Gauge/Gravity Duality and Condensed Matter Physics

Organizers:

Johanna Erdmenger (Max Planck Institute, Munich),
Moshe Rozali (University of British Columbia)

February 28th to March 4th, 2016.

Overview

String theory is a promising candidate for a unified theory encompassing both quantum physics and gravity. Recently string theory has emerged as a more general mathematical and physical framework to describe physical phenomena in a much wider range of applications. This is due to the new concept of gauge/gravity duality which has been derived within string theory.

Gauge/gravity duality provides a map by which strongly coupled quantum field theories are related to classical gravity theories. This provides an exciting new approach for describing strongly coupled quantum systems, for which conventional descriptions are scarce since the standard approach of considering quasi-particle excitations in an expansion about non-interacting theories does not apply.

Strongly coupled systems are ubiquitous in condensed matter physics. They are present for instance in high-Tc superconductors, in quantum Hall systems, in systems that exhibit parity breaking and in non-equilibrium and time-dependent configurations.

One example of the systems to be studied are quenches of quantum systems which lead to a time evolution to a new configuration. Gauge/gravity duality maps this scenario for instance to collapsing matter configurations in gravity, which eventually lead to the formation of a black hole. This example illustrates how gauge/gravity duality leads to unexpected new connections between previously unrelated areas of theoretical physics.

The aim of the meeting is to bring together leading international experts from both gauge/gravity duality and condensed matter physics to explore how the new approach may be best adapted to suitable open questions in condensed matter physics. Conversely, it will be investigated how the needs for new approaches in condensed matter physics point at desirable generalizations of gauge/gravity duality and even at a better understanding of its mathematical foundations. This may lead to further insight into quantum gravity theories more generally.

Presentation Highlights

Following are summaries of some of the talks in the workshop and the issues they raise, including future directions of research.

Thermodynamics of polarized relativistic matter (Pavel Kovtun)

Understanding transport in matter subject to external fields requires that we understand its thermodynamics first. The talk described the free energy of equilibrium relativistic matter subject to external gravitational and electromagnetic fields, to one-derivative order in the gradients of the external fields. The free energy allows for a straightforward derivation of bound currents and bound momenta in equilibrium. At leading order, the energy-momentum tensor admits a simple expression in terms of the polarization tensor. At one-derivative order, bulk thermodynamics is characterized by eight scalar functions of the external fields in 2+1 dimensions, and by twenty-one scalar functions of the external fields in 3+1 dimensions.

A Precision Test of AdS/CFT with Flavor (Andreas Karch)

In the work Karch presented he and his collaborators (Brandon Robinson and Christoph Uhlemann, both also from the University of Washington) put AdS/CFT dualities involving probe branes to a precision test.

Such probe brane embeddings are the starting points of many constructions that embed interesting field theories, with potential applications to condensed matter physics questions, directly into string theory. Such ”top-down” constructions have several advantages over the more ad-hoc bottom-up constructions that just postulate a gravitational action. In particular, the detailed dictionary between gravity side and field theory is known. Since both field theory and gravity dual are explicitly known, one can put the putative duality to stringent tests.

To perform this test, they constructed on the holographic side a new class of supersymmetric D7-brane embeddings into $AdS_5 \times S^5$, which allow to describe N=4 SYM coupled to massive N=2 supersymmetric flavors on S4. With these embeddings they compared holographic results to a field theory analysis of the free energy using supersymmetric localization. Exact agreement has been demonstrated.

The fluid manifesto: topological sigma models and dissipative hydrodynamics (Mukund Rangamani)

Mukund discussed the Wilsonian effective field theories in mixed states of a quantum field theory. The ideas was to take the Schwinger-Keldysh construction seriously and extract from the fundamental definition of the path integral a set of topological symmetries which are inherent in the construction. He demonstrate that the field redefinitions of the Schwinger-Keldysh construction lead to a pair of BRST charges. Furthermore, in thermal density matrices the KMS condition can be encoded into a second pair of BRST charges. Computing the algebra of the quartet of BRST charges he finds a structure that is well known in the topological field theory literature, called the extended equivariant cohomology algebra. The symmetry being gauged in this context is thermal diffeomorphisms, owing to the fact that the KMS condition relates operators separated along the thermal circle. A simple toy model which illustrates these structures is the linear dissipative system that is captured by Langevin dynamics.

The real pay-off comes when we turn to analyzing hydrodynamics. He shows that one can write a Landau-Ginzaburg like sigma model for hydrodynamics which incorporates the basic principles we have extracted from the underlyingSchwinger-Keldysh formalism. We argue that hydrodynamics should be viewed as a sigma model, with the low-energy variables being the Nambu-Goldstone bosons for broken global diffeomorphism (and flavour symmetries in presence of charges). Exploiting the topological symmetries unearthed in theSchwinger-Keldysh constructed he constrained the low energy theory effectively to obtain a clean action principle for dissipative hydrodynamics. He went on to show that the theory satisfies various constraints such as the second law of thermodynamics, by virtue of the Jarzynski work-energy relation appearing as a Ward identity of our symmetries. The key to the construction is to maintain manifest covariance with respect to the topological symmetries which involves introducing various ghost fields. These ideas, are expected to have a bearing on other areas especially physics of black holes, which via the fluid/gravity correspondence is related to hydrodynamics.

Stokes equations on black hole event horizons (Jerome Gauntlett)

In seeking applications of holography to real world systems, the thermoelectric DC conductivity is a very important quantity to focus on. Jerome showed, universally within holography, that the DC conductivity can be obtained by solving a generalised system of Stokes equations (time independent and linearised Navier-Stokes equations) on the horizon of the black hole spacetime that is dual to the field theory of interest. This is an exact results and does not rely on making any approximations, such as a hydrodynamic limit.

Jerome discussed how the equations can be solved in closed form for one-dimensional lattices. He also showed how when the disorder is weak, the equations can be solved perturbatively and obtained some universal results, including a kind of generalised Wiedemann-Franz Law that all holographic systems must satisfy.

A simple model of momentum relaxation in Lifshitz holography (Tomas Andrade)

Tomas expanded the holographic studies of momentum relaxation to include non-relativistic scaling symmetries in the ultraviolet. He did so by constructing black branes with Lifshitz asymptotics dressed with axions which explicitly depend on the boundary directions. Such configurations arise as analytic solutions of the Einstein-Proca theory coupled to massless scalar fields in arbitrary dimensions. Studying linear perturbations on these backgrounds, he conclude that there is a dual Ward identity which accounts for the dissipation of momentum in the system. In addition, he numerically compute the frequency dependent thermal conductivity of the branes and verify that its DC limit is finite.

Holography and the nature of strange metal entanglement (Jan Zaanen)

Zaanen reported on recent developments in main stream condensed matter where AdS/CMT inspired developments are slowly getting on steam. The highlight is discovery of hydrodynamical flows in various electron systems in the form of three back-to-back publications in Science in march 2016. Also the first indications of holographic strange metal behaviours have been seen in photoemission experiments. Zaanen stressed that the AdS/CMT community should focus on the influence of periodic potentials on holographic fermions since this has a substantial potential to impact greatly on empirical condensed matter physics.

Black Holes from Quantum Quenches (Julian Sonner)

The contradiction between black holes and local quantum field theory, manifested in the information paradox and related puzzles, is sharpest for transient black holes that form by collapse, slowly evaporate, and eventually disappear. The goal of Julian Sonners presentation was thus to describe a first-principles CFT calculation, drawing on techniques and ideas from condensed-matter physics, corresponding holographically to the spherical collapse of a shell of matter in three dimensional quantum gravity. It was shown how in field theory terms, one can analytically follow the equilibration process, from early times to thermalization, of a CFT in its groundstate with a sudden injection of energy at time t = 0. By formulating a continuum version of Zamolodchikovs monodromy method to calculate conformal blocks at large central charge c, a framework was outlined to compute a general class of probe observables in the collapse state, incorporating the full backreaction of matter fields on the dual geometry. The talk concluded with two illustrative applications: firstly calculating a scalar field two-point function at time-like separation and secondly the time-dependent entanglement en- tropy of an interval, both showing thermalization at late times. These results turn out to be in perfect agreement with previous gravity calculations in the AdS3-Vaidya geometry. Information loss appears in the CFT as an explicit violation of unitarity in the 1/c expansion, restored by nonperturbative corrections.

Hydrodynamic theory of quantum fluctuating superconductivity (Blaise Gouteraux)

A hydrodynamic theory of transport in quantum mechanically phase-disordered superconductors is possible when supercurrent relaxation can be treated as a slow process. We obtain general results for the frequency-dependent conductivity of such a regime. With time-reversal invariance, the conductivity is characterized by a Drude-like peak, with width given by the supercurrent relaxation rate. Using the memory matrix formalism, we obtain a formula for this width (and hence also the dc resistivity) when the supercurrent is relaxed by short range Coulomb interactions. This leads to a new effective field theoretic and fully quantum derivation of a classic result on flux flow resistance. With strong breaking of time-reversal invariance, the optical conductivity exhibits what we call a 'hydrodynamic supercyclotron' resonance. We obtain the frequency and decay rate of this resonance for the case of supercurrent relaxation due to an emergent Chern-Simons gauge fi eld. The supercurrent decay rate in this 'topologically ordered superfluid vortex liquid' is determined by the conductivities of the normal component of the liquid. Our work gives a controlled framework for low temperature metallic phases arising from phase-disordered superconductivity.

The holographic Weyl semi-metal (Karl Landsteiner)

Weyl semimetals are an exciting new class of 3D materials with exotic transport properties. They are characterised by pointlike singularities in the Brillouin zone at which conduction and valence bands touch. Around these points the electronic quasiparticle excitations can be described by either left- or right-handed Weyl spinors. At strong coupling such semiclassical reasoning based on fermionic quasiparticles might not be available. The question arises then if it is possible to construct a model at strong coupling that has the essential physical properties of a Weyl semimetal, in particular, if there exists any strongly coupled model in which a quantum phase transition between a topological and a topologically trivial state persists even in the absence of the notion of singularities in the band structure? A tool to answer these questions is the AdS/CFT correspondence. In my talk I present a holographic model of a Weyl semi-metal and argue that the intrinsic anomalous Hall effect can be used as an order parameter to detect the topologically non-trivial phase.

Integrable one-point functions of AdS/dCFT from matrix product states (Charlotte Kristjansen)

One-point functions of certain non-protected scalar operators in the defect CFT dual to the D3-D5 probe brane system with k units of world volume flux can be expressed as overlaps between Bethe eigenstates of the Heisenberg spin chain and a matrix product state. We present a closed expression of determinant form for these one-point functions, valid for any value of k. The determinant formula factorizes into the k=2 result times a k-dependent prefactor. Making use of the transfer matrix of the Heisenberg spin chain we recursively relate the matrix product state for higher even and odd k to the matrix product state for k=2 and k=3 respectively. We furthermore find evidence that the matrix product states for k=2 and k=3 are related via a ratio of Baxter's Q-operators. The general k formula has an interesting thermodynamical limit involving a non-trivial scaling of k, which indicates that the match between string and field theory one-point functions found for chiral primaries might be tested for non-protected operators as well. We revisit the string computation for chiral primaries and discuss how it can be extended to non-protected operators.

Fractional Wigner Crystal in the Helical Luttinger Liquid (Niccolo Traverso)

An electron confined to one spatial dimension does not have many options. It can have spin up or down and it can go right or left. In helical systems the possibilities are further reduced: the spin projection is tied to the direction of motion. This phenomenon is called spin-momentum locking and takes place at the edges of two-dimensional topological insulators. Its consequences are exciting for spintronics: since spin up and down electrons counter-propagate, spin transport can be easily generated by charge currents. During the talk, I have addressed question: Are charge density and spin correlations influenced by spin-momentum locking? For weak interactions, the density correlations are featureless and the density is not affected by impurities, while spin correlations are well represented by a planar spin helix that can be pinned by magnetic impurities (EPL 113 37002 (2016)). For strong interactions, non-helical one-dimensional systems are characterized by the formation of the so called Wigner molecule. This strongly correlated state can be modelled as a chain of electrons, free to oscillate around their equilibrium positions (charge excitations), and interacting with their nearest neighbours via a weak residual antiferromagnetic coupling (spin excitations). Such a state cannot represent the strongly interacting sector of the helical Luttinger liquid since spin-momentum locking forbids the separation between spin and charge low energy excitations. Indeed, in the helical case, a Wigner oscillation of fractional charges e/2 built on a strongly anisotropic spin wave (PRL 115, 206402 (2015)) emerges in the strongly interaction regime. The interaction process which is responsible for such an effect is correlated two-particle backscattering, which amounts to convert two right (left) movers into two left (right) movers, and is relevant, in generic helical Luttinger liquids, whenever axial spin symmetry is broken in the bulk of the topological insulator. From the methodological point of view, the weakly interacting regime is well captured by the Luttinger liquid theory, while the strongly interacting sector is analysed by means of semiclassical quantization of the sine-Gordon model at finite soliton density

Quantum Chaos and Thermalization Through Eigenstates (Anatoli Polkovnikov)

In this talk Anatoli reviewed basic notions of classical and quantum chaos in single particle systems and in particular the relation of quantum chaos and the random matrix theory (RMT). In particular I briefly reviewed the Berry conjecture on the structure of chaotic eigenstates near the classical limit, Berry-Tabor and BGS conjectures on the level statistics in generic integrable and chaotic systems and the ideas of Wigner relating spectra of complex systems to those of random matrices. Then I discussed the eigenstate thermalization hypothesis (ETH), introduced by J. Deutch and M. Srednicki, as a natural extension of RMT. I showed implications of quantum chaos and ETH to entanglement in chaotic systems, delocalization of wave functions in the eigenstate basis leading to familiar thermodynamic relations including fluctuation theorems and in some cases allowing one to extend them beyond linear response. I briefly outlined ideas on steady states in non-ergodic integrable systems with an extensive number of integrals of motion introducing ideas of the generalized Gibbs ensemble. Finally I discussed in some level of detail many-particle periodically driven Floquet systems and their close analogy to the many-body localized systems.

Fish and Hydrodynamics in a Large Number of Dimensions (Chris Herzog)

A simple setting in which to study non-equilibrium physics is a Riemann problem where the initial conditions consist of a planar interface, to the right of which the system is kept at temperature T_R and to the left at a different temperature T_L. In the context of conformal field theory in two space-time dimensions, Bernard and Doyon (2012) argued for the emergence of a non-equilibrium steady state whose properties are strongly constrained by the underlying scale and Lorentz invariance. More recently, other authors have tried to extend their work to conformal field theories in larger numbers of dimensions. Through the AdS/CFT correspondence there are further interesting connections to gravity and black hole dynamics.

An interesting limit to study is when the number of dimensions grows large. The dual black hole is described exactly by a pair of second order, nonlinear differential equations:

$$\partial_t e - \partial_\zeta^2 e = -\partial_\zeta j \ , \qquad \partial_t j - \partial_\zeta^2 j = -\partial_\zeta \left(\frac{j^2}{e} + e \right) \ .$$

In the “ideal limit where the second order terms can be dropped, the system of equations supports shock and rarefaction waves. The allowed shock and rarefaction solutions are governed by fish-like curves in the energy density and current. These curves provide a sort of phase diagram for the system.

Top-down holographic Fermi surfaces (Steve Gubser)

Gubser summarized work on holographic Fermi surfaces focusing on constructions in type IIB string theory dual to N=4 super-Yang-Mills theory at finite chemical potential. Results from an assortment of supergravity fermions in a variety of backgrounds suggest a "boson rule" for the existence or non-existence of Fermi surfaces. This rule hinges on the properties of the bosonic component of the composite operator dual to the supergravity fermion. Gubser also explained a "fermion rule" which predicts when Fermi momenta will be anomalously small compared to the chemical potential. A Luttinger count based on a particular example suggests that a large majority of the R-charge carried in an anti-de Sitter black hole comes from fermions in the dual field theory.

The calculations that support these conclusions boil down to the propagation of free fermions in curved geometries. The geometries are analytically known black holes in five-dimensional gauged supergravity. The equations of motion for the fermions come from the spin-1/2 part of the gauged supergravity action, and they are variants of the Dirac equation that include gauge couplings, Pauli couplings, and spatially variable mass terms. All the concrete results come from numerical solutions to these modified Dirac equations. The focus is on near-extremal geometries whose horizon entropy vanishes in the extremal limit.

Horizon as dynamical phase transition (Sung-Sik Lee)

We show that renormalization group flow can be viewed as a gradual wave function collapse, where an initial state associated with the action of field theory evolves toward a final state that describes an IR fixed point. The process of collapse is described by the radial evolution in the dual holographic theory. If the theory is in the same phase as the assumed IR fixed point, the initial state is smoothly projected to the final state. On the other hand, the initial state can not be smoothly projected to the final state, if the system is in a different phase. Obstructions to smooth projection appear as dynamical phase transitions, which in turn give rise to horizons in the bulk geometry. We demonstrate the connection between critical behavior and horizon in an example, by deriving the bulk metrics that emerge in various phases of the U(N) vector model in the large N limit based on the holographic dual constructed from quantum renormalization group.

Discussion on holographic disorder and instabilities led by Sera Cremonini and Daniel Arean

Daniel and I led a discussion on breaking symmetries in holography and on the resulting phenomenology. One of the topics discussed in some detail was that of instabilities associated with geometries that exhibit scaling behavior. In particular, most of the focus was on the various infrared phases of gravitational solutions describing non-relativistic systems which don't preserve hyperscaling. Recently, the effort has been on better understanding the role of broken translational invariance, but more generally a rich structure of phases is observed in the deep IR, including ones with emergent conformal symmetry. One of the questions that was posed is whether certain RG flows connecting UV to IR CFTs but traversing an intermediate non-relativistic, hyperscaling violating regime can be understood in a more generic fashion, by thinking along the lines of possible extensions of holographic c-theorems. While the latter generically fail when Lorentz invariance is not preserved along the flow, there may be special conditions on the geometry which guarantee (in certain cases) monotonic c-functions.

The second main topic that was brought up was the breaking of translational invariance, and in particular the implications for possible holographic bounds on the conductivity and on the shear viscosity to entropy ratio. For the latter, broken translational invariance leads to temperature dependence, and in certain models this seemingly causes the shear viscosity to entropy ratio to approach zero at very low temperatures. Questions were raised regarding the precise connection between the shear viscosity and correlators of the holographic stress tensor, when momentum is dissipated and the standard relation between the horizon and the boundary shear metric fluctuations is modified in a crucial way.

Anomaly matching and locality in warped conformal field theory (Kristan Jensen)

Warped conformal field theories (WCFTs) are exotic, chiral, but non-Lorentz-invariant two-dimensional theories. Little is known about them. They have been conjectured to be the theories dual to gravity on so-called warped AdS3 spacetimes, which appear in the near-horizon limit of many black holes including near-extremal Kerr. Perhaps the defining feature of a WCFT is its global symmetry algebra. What happens is that a WCFT is invariant under translations and right-dilatations; the right translation is enhanced to a right-moving Virasoro algebra, and the left translation to a right-moving abelian Kac-Moody algebra, rather than to a left-moving Virasoro algebra as in conventional two-dimensional CFT.

The punchline of my talk was that, using a combination of free-field and non-perturbative arguments, WCFTs are generically non-local, and in particular the gravity dual to warped AdS3 is “semi-local in the sense of Iqbal/Liu/Mezeis 2011 paper.

My argument had three components. The first was to show that all free WCFTs admit an infinite number of exactly marginal, non-local deformations, and so free local WCFTs are infinitely fine-tuned. The second was to classify the ‘t Hooft anomalies of a local WCFT, and to show that these are not matched by their conjectured holographic duals. The third was to consider fluctuations on top of warped AdS3 backgrounds, which it turns out have much in common with fluctuations in the $AdS_2 \times R^{d-1}$ throat of extremal charged black branes. Namely, fluctuations are dual to operators with a momentum-dependent operator dimension. This is the hallmark of a “semi-local theory, as defined by Iqbal, Liu, and Mezei.

Outcome of the Meeting

The meeting had very productive interactions between the two communities represented, those interested in condensed matter physics, and those trained in string theory and its methods. Besides the good mix represented in the talks and the issues they raised, many informal discussions were taking place. We expect those discussions to promote further collaborations between these communities, which is essential to the future of this interdisciplinary endeavour. We also are looking forward to possibly meeting again in Banff for another installment in the series of these highly productive meetings.