Il Colle di Galileo

New Developments in AdS3/CFT2 Holography

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Abstract. This workshop focused on the holographic duality between string theory on three-dimensional anti-de Sitter space (AdS_3) and conformal field theories in two dimensions (CFT_2). It featured a school intended for doctoral students and early-stage researchers, a focus week on black-hole physics and a conference where the major advances discussed in the workshop were presented. This eight-week long meeting enjoyed a wide participation, also thanks to additional funding from the Simons Foundation and the Associazione Casse di Risparmio Italiane (ACRI), bringing together specialists and young researchers from all over the world.

Keywords. AdS/CFT correspondence, two-dimensional conformal field theories, higher-spin symmetries, integrability, black holes, localisation, gauged linear sigma models, four-dimensional instantons.

Scientific background and motivation

Two of the key problems of modern theories of fundamental interactions are the understanding of strongly coupled gauge theories and of quantum gravity. Holographic duality, through the celebrated work of Maldacena, connects these two seemingly very different problems; it does so via a strong/weak correspondence, making it possible to infer the behaviour of strongly coupled gauge theory from a weakly coupled theory of gravity and vice versa. This striking conjecture has fundamentally reshaped the way we think of gauge and gravity theories in the quantum regime.

A quantitative description of holographic duals with little or no supersymmetry is an important goal of the community, since it would likely lead to a much better understanding of strongly coupled phenomena such as confinement or black-hole entropy. However, a quantitative framework of generic dualities continues to be very ambitious. Instead, it may be useful to identify examples which have interesting dynamical behaviour while retaining simplifying features that allow for a quantitative analysis.

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AdS_3/CFT_2 duality is an ideal toy-model for such investigations. Since it has a relatively small amount of supersymmetry (half of the maximally supersymmetric case of AdS_5/CFT_4) it allows for rich dynamics. At the same time, AdS_3/CFT_2 plays an important role in a variety of problems in theoretical physics, including the strong- coupling dynamics of two-dimensional gauge theories, dynamics of three-dimensional black-holes, quantum instanton moduli space of four-dimensional gauge theory, microscopic entropy counting in five-dimensional black-holes, higher-spin symmetries and integrable models, to name but a few. Below, we briefly review the principal directions of AdS_3/CFT_2 research, highlighting developments discussed during the workshop.

GLSM. A prominent feature of the AdS_3/CFT_2 correspondence, as compared with its higher-dimensional, more-supersymmetric cousins, is that CFT_2 arises as an infra-red (IR) fixed point of a renormalisation-group (RG) flow from a (non-conformal) two- dimensional gauge theory into ultra-violet (UV). These theories have (4, 4) supersymmetry as introduced in the seminal work of Gates, Hull and Roček. The renormalisation group flow of such theories can be understood using Witten's gauged linear sigma models (GLSM) paradigm. These methods have been used in the past within the context of gauge/string duality and their role in the gravity dual of strings on $AdS_3 \times S_3 \times S_3 \times S_1$ proposed by Tong was discussed during the workshop.

2-d CFT. Powerful two-dimensional conformal field theory methods have been used in two ways to investigate the AdS_3/CFT_2 correspondence. Firstly, it is believed that at some point in its moduli space, CFT_2 is described as a deformation of a symmetric- product (Sym_N) orbifold. Near such a point one can employ CFT_2 methods to compute correlation functions of many observables of the theory. Secondly, when the geometry is supported by NS-NS flux alone, the string theory can be analysed using a Wess-Zumino-Witten model, as done by Maldacena and Ooguri. During the workshop, numerous results concerning the WZW point were presented, particular attention being paid to the role of long strings in the spectrum of the theory.

Black holes. Three principal connections relate the AdS_3/CFT_2 to black-hole physics. Firstly, black holes in three-dimensional gravity (so-called Bañados-Teitelboim-Zanelli black holes), are particularly simple, allowing for the investigation of quantum gravity questions which would be challenging in other dimensions. Secondly, the D1/D5 system and its description in the IR as a Sym_N CFT_2 is a key constituent in deriving black-hole entropy via microscopic state counting for certain five-dimensional black-holes, as originally proposed by Strominger and Vafa and much subsequent work. The D1/D5 system is fundamentally connected with AdS_3/CFT_2 correspondence and these links have been extensively exploited in literature. Thirdly, the fuzzball proposal of Mathur and collaborators states that black-hole entropy can be interpreted as arising from a large number of possible classical solutions which all appear as the black hole to a distant observer but differ in the interior. In all these settings, the D1/D5 system, the AdS_3 string theory

and the Sym_N CFT_2 feature prominently. During the whole workshop and especially during the Focus week, the latest developments in black-hole physics and its relationship to low-dimensional holography were discussed. These included topics such as Siegel modular forms and black-hole entropy, entanlgement entropy, microstate geometries, higher-spin geometries and the Sachdev-Ye-Kitaev model.

Gauge theories and 4-D instantons. It is well known that the D1/D5 system gives a string-theoretic interpretation of the Atiyah-Drinfled-Manin-Hitchin (ADHM) construction of instantons in four-dimensional gauge theories and can therefore provide important insights into geometric quantities such as Donaldson or Seiberg-Witten invariants. Sigma models on the moduli space of such instantons are known to be described by CFT_2 that enter the AdS_3/CFT_2 correspondence. These moduli spaces have been investigated extensively both in literature on physics and mathematics, particularly in relation to localisation methods. These topics, related matters in GLSMs and the role of anomalies in lower-dimensional gauge theories were reviewed in lectures by Benini, Gomis and Komargodski during the doctoral school which took place during the second week of the programme.

Higher-spin symmetry. It is believed that within a suitable "tensionless" limit, string theory undergoes large symmetry enhancement and can be described by an interacting higher spin theory of the type introduced by Vasiliev. Via the AdS/CFT correspondence, this then leads to dualities between higher-spin theories and vector-like conformal field theories. While such theories can be understood in diverse dimensions, they are particularly interesting in the context of AdS_3, where the symmetry combines further with Virasoro algebra, giving rise to an even larger W-algebra of asymptotic symmetries, as discussed by Gaberdiel and Gopakumar. This offers a unique opportunity to understand such a "tensionless limit". Indeed, recent work has shown that certain quantities can be matched between higher-spin theories and the Sym_N CFT_2. In related recent developments, black holes and their properties such as entanglement entropy have been investigated in the context of higher-spin theories. Some of these results were introduced during the school by Gopakumar and Vasiliev, and the latest developments were subsequently presented during the workshop.

Integrability. Breakthroughs in understanding AdS_5/CFT_4 and AdS_4/CFT_3 have relied heavily on integrability. More recently, integrability has been shown to exist in string theories on AdS_3 backgrounds, both classically and at quantum level, through the construction of an exact all-loop integrable two-body worldsheet S-matrix. There has also been evidence of integrability on the CFT_2 side. During the workshop, the latest results, including the derivation of the protected closed string spectrum in both $AdS_3 \times S^3 \times T^4$ and $AdS_3 \times S^3 \times S^3 \times S^1$, the effect of wrapping interactions and investigations of the role of integrability in other AdS_3 and AdS_2 backgrounds, were presented. Additionally, during the school, a course on integrable methods in AdS_3/CFT_2 and an introduction to integrable spin-chains were held by Stefański and Ohlsson Sax respectively.

Workshop

The workshop saw the participation of 170 researchers over an eight-week period, with three weeks being devoted to special activities. Towards the beginning of the workshop, a one-week doctoral school was held with the aim of introducing early-stage participants to the major advances of the field. A few weeks later, a *focus week* on black-hole physics took place, to gather a critical mass of researchers interested in this important topic; the focus week was organised in collaboration with Alejandra Castro from the University of Amsterdam. Finally, towards the end of the workshop, a one-week conference was held, which served as a summary of the workshop activities and progress. During the other weeks, a regular programme involving a daily seminar (typically, a long blackboard presentation) was held. This guaranteed ample space for discussion and created a very productive atmosphere throughout the workshop, leading to numerous collaborations. Further details of the activities are described below.

School – AdS_3: theory and practice. In the second week of the workshop, from March 27th to 31st, we hosted an advanced school which was attended by 84 participants. This was intended as an introduction for junior researchers to advanced topics that are under current research developments. The lectures were given by some of the leading experts on each topic: Francesco Benini, Two-dimensional GLSM and Localisation; Jaume Gomis, Sphere Partition Functions and Geometry; Rajesh Gopakumar, The stringy symmetries of AdS_3; Zohar Komargodski, Global Aspects and Anomalies in Quantum Field Theory; Olof Ohlsson Sax, An introduction to integrable spin chains; Bogdan Stefański, The exact closed-string spectrum of AdS_3/CFT_2 from integrability; Mikhail Vasiliev, Invitation to higher spins: from general properties to open problems.

The broad spectrum of the lectures mirrors the diversified research topics related to AdS_3/CFT_2, and it connects them to other research fields. The experience of the school was particularly fruitful since the GGI setting encouraged the audience to interact with lecturers both during and after the lectures. The abundance and quality of these discussions highlighted the remarkable success of the school. Moreover, since many of the younger participants remained after the school, they were able to use their newly-acquired knowledge, to better understand the subsequent weeks' research discussions and the bigger picture in the field.

Focus week – Recent developments in AdS_3 black-hole physics. A focus week with the aim of discussing the physics of black holes in AdS_3 was held from April 10th to 14th; it was organised in collaboration with Alejandra Castro from the University of Amsterdam. This event received much attention, to the point that the number of excellent applications tested the logistic constraints of GGI. We were able to invite a total of 57 participants, 19 of whom gave seminars during the focus week. For this reason the format of the event was designed to resemble that of a conference. The schedule allowed participants to interact and work dur-

ing breaks or in the late afternoon. The number and the exceptional quality of the scientists who took part in this event made it one of the most successful moments of the workshop. While the focus was on black-hole physics, many closely related topics were discussed, including entanglement entropy, supergravity and higher-spin theories, to name but a few. This stimulated broad-ranging discussions which often continued over the following weeks, as many researchers stayed on for at least one more week after the event.

Conference – Classical and quantum aspects of AdS_3/CFT_2 correspondence. The conference had the goal of providing the broadest platform to present the latest achievements and challenges of research in AdS_3/CFT_2. It took place from May 2nd to 5th, and was attended by 61 participants; a total of 18 talks were given. This provided a natural way to conclude the workshop. With a selection of talks geared slightly more towards string theory, higher spins, and integrable and conformal field theories, it presented a wide array of excellent talks and interesting research reports. Topics discussed included the latest advances in the WZW approach to AdS_3 strings, results from classical and quantum integrability in AdS/CFT, deformations of integrable structures, Liouville theory, lattice approaches to string theory, and the latest results on the symmetric product orbifold CFTs. The broad scope and impressive quality of the talks presented was an indication of the importance of AdS_3/CFT_2 in string theory and gravity, and of the success of the workshop in presenting the latest developments in this field.

Simons Fellows

Thanks to the support of the Simons foundation, the workshop benefited from the attendance of two distinguished scientists, who helped guide the scientific discussions throughout the program.

Chris Hull FRS (Imperial College). Chris Hull is a leading expert in supergravity, supersymmetric string backgrounds and string theory. His key contributions include the understanding of string dualities and M theory, as well as non-commutative gauge theories. In his early work with Gates and Roček, he constructed a framework for sigma models with (4, 4) supersymmetry. Not only do these feature prominently in AdS_3/CFT_2 correspondence, they have also been instrumental to our understanding of generalised geometry. By way of recognition of his impact on theoretical physics, he has been elected fellow of the Royal Society and has received the Institute of Physics Dirac Medal.

Mikhail Vasiliev (Lebedev Institute). Mikhail Vasiliev is renowned for his contribution to the study of interacting higher-spin fields. He was the first, together with Efim Fradkin, to construct a consistent interaction for higher spins in 1986. A few years later he proposed a minimal theory of interacting higher-

spin fields, named after him, which is the corner stone of our understanding of such interactions to date.

Young Investigator Training Programme

The workshop received additional support from the Associazione Casse di Risparmio Italiane (ACRI) under the *Young Investigator Training Programme*. This allowed 27 young researchers from all over the world to attend the workshop for two or three weeks and visit another research institute in Italy, spending a total of at least one month in Italy. This programme was perfectly suited to our activities as it attracted young talents to our workshop and gave them additional means of establishing collaborations with Italian researchers; the institutes visited by the young researchers include ICTP and SISSA in Trieste, Scuola Normale in Pisa, as well as the INFN sections in Bologna, Florence, Padua, Parma, Rome and Turin.

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