Holography and Applied String Theory

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1 Overview of the Field

Until the middle of the 1990's, string theory had a reputation for being a rather ambitious formalism that, while being the most promising candidate for unifying gravity with the Standard Model, had provided few concrete, testable predictions or applications. This changed following Maldacena's proposal, the AdS/CFT correspondence or gauge/gravity duality [36, 2], in 1997; building on holographic notions reaching back to the work of 't Hooft and Susskind, the conjecture posits that certain quantum field theories, in say d spacetime dimensions, are equivalent to quantum theories of gravity in $d + 1$ dimensions obtained from string theory. This allows one to use string theory to obtain results, such as correlation functions or response functions related to experimental probes, that may be otherwise difficult to compute directly in a field theoretic approach. In particular, the correspondence relates some strongly coupled quantum field theories to the classical limits of certain string theories, e.g. classical gravity, allowing access to quantities where there was previously no tractable approach. Though the most precise formulations of the correspondence often involve particular field theories with large amounts of supersymmetry and in the large N limit, the hope is that the results obtained via holography will shed light on the structure of more realistic theories.

Since its inception, gauge/gravity duality has sparked enormous activity in the numerous areas of physics, both in using the classical gravity to learn about strongly coupled quantum field theories (QFT) as well as using QFTs to learn about the nature of quantum gravity. Early applications of the correspondence focused more on its uses in traditional particle physics systems, such as the behavior of QCD (quantum chromodynamics) in the strongly coupled regimes found in heavy ion collisions being explored at RHIC (Relativistic Heavy Ion Collider) and the LHC (Large Hadron Collider), but a widely growing field of late has been applying the duality to condensed matter systems, which has seen a plethora of strongly coupled systems emerge in the past few decades that challenge conventional understandings. In the other direction, the correspondence provides a precise formulation of quantum gravity and can provide useful insight and intuition into the structure of quantum gravity. As quantum gravity has proved to be a rather formidable subject, any insights are welcome and may prove invaluable to our understanding of gravity.

In this report we briefly discuss some of the major areas of current holographic research and the results presented during the workshop. Due to the widespread applicability of holographic techniques and numerous open questions regarding the nature of the duality, the topics covered in the workshop ranged over a large cross section of theoretical physics, from QCD to strange metals, turbulence to black hole microstates. Below we present a brief review of these major directions of the discussions held during the workshop.

2 Topics

2.1 Holographic QCD

Since its discovery, gauge/gravity duality has been frequently used to learn more about different properties of QCD in the strongly coupled regime and to probe different regions of the QCD phase diagram. In this workshop different aspects of the holographic QCD were addressed.

N. Evans presented a study of dual gravity theories to conformal field theories (CFT) at the lower end of the so-called conformal window of QCD [3]. The conformal window ranges from x_c approximately 4 to $x = N_f/N_c = 11/2$. Below x_c the CFT turns into a theory with chiral symmetry breaking and a mass gap. In this talk two models were presented in which the lower bound of the conformal window x_c was computed. The first model is based on a D3/ probe D7 system with a running dilaton, which was put in by hand. In this model they find chiral symmetry breaking at $x_c < 2.9$, however the anomalous dimensions of QCD are not encoded correctly. In the second model they start by imposing the correct anomalous dimensions. They find that a BKT phase transition occurs at $x_c = 4$. Finally he shows that this model is suitable to model small field inflation.

QCD is believed to deconfine at high temperatures and large densities, so that hadrons are separated into their consituent quarks and gluons, and these constituents form a so-called quark-gluon plasma (QGP). C. Ewerz showed a study of different properties of holographic strongly coupled plasmas, which may model some features of QGP [25]. Their aim is to find robust properties which are universal in strongly coupled theories at finite temperature. A natural observable in such theories is the screening length. They find that all deformations of $\mathcal{N} = 4$ $SU(N_c)$ SYM (super Yang-Mills) theory have a longer screening length then the undeformed one. However, they expect that for theories at finite chemical potential this bound does not hold anymore.

One of the topics discussed by J. Erdmenger in her talk were the results published in [11]. There, in the context of gauge/gravity duality, the authors find the ground state of two asymptotically AdS backgrounds with an SU(2) magnetic field near some critical value. This ground state forms a triangular Abrikosov lattice, which may be interpreted as a ρ meson condensate perhaps detectable in off-centre heavy ion collisions.

Not only does holography prove helpful for analysis of QCD at high temperature and large densities, but it also allows the study of QCD in a background magnetic field; N. Callebaut presented an overview over different studies in such a regime. In QGP very large magnetic fields are generated by non-centred heavy ions collisions. It turns out that in QCD-like theories a ρ meson condensate is formed above a critical value of the magnetic field [15]. This behaviour is the opposite of that in a conventional superfluid/superconductor, where the condensate vanishes for high enough magnetic fields. Furthermore this condensate forms a lattice. A similar effect can be seen holographically, where the groundstate of a holographic superconductor with a magnetic field forms a Abrikosov lattice [13, 11]. S. Sin showed how non-spherical gravitational collapse is related to early thermalisation in QGP. In [38] they claim that in AdS space an arbitrarily shaped shell collapses to form a black hole. The collapse is independent of the initial conditions, coming from the fact that the process is taking place in AdS space. Furthermore they write that the time a massive particle needs to fall into the centre is $T = \pi R/2c$ independent of its starting position.

2.2 Entanglement Entropy

A key property of quantum systems is the fact that they can support entangled states, which can be quantified by the entanglement entropy; the entanglement entropy is obtained by first considering a subsystem $A \subset R$ of the total region R and tracing out the degrees of freedom in the complement $A^c = R - A$, i.e. defining a reduced density matrix for the subsystem to be $\rho_A = \mathrm{tr}_{\mathrm{A^c}}\rho$ where ρ is the density matrix for the full system. The entropy is then obtained from $S_A = -\mathrm{tr}(\rho_{\mathrm{A}} \log \rho_{\mathrm{A}})$. The entanglement structure of a theory can provide hints at how the degrees of freedom organize in many body systems and suggest efficient numerical simulation schemes.

However, field theoretic calculations of the entanglement entropy have proved rather difficult even in the simplest cases. In 2006 Ryu and Takayanagi conjectured a formula (RT formula) to holographically compute the entanglement entropy (EE) of a field theory by minimising an area in the dual gravity theory [40]. This lead to the use of gauge/gravity as a tool to determine this kind of entropy. In this workshop different aspects of AdS/CFT and entanglement entropy were discussed.

T. Faulkner presented a holographic computation of the entanglement entropy and Rényi entropies for disjoint intervals in a 1+1 CFT using the so-called replica trick. The replica trick consists of taking n “replicas” of the same theory glued together in a particular fashion and then taking the limit $n \to 1$ in the analytically continued entanglement Rényi entropy, which is defined as $S_A^{(n)} = (\ln \mathrm{Tr}\, \rho_A^n)/(1-n)$; this gives the usual entanglement entropy [32]. The trace of the reduced density matrix can be related to the ratio of a partition function for n copies of the system (Z_{M_n}) to the partition of the original theory. In this talk T. Faulkner presented a way to compute Z_{M_n} using the usual rules of AdS/CFT. He found that the EE ($n \to 1$) of one disjoint interval computed using the RT formula and computed using the replica trick and AdS/CFT agree. Finally it was shown that for $n = 2$ case the holographic and the field theoretic calculation also agrees.

C. Herzog showed a study of the effect of temperature and mass gap onto EE. For that they looked at $1 + 1$ dimensional fermions and bosons on a torus. The results they find are

$$S_A(T) - S_A(0) \sim \mathrm{e}^{-m_{\text{gap}}/T} \quad \text{and} \quad S_A(T) - S_B(T) \sim \mathrm{e}^{-m_{\text{gap}}/T}, \tag{1}$$

where S_A and S_B are the entanglement entropies of the regions A and its complement B respectively, and T the temperature. Note that this result is valid for low temperatures. To compute these quantities they use bosonization of massless fermions and then the replica trick described above or alternatively for massive fermions lattice methods. For the scalars the results were computed by lattice methods. These are solely field theoretic computations, therefore the question C. Herzog arose at the end of his talk was how to compute this effect on the gravity side. Since they expect that above results correspond to $1/N$ corrections in the $\mathcal{N} = 4$ SYM case, one might expect to see this as higher derivative corrections on the gravity side.

In the discussion session about entanglement entropy J. Karczmarek asked how gravitational spacetime could emerge from some QFT. In this context she posed the question if entanglement structure has a geometrical interpretation and could therefore be interpreted as a dual gravitational metric. V. Hubeny discussed possible generalizations of EE and the RT formula to time dependent theories. Furthermore she also pointed out that it would be interesting to figure out how to reconstruct the spacetime from the known EE. Finally she presented an analysis of the regions in the gravitational bulk which are influenced by the reduced density operator ρ_A. M. V. Raamsdonk gave the last contribution to this discussion session about the entanglement of two different regions in pure AdS. Since they considered thermal theories, i.e. black hole solutions, both regions are characterised by a thermal density matrix $\rho_{\text{L/R}}$.

2.3 Holographic Hydrodynamics

In the context of holography, the computation of two point functions in a strongly coupled field theory with a gravity dual is relatively easy to perform. This is due to the fact that, on the gravity side, calculations involve well-known perturbative methods. Taking the low frequency and large wave length limit of this Green’s functions leads to a low energy effective theory: hydrodynamics. In addition, computations in gauge/gravity duality provides motivation for new transport phenomena, e.g. anomalies [21, 6]. In this workshop different aspects of hydrodynamics were covered.

A. Yarom discussed anomalies in the context of hydrodynamics, from a purely field theoretic standpoint. They find that pure and mixed gravitational anomalies, arising from placing the field theory on a non-trivial background, generate coefficients in the stress tensor and charge current at a lower order of the gradient expansion as one would expect from the equations of motion [34]. Therefore, in principle, these anomalies could be measurable. To compute these coefficients they rely on a prescription developed in [33] and [7]. In this prescription the constitutive relations for the thermodynamical equilibrium state are derived by variation of an effective action. Furthermore the response of the system to perturbations in the hydrostatic equilibrium (i.e. zero frequency) can be calculated by the same means.

K. Jensen presented how to derive anomaly-induced transport by using variational methods [34]. Including the appropriate Chern-Simons-terms to the partition functions, the generic anomaly-induced transport terms are then obtained using the methods introduced before by A. Yarom for the derivation of consitutive relations in hydrostatics. As an example he presented this specific construction in 2d field theory.

M. Petropoulos discussed vortices in the holographic context. The aim is to use AdS/CFT to describe rotating fluids in $2+1$ dimensions in the hydrodynamics regime. For that they look at a 4 dimensional bulk theory with nut charge, generating monopolar vertices at the boundary with a cotton tensor and satisfying topological massive gravity equations. Additionally they find the break down of ergodicity in this setup.

J. Erdmenger showed recent results on the hydrodynamic limit of supersymmetric field theories with a gravity dual [24]. In this regime a transport coefficient was shown to have similarly universal properties as η/s (shear viscosity over entropy density) by relating its Kubo formula to a universal fermionic absorption cross section result. She also presented a study of transport phenomena in backreacted p-wave superfluids in the context of gauge/gravity duality [23, 20]. Due to the spacetime anisotropy of this system, the tensorial structure of the transport coefficients is non-trivial in contrast to the isotropic case. In particular, there is an additional shear mode which leads to a non-universal value of the shear viscosity even in an Einstein gravity setup. Furthermore a third non-vanishing component λ of the viscosity tensor, which at the phase transition to the AdS Reissner-Nordström phase turns into the well-known isotropic shear viscosity, also has a non-trivial temperature dependence when divided by the entropy density.

In the discussion session about holographic hydrodynamics one question that was asked several times was the use of gauge/gravity duality to discuss hydrodynamics. It was claimed that all that was discovered about hydrodynamics in the context of gauge/gravity duality could also have been found out without relying on holographic methods. However, in order to discuss this and other questions P. Kovtun set the scene by giving a brief overview of hydrodynamics as a long wavelength, low frequency effective theory. Furthermore he stated that AdS/CFT gave qualitative as well as systematic insight into hydrodynamics: qualitatively for describing near-ideal-gas equation of state with a very small viscosity, and systematic, since in the holographic context a systematic treatment of derivative expansions in hydrodynamics was established. He also posed the question what could be learnt in gravity from hydrodynamics. He suggested that hydrodynamics can provide some insight into stability analysis. Furthermore the finding of new solutions to the hydrodynamic equations may lead to new geometries. He also mentioned further open issues, e.g. the systematic formulation of non-relativistic hydrodynamics, of anisotropic hydrodynamics, how to formulate hydrodynamics as a field theory, how to interpret the entropy current from a field theoretic point of view, among others. K. Jensen formulated the opening question even more drastically, claiming that holography has nothing new to contribute to hydrodynamics. However, the inverse may not not be true. Furthermore he sketched how to write down a partition function for thermodynamics and derivative corrections to it. Finally R. Leigh presented a discussion about turbulences based on [14, 1]. In the first paper they demonstrate that relativistic conformal hydrodynamics in $2+1$ dimensions show turbulent behaviour leading to a energy cascade from the UV to the IR. In the second paper the authors construct turbulent flows in holographic superfluids. They find an energy cascade which behaves opposite to the first paper, i.e. here the energy cascades from the IR to the UV.

2.4 "Novel Phases"

In addition to being an efficient calculational tool, holography can illustrate more broadly the various types of phases that can emerge (or persist) in the strongly coupled regime. A number of discussions focused on such novel phases.

G. Semenoff presented a study of probe D5 branes dual to a defect field theory, modelling the integer quantum hall effect [35]. For a certain number N_5 of D5 branes they turn into a D7 brane. Depending on the filling fraction of the Landau levels, the N_5 probe D5 branes or the D7 brane is the energetically preferred solution. Finally, for certain values of the ratio of filling fraction to $N_5/\sqrt{\lambda}$ (with λ the 't Hooft coupling) they find that in the D5 probe brane system the chiral symmetry is restored whereas in the D7 system it is not.

M. Rozali discussed the holographic study of an interface between fractional topological insulator and a ordinary insulator [39]. They induce a finite matter density at the interface by switching on a chemical potential. The gravitational system of interest consist of 7 branes embedded in AdS_5 and wrapping a 3-sphere inside the 5-sphere. The interface is generated by giving the embedding function χ a profile in the form of a step function in one of the spatial AdS_5 boundary directions. Finally they are able to analyse the thermodynamic properties of this system , with the main result being the dependence of the density on the temperature or the chemical potential. They find that, in agreement with realistic models of gapless strongly coupled fermionic excitation on the interface, the free energy $F = T^4\mathcal{F}$ goes like $\mathcal{F} \sim (\mu/T)^4$.

M. Natsume reviewed recent work on stimulated superconducting transitions in holography. Classic work in traditional BCS superconductivity has shown that time-dependent couplings among quantum fields, obtained physically by e.g. pumping high-frequency electromagnetic fields into the system, can lead to modifications of the fermionic density of states and possibly increase the transition temperatures of these materials. Recent holographic work has demonstrated similar effects by including time-dependent perturbations in strongly-coupled superconductors. Natsume discussed previous work on the subject and the subtleties associated with the time dependent chemical potentials used as well as presenting preliminary results on resolution of these subtleties.

J. Erdmenger presented a study of Homes' law in a holographic context [22]. Homes' law describes an empirical relation among various superconducting systems and is believed to shed light on the strange metal region above the superconducting dome of high temperature superconductors. She presented a possible holographic realization by exploring gravitational duals exhibiting features characteristic for real world superconductors. In particular, she focused on so called s- and p-wave superconductors where they calculated diffusion constants and respective timescales connected to a universal timescale signalling a perfect strongly correlated quantum fluid.

2.5 Non-equilibrium physics

Recently AdS/CFT has also been used to provide insight into the evolution of far from equilibrium systems to equilibrium. In this context one tries to e.g. model the thermalisation of quark-gluon plasma, where traditional field theory methods prove inadequate.

J. Sonner discussed the far from equilibrium dynamics of a holographic superfluid [9]. The system of interest is the so-called holographic s-wave superfluid (see e.g. [29]) in AdS_4. To analyse the far from equilibrium dynamics they apply a Gaussian-type quench to the boundary value of the scalar field. Due to the choice of boundary conditions which keep the initial and final charge density the same, this quench corresponds to the injection of energy into the system. They find three distinct phases related to the strength of the quenches at temperatures below the critical temperature, i.e. the system is in the superfluid phase. For the weakest quench the system returns to the superfluid phase in a damped oscillatory manner. For intermediary strengths the system also comes back to the superfluid phase, however due to a non-oscillatory decay. Finally for strength of the quench above a certain value the system decays towards the normal phase. In addition to the far from equilibrium analyses a study of the late time behaviour, i.e. of the quasi-normal modes of the system, was presented, also showing the three distinct regions depending on the temperature of the final state.

E. Caceres presented a study of holographic thermalisation with a chemical potential [12]. They analyse a background which interpolates between AdS-Schwarzschild and AdS-Reissner-Norsdström in 4 and 5 (AdS) dimensions. In this setup they compute different non-local operators, such as the entanglement entropy, two-point functions and Wilson loops. The entanglement entropy turns out to be the quantity that thermalises last and therefore sets the time-scale of the thermalisation.

2.6 What field theory can do for holography

An important goal of current research is to gain a deeper understanding of the regimes of validity of holographic methods and what exactly can be captured via the correspondence. To this end, numerous discussions during the workshop presented results from purely field theoretic calculations that can motivate new directions of holographic models or be used as non-trivial tests of the correspondence. Examples mentioned above include the numerous discussions regarding the role of anomalies in hydrodynamics, which provide stringent exact results to test against holography, and the structure of entanglement entropy, where results from field theory may provide insight into how the RT prescription arises or even possible insight into the structure of quantum gravity itself.

As gauge/gravity duality is best understood in situations where the dual field theory is conformal, it is desirable to see how one can gain analogous control when the dual is a deformed CFT. D. Hofman presented work on two dimensional warped conformal field theories (WCFTs) that makes progress in these directions [31]. In two dimensional CFTs, the four global symmetries resulting from Poincare and scale invariance are enhanced to infinite-dimensional local symmetries; Hofman and collaborators have shown that even with only three global symmetries, two translations and one chiral dilatation (and no Lorentz symmetry), the symmetries can be enhanced to an infinite dimensional local symmetry algebra, analogous to the traditional CFT case. These symmetry structures have been observed in holographic models with warped AdS_3 geometries and therefore one may hope that a greater understanding of WCFTs will prove useful in understanding these holographic models as well as the structure of black holes.

2.7 Holographic transport

A recently growing field of applications for holography has arisen from condensed matter contexts. Exotic new materials and their phase diagrams found experimentally over the past few decades have presented significant challenges for theorists due to their strongly coupled nature, defying the conventional understanding of metallic phases through Landau Fermi liquid theory. In particular, various transport measurements of these materials reveal that the low energy structure and their transport properties are drastically different from conventional metals; these properties are likely the result of the strong coupling between excitations, which makes a weakly coupled description a la Fermi liquid theory inappropriate. Holographic metals are by definition strongly coupled on the dual field theory (in the regime where we can usefully talk about them via classical gravity) and therefore it is hoped that they may provide understanding of transport in the strongly coupled regime. Furthermore, transport properties, such as conductivities, are rather straightforward (though can be quite non-trivial) to obtain in holographic settings, as the computations required are simply current-current correlation functions.

A few participants presented results from their work on holographic transport, including the resolution of the Drude peaks and the unconventional scaling behaviors of the optical conductivity. S. Hartnoll briefly reviewed the outstanding questions on the structure of the optical conductivities observed experimentally before moving onto the role of momentum relaxation and the structure of Drude peaks. For conventional metals with sharp Drude peaks, the momentum relaxation rate is viewed as a small parameter which governs the translation invariance breaking operators of the effective IR theory [30]; the classic example of this is momentum relaxation via Umklapp scattering in Fermi liquids. This leads to a picture of metal-insulator-transitions (MITs) in which a momentum non-conserving operator becomes relevant and drives the system to an insulating phase. Hartnoll then discussed a simple holographic realization of this MIT program [19].

D. Vegh also presented work on holographic approaches to non-Drude transport. Vegh studied holographic models which explicitly break translation invariance, allowing for momentum relaxation and hence finite conductivity, via adding a graviton mass [41]. The conductivity then scales as $|\sigma| \sim \omega^{-\gamma}$ for some $\gamma \in [0, 1]$ that depends on the details of the graviton mass; note that the Drude formula implies a scaling of $|\sigma| \sim \omega^{-2}$ for large frequencies. This holographic framework provides a simple scenario to investigate what types of dynamics can lead to anomalous scalings of the optical conductivity.

2.8 Understanding IR completions

A current topic of investigation in holography is the resolution of IR singularities in common holographic geometries. Holography can have rather peculiar features that are undesirable for realistic applications, e.g. the extensive ground state entropy *density* of the Reisner-Nordstrom $\mathrm{AdS}_2 \times \mathbb{R}^2$ phase or the IR singularities of the Lifshitz/hyperscaling geometries as pointed out in the discussion session with B. Gouteraux, L. Huijse and M. Haack. It is unsure what the origin of such features are, e.g. are these artifacts of the large N expansion, and what the ground state structures of such theories end up as. Therefore, a lot of effort is being put into finding the far IR completions of these "singular" geometries and characterizing the possible instabilities of these phases.

Numerous workshop discussions focused on these resolutions from multiple viewpoints.

A number of participants discussed how these interesting scaling geometries arise to begin with. E. Kiritsis presented work on a systematic classification of possible emergent geometries in Einstein-Maxwell-dilaton theories, with or without breaking the $U(1)$ symmetry [28]; here Kiritsis and collaborators have adopted a Wilson-esque view and focus on constructing general effective holographic theories in order to characterize possible emergent scaling behavior and how to connect these scaling behaviors via renormalization group flows. M. Ammon discussed the classification and properties of holographic probe brane states with a massless hypermultiplet propagating along a defect at finite density, in particular focusing on D3/D7 setups; Ammon and collaborators demonstrated the perturbative stability of the setup and discussed the structure of the moduli space [5]. M. Kaminski discussed holographic probe settings in which the dual field theory is understood and demonstrated how hyperscaling emerges from the holographic description [4]. This can provide interesting examples of field theories exhibiting hyperscaling violation and in which maybe we have more hope of finding hidden Fermi surfaces directly in the field theory. Moving onto non-relativistic (NR) quantum field theories, A. Karch reviewed the structure of spurionic symmetries, i.e. symmetries which are not global symmetries but leave the action invariant provided coupling constants transform non-trivially, and discussed how the formalism can be used to constrain the low energy effective actions of NR systems; from these symmetry considerations, Karch and collaborators have conjectured that Horava gravity may play a crucial role in holographically describing NR conformal field theories.

J. Gauntlett discussed recent work on the rich variety of phases that can be obtained from top down string and M-theory constructions. Such novel behavior includes the existence of spatially modulated phases, which can arise as instabilities of $\mathrm{AdS}_2\times\mathbb{R}^2$ as well as solutions of EMD, competition between superconducting and striped phases, and metamagnetic transitions [27, 18, 17]. S. Cremonini complimented these discussions with results on the instabilities of EMD theories which exhibit hyperscaling violations. In particular, Cremonini and collaborators have found that the far IR of the hyperscaling violating geometries with constant magnetic flux flow to $\mathrm{AdS}_2\times\mathbb{R}^2$ and inherit the associated instabilities to spatially modulated phases [10, 16]. Similarly, X. Dong presented work on stringy resolutions to the tidal force singularities in Lifshitz geometries, arguing that since the geometry isn't a solution to the vacuum Einstein equations, there must be some sources of stress-energy in the IR; these sources can then prevent the divergent string modes responsible for the divergent tidal force from proliferating and rendering the space singular [8].

2.9 Holographic Fermi surfaces

A major goal of modern condensed matter is to understand and classify compressible phases of matter, that is phases with a conserved current whose density varies smoothly as a function of the chemical potential at zero temperature. If we require that the global $U(1)$ symmetry associated with the density be preserved, there are a surprisingly few simple systems with these properties, the prototypical example being the Fermi liquid; if we move away from weakly coupled theories, then the list grows even shorter. However, Fermi surfaces are generally expected to be present in such states, which leads to the goal of understanding emergent Fermi surfaces in strongly coupled theories. Fermi surfaces are rather peculiar objects and are directly responsible for the characteristic behavior of Fermi liquids, such as low energy spectral weights and Freidel oscillations; therefore it is desirable to understand their behavior away from the Fermi liquid fixed point with the hope of gaining insight into the low energy theory.

Holography provides a rather natural route to constructing compressible phases, as the fact that the dual field theory is at finite density translates into boundary conditions for the bulk gauge field; the finite density at the boundary is then thought of as electric flux that is sourced from the bulk, either via explicit charged matter in the bulk or from a charged horizon. In the discussion session by B. Gouteraux, L. Huijse and M. Haack as well as discussions during the workshop regarding the charged horizon case focused largely on the possibility of "hidden" Fermi surfaces: these are systems at finite density that, despite having no explicit fermionic matter, exhibit behavior characteristic of a Fermi surface. Particular emphasis has been placed on the role of the entanglement entropy in detecting Fermi surfaces, as conventional Fermi surfaces exhibit distinct logarithmic scaling; while these systems exhibit tantalizing hints to the presence of a Fermi surface in the theory, it is difficult to directly probe the Fermi surface and thus far we are only able to see indirect properties such as the entanglement entropy or the scaling properties of the system. A major goal of future work would be to find clear and direct ways to holographically test for the presence of Fermi surfaces.

N. Iqbal discussed holographic compressible phases in $1+1$ dimensions via a charged BTZ black hole in AdS_3. A crucial result of Fermi liquids is Luttinger's theorem, which relates the volume of the Fermi surface to the charge density; since the fundamental charges of the theory are quantized, this raises the question of how the holographic description will capture this charge quantization, as the flux emerging from the black hole is not quantized. The quantization of charge is a manifestation of the compactness of the $U(1)$ gauge group, which motivated Iqbal and Faulkner to consider the role of another characteristic feature of compact gauge groups, namely monopole excitations. By considering the effect of these monopoles, which are subleading effects in the large N expansion, Iqbal and Faulkner demonstrated that these holographic liquids exhibit Freidel oscillations and satisfy Luttinger's theorem just as one would expect [26]. More generally, these results emphasis the crucial role of the compactness of the gauge group and how subleading terms in the large N expansion may be critical to understanding holographic Fermi surfaces.

J. Zaanen reviewed the structure of Fermi liquids and their BCS instabilities, discussing how they can emerge from holographic matter from Reissner-Nordstrom black holes coupled to fermionic matter and holographic superconductors. Zaanen sharply emphasized the similarities and differences of these holographic states with conventional condesned matter behaviors, in particular looking at the interesting behvaiors of the fermion self-energies as well as the surprisingly BCS-like relaxational dynamics of holographic superconductors. K. Schalm then followed up this discussion emphasizing how moving beyond the large N expansion can be qualitatively important in resolving singularities [37]. In particular, he focused on the standard holographic strange metal, i.e. AdS Reissner-Nordstrom coupled to fermionic metal, and its instabilities by addressing the existence of normalizable modes in the spectrum that allow system to decay to the new normalizable state.

3 Conclusion

In this workshop a variety of topics in the context of gauge/gravity duality were covered which let to interesting discussion among the participants. Since AdS/CFT is a tool with which one can get insights into many different areas of physics, the themes that were covered were very diverse. There were various presentations analysing QCD systems, specially in the Quark-Gluon-Plasma regime, where one tries to derive experimental observables which may be measurable at the LHC or RHIC. Furthermore condensed matter physics is playing a prominent role in holographic investigations which was reflected in the many different condensed matter topics covered during the workshop. Specially Fermi surfaces, strange metals, non-fermi liquids, entanglement entropy among others appeared in various talks. In this context one tries to get theoretical insight into different properties found in materials, as high T_c superconductors or the temperature dependence of the resistivity in strange metals. Connected to this direction is the analyses of different scaling behaviours of IR geometries of holographic gravitational systems. Another important aspect is the application to fluid dynamics. Although AdS/CFT is in principle not needed for many results derived over the last few years, the importance of anomalies or a systematic derivation of the gradient expansion in hydrodynamics was first discovered in the holographic context. Recently there are attempts to model far from equilibrium physics in strongly coupled systems using the correspondence. Also in this respect new developments were presented.

All in all the workshop provided a very good overview of the different directions which are being pursued in the applied AdS/CFT community. The workshop provided a fruitful frame for discussions among the participants and the presentation of the newest results obtained in the field.

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