdS setup which incorporates the Hubbard physics at the level of spectra consists of (1) inhomogenous bulk geometries with hyperscaling violation obtained by solving the Einstein-Maxwell-dilaton equations in the presence of the lattice (2) high-frequency dynamical cutoff which gives rise to sum rules (3) bulk dipole coupling which provides Mottness, a clear separation of the spectrum into IR (quasiparticle and Hubbard bands) and UV (exponentially decaying tails) scales. The fit of the holographic spectra to the Quantum Monte Carlo data is not strongly dependent on the specific choice of the bulk parameters as long as all the ingredients are present. We conclude that the key properties of spectral functions in the Hubbard model are not strongly dependent on microscopy, however they crucially depend on the presence of Motness, even in the Fermi liquid phase.

Day 2

15:15-15:45

Waseem Bakr
Princeton University, New Jersey, USA

Observation of strange metallicity in "hot" atomic Hubbard systems

The normal state of high-temperature superconductors exhibits anomalous transport and spectral properties that are poorly understood. Cold atoms in optical lattices have been used to realize the celebrated Fermi-Hubbard model, widely believed to capture the essential physics of these materials. The recent development of fermionic quantum gas microscopes has enabled studying the normal state of Hubbard systems with single-site resolution. I will start by introducing the atomic platform and reviewing experiments that have been done on measuring spin and density correlations. Next, I will describe the development of a technique to measure microscopic diffusion, and hence resistivity, in doped Mott insulators. We have found that this resistivity exhibits a linear dependence on temperature in an intermediate temperature regime, and it violates the Mott-Ioffe-Regel limit, two signatures of strange metallic behavior. I will compare our experimental results to state-of-the-art numerical techniques.

15:45-16:15

Michel Ferrero
École polytechnique, Paris, France & Collège de France, Paris, France

16:15-16:45

Darko Tanasković
Institute of Physics Belgrade, Serbia

Conductivity in the Hubbard model at high temperatures

Charge transport in doped Mott insulators typically features linear in temperature dc resistivity surpassing the Mott-Ioffe-Regel limit. We will briefly review these universal features of the charge transport from the perspective of Mott quantum criticality. In the second part of the talk we will focus on numerically exact solution of the Hubbard model on the square and triangular lattice. We will show that the vertex corrections to conductivity are substantial even though the correlations are nearly local at high temperatures. We will demonstrate that the finite-temperature Lanczos method on the 4x4 lattice gives close to exact result for conductivity in the strongly correlated regime at temperatures comparable or larger than the hopping parameter.

17:15-18:00

Blaise Goutéraux
École polytechnique, Paris, France

Charge transport in gapless, pinned charge density waves

In this talk, I wish to illustrate how holographic methods can contribute to condensed matter problems. I will do so by describing how holographic computations of transport in phases with pseudo-spontaneously broken translations predicted the existence of a new transport coefficient controlling the resistivity of gapless, pinned charge density waves. This prediction was recently confirmed by field theory calculations. I will comment on the possible relevance of this transport mechanism to high Tc superconductors, where charge density fluctuations are present across the phase diagram.

18:00-18:30

Richard Davison
Heriot-Watt University, Edinburgh, UK

Hydrodynamic diffusion and its breakdown near AdS2 quantum critical points

Hydrodynamics provides a universal description of interacting quantum field theories at sufficiently long times and wavelengths, but breaks down at scales dependent on microscopic details of the theory. In the vicinity of a quantum critical point, it is expected that some aspects of the dynamics are universal and dictated by properties of the critical point. I will discuss the breakdown of hydrodynamics in holographic states that are governed by AdS2 critical points in the IR. I will show that the local equilibration time characterising this breakdown is set by the scaling dimension of an operator at the critical point, and that the local equilibration length is set simply by the hydrodynamic diffusivity. I will confirm that these universal relations also hold in an SYK chain model in the limit of strong interactions.

18:30-19:00

Aristomenis Donos
Durham University, UK

The Higgs/Amplitude Mode from Holography

Second order thermal phase transitions are driven my an order parameter which comes with an amplitude. Fluctuations of this amplitude lead to a slowly decaying mode whose gap closes to zero at the critical point. I will use holographic techniques to discuss in detail how this gapped mode determines the linear response of scalar operators close to the phase transition and give a geometric expression for the dissipative coefficient that fixes the relevant Green's functions.

Day 3

15:45-16:15

Rok Žitko
Jožef Stefan Institute, Ljubljana, Slovenia

Universal Magnetic Oscillations of dc Conductivity in the Incoherent Regime of Correlated Systems

I will present the formalism for investigating the magnetic field dependence of dc conductivity within the dynamical mean field theory, fully taking into account the orbital effects of the field introduced via the Peierls substitution. The formalism has been applied to the Hubbard model on the square lattice, where in addition to the conventional Shubnikov–de Haas quantum oscillations, associated with the coherent cyclotron motion of quasiparticles and the presence of a well-defined Fermi surface, we have found an additional oscillatory component with a higher frequency that corresponds to the total area of the Brillouin zone. These paradigm-breaking oscillations appear at elevated temperature. For their interpretation one must properly account for the off-diagonal elements of the current vertex and the incoherence of electronic states. The theory explains the trends with respect to temperature and doping. Such systematic investigations could be used to distinguish different scattering mechanisms in correlated materials.

16:15-16:45

Jake Ayres
H. H. Wills Physics Laboratory, University of Bristol, UK

Incoherent Transport and the Evolution of Power-law scaling of the Magnetoresistance in Cuprate Superconductors

The “strange” metal is typically characterised by a T-linear contribution to the resistivity that persists to zero temperature. In overdoped cuprates, this regime covers an extended region of dopings between that at which the pseudogap closes at zero-temperature and the end of the superconducting dome (on the overdoped side). We have shown that the anomalous T-linearity of the strange metal regime is also tied to by a pervasive H-linear magnetoresistance via a “Planckian-quadrature” scaling relation that is seemingly unresponsive to both impurities and magnetic-field orientation [1]. These findings are difficult to reconcile with our conventional understanding of metallic transport and we interpret them as signatures of incoherent transport. More recently, we have revealed the doping dependence of the H-linear magnetoresistance both within the strange metal regime, to lower dopings within the pseudogap phase and to higher dopings beyond the superconducting dome [2]. Within each doping regime, the magnetoresistance adheres to a distinct scaling relation. Whilst conventional Kohler scaling is restored beyond the superconducting dome, single power-law scaling – albeit with different exponents – between H and T is adhered to in all superconducting samples.

[1] Ayres, Berben et al. Nature 595, 661-666 (2021)
[2] Berben, Ayres et al. (under review)

17:15-18:00

Koenraad Schalm
Instituut-Lorentz for Theoretical Physics, Leiden University, Netherlands

Black hole signatures in Quantum Matter Experiments

We show that a highly precise experimental determination of the electronic self-energy in the cuprate strange metal $(Pb,Bi)_2Sr_{2-x}La_xCuO_{6+\delta}$ have a non-Lorentzian lineshape at the nodes. In particular the nodal self-energy is k dependent. We show that the experimental data are captured remarkably well by a description that emerges naturally from AdS/CFT-based semi-holography. This puts a spotlight on holographic methods for the quantitative modelling of strongly interacting quantum materials like the cuprate strange metals.

18:00-18:30

Jie Ren
Sun Yat-sen University, Guangzhou, China

Holographic superconductors at zero density

We construct holographic superconductors at zero density. The model enjoys a luxury property that the background geometry dual to the ground state is analytically available. It has a hyperscaling-violating geometry in the IR and is asymptotically AdS in the UV. We numerically construct the finite temperature solution of hairy black holes and verify the phase transition by tuning a double-trace deformation parameter. For a holographic superconductor from M-theory, we obtain an analytic solution of the AC conductivity, which explicitly shows a superconducting delta function and a hard gap.

18:30-19:00

Alexander Krikun
Nordita, Stockholm, Sweden

Thermo-electric transport properties in holographic models with pinned charge density waves

I will explain how the thermo-electric transport properties in the strongly correlated quantum systems with emergent charge density waves can be studied via the holographic models, based on AdS/CFT duality. These models provide a calculable framework where phenomenology quite different from the conventional approaches can be explored. The useful outcome of this method is the generalization of hydrodynamic effective theory and its transport coefficients, which can in turn be used in the analysis of the real experiments. In this way the novel phenomenological analysis of the strongly correlated quantum systems with charge density waves can be developed.