Cargese Summer Institute 2014: String Theory and Holography Scientifique Report

1 Summary

The French village of Cargese on the island of Corsica is home to an institute which has been hosting conferences, schools and workshops in various areas of physics for several decades. Among these, there have quite regularly (once every one of two years) been schools in theoretical high-energy physics, formal aspects of quantum field theory, and in more recent years string theory. These schools have been, and still are, very successful, and are among the most important schools in the field. Being a student or lecturer in Cargese has been an essential step in the education of generations of theoretical high-energy physicists.

What makes the Cargese school special is that it is a relatively small school in a somewhat isolated location, so that the opportunities for a direct interaction between lecturers and participants is unprecedented. It also brings together students from all over the world, in particular the US and Europe, and there probably is no school that generates so much intercontinental interaction. Many scientists have made lifelong friends in Cargse.

The 2014 edition of the Cargese summer school in high energy physics took place June 2-June 14 under the theme *String Theory and Holography*. There were 62 participants from 13 countries and 16 speakers gave a total of 44 hours of lectures. Generically each lecturer gave two 1.5hr lectures and in addition two lecturers gave a single 1.5hr lecture.

The participants were chosen by our committee of six organisers from a pool of 220 applicants based on publications and their letter of recommendation. We were extremely successful in attractors the very best researchers in the field as lecturers.

The structure of the school was as follows: excluding the arrival and departure days of June 2 and June 14, there were 9 1/2 days of lectures and one rest day (Sunday June 8). The typical schedule was two 1.5hr lectures in the morning session at 9am and 11am followed by lunch and a lengthy afternoon break until two one hour lectures at 5pm and 6pm. The center at Cargese provides an ideal setting for informal discussions and collaboration between faculty and participants on the instittute grounds and on the nearby beach and this was typically the focus of the afternoon break between sessions.

The lectures were at a level such that advanced graduate students and beginning postdocs would most benefit. A fair characterization would be that each lecturer expanded the subject matter of a typical one hour research level seminar into three hours by including pedagogical material.

2 Scientific Program

2.1 Ignatios Antoniadis

Title: Aspects of String Phenomenology in the LHC era
Summary: The present status of LHC physics is reviewed and future projects are presented. The main directions of physics Beyond the Standard Model are discussed in connection the the mass hierarchy problem. An overview of string phenomenology is presented and the main issues are described in the context of heterotic and type II strings.

2.2 N. Arkani-Hamed

Title: The Amplituhedron
Summary: A introduction to planar scattering amplitudes in $\mathcal{N} = 4$ SYM and the amplituhedron.

2.3 C. Bachas

Title: Defects in Conformal Field Theory
Summary: Rapid review of defects in QFT and their uses. I will then focus on codimension-1 defects in the two maximal superconformal theories: N=4, d=4 SYM and N=6,8 d=3 ABJM theory, and describe some recent work on their supergravity duals.

2.4 Tom Banks

Title: Holographic Space-Time
Summary: Description of a general formalism for quantum gravity, which is supposed to include known string models as special cases. I will mostly concentrate on a model for 11D SUGRA compactified on a 7 torus of Planck size, where the variables satisfy simple anti-commutation relations. I'll present a collection of models describing scattering in such a space-time, all of which have many properties one would want for a theory of QG: particle like states, as well as black hole like states, with the qualitative properties of real black holes and particles.

2.5 Alejandra Castro

Title:Holographic Entanglement Entropy in AdS_3/CFT_2
Summary: AdS_3 gravity provides a useful lab to test non-linear and non-local properties of quantum gravity. The goal of these lectures is to cast non-perturbative aspects of these theories, such as black holes and entanglement entropy, in a way that respects the non-local features.

2.6 Sergei Gukov

Title: Exactly Solvable SQCD
Summary: We explore dynamics of two-dimensional non-abelian gauge theories with N=(0,2) supersymmetry that include N=(0,2) supersymmetric QCD and its generalizations. In particular, we present the phase diagram of N=(0,2) SQCD and determine its massive and low-energy spectrum. We find that the theory has no mass gap, a nearly constant distribution of massive states, and lots of massless states that in general flow to an interacting CFT. For a range of parameters where supersymmetry is not dynamically broken at low energies, we give a complete description of the low-energy physics in terms of 2d N=(0,2) SCFTs using anomaly matching and modular invariance. Our construction provides a vast landscape of new N=(0,2) SCFTs which, for small values of the central charge, could be used for building novel heterotic models with no moduli and, for large values of the central charge, could be dual to AdS_3 string vacua.

2.7 Sean Hartnoll

Title: Disorder in QFT and holography
Summary: In QFT the relevance of disorder is described by the Harris criterion, which I will derive. I will also discuss the phenomenon of Griffiths singularities, which arise when the partition function is dominated by rare disordered events. I will explain the difficulty of finding a disordered fixed point in QFT. I will show that using holographic methods one can find a disordered fixed point. The fixed point is described by a disordered spacetime whose averaged metric takes the Lifshitz form.

2.8 Jeff Harvey

Title: Moonshine and (Mock) Modular forms
Summary: I give a brief overview of modular forms and the connection between the modular j function and the Monster group known as Monstrous Moonshine. I then go on to discuss Mathieu moonshine, involving a connection between the elliptic genus of K3 surfaces and the Mathieu group M24 and Umbral Moonshine which a mathematical extension of this involving 23 pairs of finite groups and vector-valued mock modular forms. Some mathematical properties of mock modular forms are discussed and they way they arise in the computation of elliptic genera of noncompact spaces is outlined. Finally, some aspects of the discriminant property of Umbral moonshine are covered along with some possible extensions to Monstrous Moonshine.

2.9 Juan Maldacena

Title: Entanglement and geometry
Summary: discuss connections between entanglement and geometry. We discuss the interpretation of the eternal black hole as an entangled system and some of its implications for the black hole information paradox.

2.10 Zohar Komargodski

Title: The Geometry of the Space of Theories
Summary: I review the Riemannian geometry that is present on the space of d-dimensional conformal field theories, and specialize to supersymmetric examples. For theories with four supercharges in $d > 2$, I explain the structure of the space of theories as an algebraic variety and count the dimension of the space. In two dimensions, I explain how to the geometry can be extracted using recent progress on supersymmetric localization.

2.11 Yaron Oz

Title: Lifshitz Field Theories and Turbulence
Summary: First Lecture: We introduce Lifshitz scaling and its realization in quantum field theories and gravity. We construct the hydrodynamic limit and apply it to quantum critical points. Second Lecture: We introduce turbulence, its universal structure in the initial range of scales and the singularity problem. We show how embedding in relativistic CFT hydrodynamics and the use of gravitational variables provide new insights towards the solution of these two fundamental problems.

2.12 Eliezer Rabinovici

Title: Geometry and Noise
Summary: We describe the fine structure of long-time quantum noise in correlation functions of AdS/CFT systems. Under standard assumptions of quantum chaos for the dynamics and the observables, we estimate the size of exponentially small oscillations and trace them back to geometrical features of the bulk system. The noise level is highly suppressed by the amount of dynamical chaos and the amount of quantum impurity in the states. This implies that, despite their missing on the details of Poincare recurrences, 'virtual' thermal AdS phases do control the overall noise amplitude even at high temperatures where the thermal ensemble is dominated by large AdS black holes. We also discuss EPR correlations and find that, in contrast to the behavior of large correlation peaks, their noise level is the same in TFD states and in more general highly entangled states.

2.13 S-J. Rey

Title: Extracting Physics out of SUSY Localization
Summary: SUSY localization technique enables to compute partition function (as well as a limited set of local observables) in supersymmetric field theories. I present physical interpretation of the result from the viewpoint of large-order behavior in perturbation theory in d=2,3,4,5,6 superconformal field theories. I draw intuition from Schwinger pair production in constant electric background in 1+1 dimensional QED, and apply it to the Coulomb branch matrix integral representation of the partition function. I demonstrate that Borel resummability structure combines perturbative and nonperturbative parts of the integrand such that the resurgence property is manifest.

2.14 Slava Rychkov

Title: 3d Ising model and how to solve it
Summary: Basics of 3d Ising model. $\mathbb{Z}_2$ broken, $\mathbb{Z}_2$ unbroken, and critical theory. RG interpretation. Focus on T=Tc. Scale invariance and consequences. Conformal invariance and consequences. "Scale implies conformal generically" and why. OPE and its convergence; associativity of OPE. Conformal bootstrap analysis for $\langle ssss \rangle$ in the 3d Ising CFT. The story of exactly two relevant scalars. C minimization conjecture for the 3d Ising CFT and numerical evidence for its validity.

2.15 Amit Sever

Title:Scattering amplitudes in planar N=4 SYM at finite coupling
Summary: Two very fundamental observable in any gauge theory are scattering amplitudes and Wilson loops. Scattering amplitudes measure how particles in the theory interact with each other. These are the building blocks of what we measure today at the LHC. Wilson loops are a generalization of the Aharonov Bohm phase. They measure how charged particles interact with the gauge degrees of freedom and may serve as a probe for the phase of the theory. Recent study of these objects reviled a structure that go well beyond perturbation theory and in some special cases even allow for a non-perturbative solution. In these lectures we will glimpse into this beautiful structure. We will use integrability techniques which turns out to be extremely powerful in certain theories.

2.16 Dam Son

Title: Spacetime symmetries of the quantum Hall effect
Summary: An introduction to the problem of the quantum Hall effects. I discussed the nonrelativistic general coordinate invariance, and how this invariance is not respected by the Chern-Simons theory. Then I introduced the formalism of Newton-Cartan geometry, and showed how one can use it to write down a general effective action that preserves general coordinate invariance. We then discussed the physical consequences of the effective action, in particular derived the first q^2 correction to Hall conductivity.

2.17 Andrew Strominger

Title: Soft Theorems and Asymptotic Symmetries
Summary: A pedagogical introduction was given to the relation between soft theorems and asymptotic symmetries. As an example it was demonstrated that Weinberg's soft graviton theorem is equivalent to the asymptotic BMS symmetry.

2.18 Erik Verlinde

Title: From Strings to Dark Matter
Summary: The long string phenomenon, in which short (= high tension) strings form bound

states of longer strings with lower tension, is a key feature of string theory that is crucial for the correct microstate counting of black holes. In a seemingly unrelated development, it is argued that space time is connected due to entanglement of the vacuum. In anti-de Sitter space-time the associated entanglement entropy is known to be given by the Bekenstein-Hawking formula. By combining these observations a description is presented of AdS space-time as the ground state of an entangled network of long strings whose tension is set by the AdS radius. AdS black holes correspond to local regions in which these long strings have become excited. We discuss the flat space limit of this proposal and present a natural generalisation to de Sitter space. We find that dS space is represented as a homogeneous entangled network of excited long strings at the Hawking-Page transition point (i.e. where the Cardy formula becomes valid). This description of the dS space correctly reproduces the Gibbons-Hawking entropy and temperature and can also be extended to Narai black holes. Following an analogy with entangled polymer networks, we argue (and present evidence for the fact) that this view on de Sitter space has observable consequences. Specifically, it leads to a formula that quantitatively describes effects currently attributed to dark matter.

3 Assessment

Attendance at the Cargese summer school can be a deeply important part of a graduate students education and similarly for young postdocs it can give a great boost to their research career.

The central strategy of each lecture course was to bring the students up to speed with state of the art research, starting from a good graduate level background in quantum field theory, general relativity and string theory.

The theme of the conference was *String Theory and Holography* but with some perspective one might say that the most universal thread through the various lectures series was quantum field theory. The lectures of Rychkov explained novel non-perturbative methods in three dimensional conformal field theory. The non-perturbative technqiues discussed have been developed in the last few years and promise to form a central role in non-perturbative quantum field theory for years to come. Quite broadly the students declared this series to be the most rewarding, the lectures were grounded in a simple example but have far reaching consquences.

Complementing these lectures were several interesting series by Komargodksi, Bachas, Sever and Gukov on aspects of conformal field theory in various dimensions. Sever presented an overview of many aspects of integrable structures in $\mathcal{N} = 4$ SYM in four dimensions and argued that the planar limit may soon admit a complete solution. There has been several papers in the very recent literature combining the conformal bootstrap techniques of Rychkov et al. with integrable structures in $\mathcal{N} = 4$ SYM and while this was not discussed directly in the lectures, we feel that the students were left well equipped to enter this research field.

The presentations of Bachas and Gukov were designed to give the students an overview of the many exotic (and not so exotic) applications of conformal field theory in two and three dimensions. The models presented typically involved some minimal ammount of supersymmetry and in certain cases can be solved non-perturbatively. This provided an interesting counterbalance to the conformal boostrap but it is quite likely that the next five years will see a synthesis of many of these techniques.

It was instructive that we had lectures centered on perturbative quantum field theory, which for many students is how they learned the subject. Strominger discussed his new interpretations of Weinberg's soft graviton theorem through holography of flat space. Antoniadis described his methods for deriving phenomenological models of particle physics from string theory.

Many lecture series (Banks, Castro, Hartnoll, Maldacena Oz, Rabinovici) were focussed on new developments in holography. Typically these new developments are pushing the boundaries of applicability of holography in that these research programs are studying dualities between models with much less symmetries that the AdS/CFT duality.

In summary we saw a broad swath of formal high energy physics represented in the lectures. Typically this research field snowballs every few years with different sectors consuming each other and as such young researchers need to have a good understanding of several areas at any given time. The timeliness and scope of these lectures has given the students an excellent opportunity to contribute in the near future.

There are two particular elements of the program which we are quite proud of and deserve particuar mention. Firstly on the afternoon of Thursday June 5, we organised a "gong show" involving 3-minute presentations from each participant. Even with the strictest timekeeping, this adds up to over 3hours of continuous presentations. The participants were encouraged to take a lighthearted approach and collectively this provided a excellent way of introduction for all the students such that they get a feeling for the research problems each other were working on. In addition it is a very interesting overview of the entire field.

Secondly on the afternoon of Tuesday June 10 we held our traditional "Wisdom Tree" session. This took place in the garden of the institute and involved four particularly well-regarded faculty answering a slew of questions from the particpants on a whole range of scientifique issues, ranging from philosophical questions of science, to concerns about the job market and broad questions regarding research directions. The questions were submitted anonymously in advance. Our four faculty members included two pre-eminent senior faculty in Jeff Harvey and Erik Verlinde as well as two of the most accomplished young researchers in the field Zohar Komargodski and Slava Rychkov. We were particularly pleased that this quartet balanced against each other so well and we were all confident that the particpants had an enriching and unique experience.

4 Annexes

List of Organisers:
Laurent Baulieu(LPTHE)
Karim Benakli (LPTHE)
Jan de Boer (Amsterdam)
Nick Halmagyi (LPTHE)
Zohar Komargodski (Weizmann)
Eliezer Rabinovici (Jerusalem)

List of Speakers[1]:
I. Antoniadis (CERN)
N. Arkani-Hamed (IAS)
C. Bachas (ENS Paris)
T. Banks (UCSC and Rutgers)
A. Castro (Amsterdam)
S. Gukov (Caltech)
S. Hartnoll (Stanford)
J. Harvey (Chicago)
Z. Komargodski (Weizmann)
J. Maldacena (IAS)
Y. Oz (Tel Aviv)
S. Rychkov (UPMC, ENS and CERN)
A. Sever (IAS)
D. Son (Chicago)
A. Strominger (Harvard)
E. Verlinde (Amsterdam).

[1]K.Papadodimas (Groningen and CERN) cancelled at the last minute due to a medical condition

Program

	9h00-10h30	11h00-12h30	17h00-18h00	18h00-19h00
Mon June 2				Arrival
Tues June 3	Rychkov	Sever	Antoniadis	Strominger
Wed June 5	Sever	Rychkov	Strominger	Harvey
Thu June 6	Antoniadis	Harvey	[—- Gong	Show—–]
Fri June 4	Rey	Oz	Hartnoll	Rabinovici
Sat June 7	Verlinde	Hartnoll		
Sun June 8		rest	day	
Mon June 8	Gukov	Son	Komargodski	Oz
Tues June 9	Castro	Komargodski	Verlinde	Wisdom Tree
Wed June 10	Banks	Bachas	Son	Arkani-Hamed
Thu June 11	Arkani-Hamed	Maldacena	Gukov	Bachas
Fri June 12	Castro	Maldacena	Banks	
Sat June 13	Departure			

Participant List

Last Name	First Name	Institute	Country
Afshar	Hamid Reza	Groningen University	Netherlands
Azeyanagi	Tatsuo	ENS	France
Babinet	Nicolas	LPTENS	France
Bae	Jinbeom	Seoul National University	Korea
Banerjee	Sibasish	University Montpellier 2	France
Banerjee	Souvik	University of Groningen	Netherlands
Bautista	Teresa	LPTHE	France
Bourget	Antoine	LPTENS	France
Camps	Joan	DAMTP, Cambridge University	England
Chapman	Shira	Tel Aviv University	Israel
Darme	Luc	LPTHE	France
Donnay	Laura	ULB	Belgium
Erbin	Harold	LPTHE	France
Fan	Yale	Harvard University	USA
Folacci	Antoine	Université de Corse	France
Gaddam	Krishna	Utrecht University	Netherlands
Golkar	Siavash	University Of Chicago	USA
Hansen	Tobias	Universitaet Hamburg	Germany
He	Temple	Harvard University	USA
Hogervorst	Matthijs	LPTENS	France
Hunter-Jones	Nicholas	Caltech	US
Ilgin	Irfan	University of Amsterdam	Netherlands
Kabir	Laurens	University of Amsterdam	Netherlands
Kapec	Daniel	Harvard University	USA
Karlsson	Anna	Chalmers	Sweden
Kelm	Maximilian	ETH	Switzerland
Kol	Uri	Tel Aviv University	Israel
Kuznetsova	Zhanna	Federal University of ABC	Brasil
Leduc	Letitia	LPTENS	France
Lewkowycz	Aitor	Princeton University	USA
Li	Wei	Max Planck Institute	Germany
Lloyd	Tom	City University London	England
Longhi	Pietro	Rutgers University	USA
Lupsasca	Alex	Harvard University	USA
Mayerson	Daniel	University of Amsterdam	Netherlands
Mazac	Dalimil	Perimeter Institute	Canada
Mekareeya	Noppadol	CERN	Switzerland

Melgar	Luis	IFT UAM/CSIC	Spain
Merbis	Wout	University of Groningen	Netherlands
Meyer	Adiel	Tel-Aviv University	Israel
Mitra	Prahar	Harvard University	USA
Mosk	Benjamin	University of Amsterdam	Netherlands
Murata	Masaki	Institute of Physics	Czech Rep
Nazaroglu	Caner	University of Chicago	USA
Oblak	Blagoje	ULB	Belgium
Park	Daniel	Stony Brook University	USA
Pasterski	Sabrina	Harvard	USA
Pathak	Abhishek	Harvard University	USA
Pei	Du	Caltech	USA
Pinzani	Natalia	University of Amsterdam	Netherlands
Probst	Jonas	University of Oxford	England
Rabinovich	Eugene	Duke University	USA
Routh	Alasdair	DAMTP, University of Cambridge	England
Rudra	Arnab	University of Cambridge	England
Shamir	Itamar	Weizmann institute of science	Israel
Solard	Gautier	LPTHE	France
Tangarife	Walter	The University of Texas at Austin	USA
Toppan	Francesco	CBPF	Brasil
Torres	Terrence	UC Santa Cruz	USA
Vanhoof	Joris	Vrije Universiteit Brussel	Belgium
Vieira Gomes	Joao Miguel	DAMTP, University of Cambridge	England
Vitale	Lorenzo	EPFL	Switzerland
Zojer	Thomas	University of Groningen	Netherlands