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REVIEW ARTICLE

Proceedings of the D2 parallel session on Strings, Branes and M-Theory

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Abstract This is a very brief summary of the parallel presentations made in the D2 session of GR20. It also contains a short report on the joint D1, D2, D4 session on the quantum mechanics of black hole evaporation.

Keywords String theory · AdS/CFT Correspondence · Black holes · Branes · M-Theory

1 Introduction

There were eighteen talks in the different afternoon sessions of the D2 section of GR20 which covers the topics of Strings, Branes and M-Theory. They were on topics such as the AdS/CFT correspondence (its applications to questions in quantum field theory as well as its implications for gravitational physics), higher spin theories and their holographic duals as well as more generally on black holes and other solutions in string theory. In Sect. 2 we briefly summarise some of the presentations under each of these headings. In Sect. 3 we report on a topical joint session on the ever provocative topic of black hole evaporation and information loss. This was co-organised by the D1, D2 and D4 chairs.

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2 The D2 session talks

2.1 AdS/CFT correspondence

Gary Horowitz described how some of the features of high T_c superconductors can be obtained quantitatively from general relativity through an application of the AdS/CFT correspondence. These include certain striking features of their conductivity. Veronika Hubeny presented a new construct—the causal wedge—in AdS which might carry important information about the boundary CFT and function in ways analogous to the entanglement entropy which is measured by extremal surfaces in AdS. Mukund Rangamani reviewed aspects of the fluid/gravity correspondence and its applications to understanding better the membrane paradigm combining it with features of the black-fold approach. Romuald Janik demonstrated a striking application of the AdS/CFT correspondence to the dynamics of non-perturbative plasma by considering very high order dissipative hydrodynamics and its relation to non-hydrodynamical modes.

2.2 Higher spin theories and holography

Andrea Campoleoni described how the algebra of higher spin gauge theories on AdS_3 is determined to be a W-algebra in a Chern–Simons frame like formulation. He went on to give a new perspective on this in a metric like approach. Joris Raeymakers presented a novel class of conical surplus solutions in 3d higher spin theories and described their relevance to holographic dualities. Eric Perlmutter presented several results on nontrivial checks of holographic duals to 3d higher spin theories which were not fixed by the symmetries of the system. Alejandra Castro presented a proposal for computing the entanglement entropy of CFTs dual to higher spin theories in terms of Wilson lines of the underlying Chern–Simons framework.

2.3 Gravitational problems in string theory

Finn Larsen presented intriguing observations on a quantisation rule for the horizons of several charged black holes. William Kelly described a positive energy theorem (stability) for gravity on AdS with dirichlet boundary conditions. Benson Way constructed a black funnel solution as the holographic dual to strongly interacting $\mathcal{N} = 4$ plasma in the Hartle–Hawking state in a black hole background. Gavin Hartnett described new geon solutions as perturbations of the AdS soliton geometry. Keiju Murata described the instability of a massive scalar field at the horizon of an extreme Reissner-Nordstrom black hole.

2.4 Stringy gravity

Michael Koehn talked about $\mathcal{N} = 1$ supergravity theories with higher derivative scalar field couplings with potential applications to particle physics and cosmology models. George Alekseev described a general technique for solving the supergravity equations of motion that arise from string theory. Alexander Burinskii presented results on the $\mathcal{N} = 2$ superstring and the Kerr geometry. Jen-Chi Lee reviewed work by his group of researchers on proving existing and discovering new recursion relations for scattering amplitudes in string theory. Piotr Sulkowski talked about new geometrical insights from Chern-Simons theories and their refinements.

3 Quantum mechanics of black hole evaporation

This session was spread over a full afternoon and had a very large audience. The format of the session was the following. There were four perspective talks by Robert Wald, Abhay Ashtekar, Gary Horowitz and Don Marolf which presented different viewpoints on the problem of information loss. These talks were interspersed with slightly shorter research talks by Aron Wall, Daniele Pranzetti and Kyriakos Papadodimas. In addition to short question sessions after each talk there was a long period of about 25 min at the end where the speakers jointly fielded questions from the audience leading to a stimulating discussion. Below is a quick report of the salient aspects of the talks.

Bob Wald's talk, titled "Information Loss" first described the notion of entanglement in quantum mechanics and QFT and how it is central to the Hawking radiation process and leads to an entanglement of the interior with the exterior. It leads to a semi-classical picture in which a pure state evolves to a mixed state. He then laid out the various possibilities for this picture in a fully quantum theory. These were

- Semiclassical picture is correct in its essential features and pure $\rightarrow$ mixed.
- Remnants remain behind
- Correlations are restored either (a) in a final burst or (b) gradually during the evaporation process so that the final state is pure.

He went on to outline the problems he saw with the second and third alternatives above. Namely, either one has to deal with how to have a planckian object store a lot of information or have a concrete way of seeing why effective field theory breaks down in a regime where one expects it to be valid. It is this latter possibility that leads to firewall like conclusions. He therefore felt that the first was the only workable alternative. However, he stressed that this is not the same as questioning the validity of quantum theory, since pure $\rightarrow$ mixed evolution does take place when one evolves to a non-cauchy time slice. In his opinion this was the kind of evolution that takes place in black holes and he refuted some objections to this scenario based on energy non-conservation and expressed scepticism about the AdS/CFT correspondence being the solution to the unitarity restoration in the absence of a complete prescription.

Abhay Ashtekar put forward his perspective on black hole evaporation based on an extensive analytic cum numerical study of a solvable system of black hole formation and evaporation in two dimensions. This is the CGHS model which consists of 2d dilaton gravity coupled to a large N number of scalar matter fields. This was studied in the mean field approximation which holds when $N \gg 1$ and in this limit one can neglect the backreaction due to matter. One finds a weak singularity which does not reach $\mathcal{I}^+$ and thus no thunderbolt. But there was a remnant which was universal and independent of the initial mass. The bondi flux was also universal and incompatible with the Hawking thermal flux. In a fully quantum framework, a scenario was outlined which would have no remnants and would replace the singularity of the mean field approximation by a quantum region of space-time. The main message he wished to convey from this study was that quantum spacetimes might in a some precise way be larger than classical spacetimes since the singularity is resolved and "opens up" a new region. Semi-classically information appears to be lost since the region $\mathcal{I}^+$ in this approximation is "smaller" than the region of $\mathcal{I}$ from which matter falls in. He believed this mechanism is also applicable for the big bang and leads to the restoration of the entropy bound conjectured by Bousso.

Gary Horowitz outlined the issues related to information loss as perceived by string theorists. He cautioned however about the varying degrees of consensus on various aspects that he would describe. Gauge-gravity duality is agreed upon by everyone as a framework within which to study this question concretely since people believe in the essential correctness of this duality. There is a smaller group of people who believe that fuzzballs are the correct description of black hole micro states and play an important role in the resolution of the information paradox. Finally there is the question of the black hole final state (a proposal of his with Maldacena) on which there was no agreement! He went on to describe the essentials of the AdS/CFT correspondence including black holes in AdS space-time and their properties such as the Hawking-Page phase transition. He pointed out the many successful checks of the correspondence together with the proposal that black holes are described as a thermal state in the dual field theory. The unitarity of the dual QFT description suggests that the Hawking evaporation process is unitary though it was mentioned that it has not yet been pinpointed where Hawking's arguments are evaded. He then went onto describe the fuzzball proposal whose key ingredient is that individual micro states of black holes correspond to geometries which have no horizon and quantum mechanically are states which extend out until the horizon. Thus in this picture semi-classical physics breaks down at the horizon itself and then there is no information puzzle. Finally, he outlined the final state proposal in which one modifies standard quantum theory in that final state boundary conditions are imposed at the singularity in such a way that external observers see unitary evolution.

Don Marolf put forward the point of view of the AMPS collaboration who conclude that variously commonly made assumptions about the validity of effective field theory at the horizon, restoration of unitarity etc. lead inevitably to the conclusion that there is a firewall at the black hole horizon. In his talk, Don described a variant of the original argument phrased in the language of the AdS/CFT conjecture. This argument considers the microstates corresponding to a large black hole (so that the energy spacing $\Delta E \approx \exp -S$ is very small, where S is the entropy). It goes on to show that what the infalling observer would have viewed as the vacuum state—so that it is annihilated by appropriate modes a—is not really so. This is because the micro state as an eigenstate of energy, as viewed by the boundary theory can also be viewed as approximate eigenstates of the number operator $b^\dagger b$ for exterior modes b. However, the number operator of the a modes, being maximally entangled with the interior have a non-zero value on eigenstates of $b^\dagger b$ (a and b are related by a Bogolyubov transformation) and hence a nonzero expectation value on any microstate. The expectation value of $a^\dagger a$ is well defined since there is a finite density of states in the dual field theory. This seems to indicate that one does not have the vacuum at the horizon but instead a firewall.

Marolf then went on to address various objections and criticisms that had been raised about the firewall argument. Finally, he ended with some thoughts on the formation and potential consequences of a firewall.

Aron Wall gave a sketch of his proof that the generalised second law holds, namely that the generalised entropy increases locally at every point on the horizon. This exploited a large symmetry that is present for a stationary killing horizon. Daniele Pranzetti described the black hole evaporation process as driven by the dynamical evolution of the quantum gravitational degrees of freedom resident at the horizon, as identified by the loop quantum gravity kinematics. He argued that this enables one to learn about the final stage of the evaporation process and show how the dynamics leads to the formation of a massive remnant. Kyriakos Papadodimas described how the interior of a black hole can be reconstructed from the point of view of the dual gauge theory in the framework of the AdS/CFT correspondence. He argues that the infalling observer does not notice anything special when crossing the horizon and that it is possible to resolve the information paradox without dramatic violations of effective field theory as opposed to the firewall and fuzzball proposals.