Il Colle di Galileo

Holographic Methods for Strongly Coupled Systems

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Abstract. The "holographic correspondence" – the mapping between quantum field theories and higher dimensional theories of gravity – can be used as a tool to understand strongly interacting systems describing relevant phenomena in nature. Counting on the participation of many of the top world experts in the field, the Workshop succeeded in bringing together an international community of theoretical physicists, providing an overview and assessment of recent progress and identifying priorities and coordinated efforts for a better understanding of strongly coupled phenomena using holographic methods. World-renowned scientists, together with brilliant young researchers, presented their recent results on applications of holographic methods to QCD, condensed matter systems and general quantum field theories. The Workshop hosted the "Gauge/Gravity Duality 2015" conference, the last edition of a series of bi-annual meetings of the European Science Foundation network HoloGrav, also sponsored by a COST action.

Keywords. Holography, AdS/CFT, string/field theory correspondence, QCD, QGP, supersymmetric field theory, condensed matter physics, entanglement.

Scientific motivation

Many of the fundamental outstanding questions in modern theoretical physics involve strongly coupled systems, which necessitate going beyond traditional paradigms based on standard weakly interacting quasiparticles. Strongly coupled quantum field theories are, in fact, at the basis of our current description of many relevant phenomena in Nature.

In the realm of particle physics the prototypical example is provided by quantum chromodynamics (QCD), the fundamental theory of quarks and gluons. QCD becomes strongly coupled at low energies and, as a result, both its hadronic and its deconfined quark-gluon plasma phases – in the temperature ranges relevant

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for current heavy ion collision experiments – as well as its finite density phases (relevant at the core of neutron stars) require non-perturbative theoretical descriptions. A first-principle approach to QCD at strong coupling is provided by a reformulation of the theory on Euclidean lattices and by the use of numerical Monte Carlo methods. This technique, powerful as regards the study of certain equilibrium properties, still has severe limitations in terms of analysis of real-time dynamical issues or the study of finite quark density regimes.

Strongly coupled field theories also appear in the hidden sectors of various theoretical speculations on high energy completions of the Standard Model for elementary particles. This is the case, for example, of technicolor or dynamical supersymmetry breaking models.

Other paradigmatic examples, of high technological relevance, arise in the realm of condensed matter physics. Quantum critical systems, superconductors with a high critical temperature, ultracold Fermi gases at unitarity, quantum Hall systems and strange metals all appear to evade most of the traditional paradigms (e.g. Landau-Fermi liquid or BCS theories) based on sharp quasiparticles or weakly coupled degrees of freedom. There is thus an extremely urgent need to develop new theoretical frameworks in which these systems can be modeled and analyzed.

The Workshop provided novel contributions towards facing these challenges by bringing together many of the top experts in that promising powerful technique, introduced 17 years ago, which goes under the name of AdS/CFT correspondence, often referred to as holography or gauge/gravity duality. The latter is founded on a proposed duality map between ordinary quantum field theories and higher-dimensional models of gravity. Remarkably, this allows suitably defined regimes, where a quantum field theory is strongly interacting, to be described by means of a classical, weakly coupled gravitational theory. In this way, hard-to-solve quantum problems are mapped into easier, classical ones in the dual description. Very powerful techniques have been further developed to extend this duality beyond the classical gravity regime, relying on integrable structures uncovered both in field theory and in string theory. This permits the exact computation of relevant observables, such as spectra of anomalous dimensions of operators. Moreover, new relations between field theory quantities have been discovered with the aid of the AdS/CFT correspondence, such as the connection between scattering amplitudes and Wilson loops.

Holographic methods complement other established non perturbative tools, in that they are appropriate to study not only equilibrium physics but also real-time processes, phases with non-zero fermionic densities, transport coefficients and response to perturbations. Moreover, they offer simple geometrical pictures of dynamical processes at strong coupling. The models for which they can be systematically employed (that is, for which a precise one-to-one map between field theory and the corresponding gravity model is known), are still limited to idealized versions of realistic field theories. Finding more faithful duals of QCD-like theories, for example, requires control of the quantum string theory completion of the corresponding gravity models.

At the same time, as extensively demonstrated during the Workshop, a more practical approach is emerging. It consists of using holographic methods to produce new effective theories. Once the main symmetries and order parameters of a quantum field theory process are identified, they are translated into a dual gravity model from which computations are extracted. This strategy is producing unique and remarkable results, for example on the description of the transport properties of quark-gluon plasma examined in heavy ion collision experiments at RHIC and LHC. The same strategy is also the guideline for the very recent applications of the correspondence to advanced materials and condensed matter phases around quantum critical regions. As illustrated during the Workshop, great efforts are being devoted to extending these methods to larger classes of phenomenologically-relevant models with the aim of studying not only equilibrium properties (phase space structures, spectra and so on), but also non-equilibrium ones (thermalization, response to quantum quenches, transport). Information about the latter has emerged from experiments only in the last decade, and their analysis is one of the most important challenges for theoretical physics.

The Conference

The "Gauge/Gravity Duality 2015" conference was held during the Workshop, from April 13 to 17, 2015. It was the last edition of a series of bi-annual meetings of the European Science Foundation network HoloGrav and was supported by HoloGrav and the COST Action MP1210. The conference included 16 talks by invited speakers as well as 56 presentations by registered participants, and was attended by 125 participants from all over the world. The "Gauge/Gravity Duality 2015" conference succeeded in bringing together the international community of theoretical physicists, both world-renowned scientists and brilliant young researchers, to identify priorities and coordinate efforts for a better understanding of strongly coupled phenomena using holographic methods.

The Workshop

More than 110 scientists from the five continents attended the Workshop (Conference excluded) with an average participation of more than 35 visitors per week. Among them, many young post-docs and ten students, supported by the GGI funding scheme dedicated to young researchers, contributed to the lively atmosphere of collaboration and exchange of ideas that characterized the Workshop.

Most of the results discussed during the Workshop and the Conference, and their possible impact on future directions in the field, can be grouped under the following subject headings.

– Holography and QCD

The use of holography has provided great insight into the high temperature and density regime of QCD by studying theories that share many of the properties of QCD, but for which a gravity dual is readily available. This can be used to look for universal properties and general guidance, beyond the regime where perturbation theory and lattice results are fully reliable.

Concerning the many applications to QCD physics, relevant issues include holographic "top-down" models (i.e. models which are systematically embedded in string theory) as well as effective ("bottom-up") holographic theories, aimed to describe phases of QCD (both at zero and at finite temperature and density), with a special focus on chiral symmetry breaking, hadronic physics and dynamical flavor effects.

– Holography and condensed matter

The holographic approach has also been recently employed in promising applications to lower dimensional models for condensed matter. Traditional tools, based on weakly interacting quasiparticles such as Landau-Fermi liquid theory and BCS theory, provide extremely successful descriptions of standard materials. However, these standard methods do not give reliable theoretical descriptions of unconventional systems for which, thus, a quasiparticle interpretation is lacking. The physics of many such systems is expected to be governed by theories in the vicinity of scale-invariant quantum critical points, the most famous example being that of strange metals and high-Tc superconductors.

Many attempts to use the AdS/CFT approach to model strongly coupled condensed matter systems were demonstrated during the Workshop. Transport properties, such as conductivity, were then extracted holographically.

Remarkably, the use of holography has led to the discovery of completely new classes of non-Fermi liquids and marginal Fermi liquids. These enlarge the family of theoretical models of strongly interacting fermions. Moreover, in a few cases they share some interesting properties with realistic unconventional materials. It is possible that this line of research will uncover some aspects of the mechanisms responsible for the "strange" behavior of certain unconventional metals.

Holographic approaches to topological insulators and quantum Hall devices, just to mention a few systems, were also considered during the Workshop and the Conference. Progress here is still ongoing and the recently-introduced models need to be improved with a view to phenomenological applications.

As a significant related issue, important works were presented during the Workshop in which holography is used to understand the entanglement entropy of quantum field theories.

– Holography and out of equilibrium physics

Holographic methods have significant applications in the study of non-equilibrium physics of strongly coupled quantum field theory models. In most cases they indeed prove to be the only available tools. The evolution of a QFT perturbed away from thermodynamical equilibrium is mapped into the dynamics of classical fields in black hole backgrounds. Exploration of black hole geometries which are holographically dual to strongly coupled plasmas/fluids has disclosed profound relations between Navier-Stokes equations on a fixed background and Einstein's equations in one dimension higher. This "fluid-gravity" correspondence, while retaining its original motivation as a model for strongly coupled plasmas (as observed in ALICE), has now been developed into a much more acute conceptual tool. More specifically, the general holographic relation between fluids and gravity has potential implications/restrictions for the behavior of gravity at short distances ("stringy" scales). Conversely, the correspondence has made it possible to define new, more general effective theories for strongly coupled fluids.

The correspondence has been exploited in the hydrodynamic regime (long-wavelength fluctuations around equilibrium) and beyond. In the first case, holographic studies have provided direct access to the transport coefficients of strongly interacting plasmas. In the second case they have offered a unique opportunity to model the evolution of a quantum system towards equilibrium (thermalization) as well as its response to quantum quenches. From the holographic point of view, non-stationary spacetimes or colliding shock waves describing the formation of a black hole, have been considered accordingly.

– Holography and Information

Recently there has been considerable interest in how entanglement in a quantum field theory manifests in the AdS/CFT correspondence. On one side, quanta are entangled whilst on the other classical fields are not. It has been suggested that quanta are linked in the gravity dual by worm holes and some explicit examples have been constructed. These ideas have profound implications regarding whether information is lost in black hole formation and evaporation and holography is providing real insight. Another strand of this work is the gravity dual description of entanglement entropy in field theory through the computation of minimal areas in gravitational backgrounds, as in Fig. 1.

– More formal developments

While it is important to orient holographic techniques towards phenomenologically relevant systems, it is mandatory to explore the correspondence at its roots, in the hope of providing novel validity checks and of discovering new unexpected relations between gravity, string and quantum field theories. This is often a very difficult task which, for example, entails investing the quantum field theory models under study with some special property (such as supersymmetry) which makes it possible to perform computations at strong coupling. Significant results on supersymmetric gauge theories, as well as theories where supersymmetry is dynamically broken, were illustrated at the Workshop.

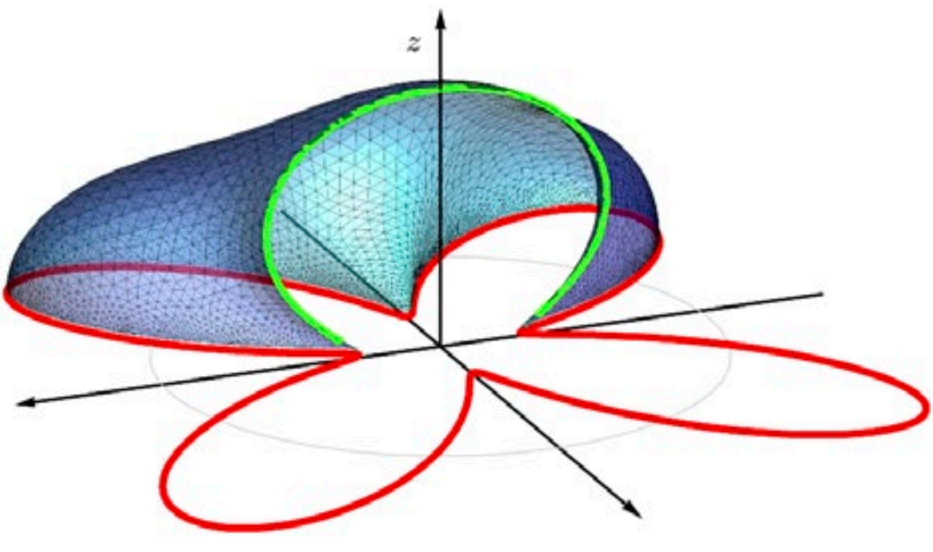

Figure 1. The entanglement entropy between the interior and exterior regions of the red curve in the xy plane (the "boundary"), is computed holographically by the area of the minimal surface extending in the "bulk" direction z and anchored to the curve on the boundary. From P. Fonda et al., JHEP 1502 (2015) 002.