Holography and Black Holes

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YITP@40

Stony Brook, May 5, 2007

My Stony Brook years

I arrived at Stony Brook in 1991 and left in 1996. These were 5 wonderful years, full of physics.

I would like to thank all member of the YITP and especially my advisor, Peter van Nieuwenhuizen, (and also Martin and Warren) for their contribution to my education.

I worked closely with Peter on a number of topics (path integrals, renormalization) and I also had the privilege to have access to the "Books" or better "Peter's encyclopedia of Theoretical Physics, Vol. 1 to Vol. N".

Random YITP memories

• Working late with Peter till Marie would call and Peter would have to rush home.

• Spending Sunday mornings in Bonnie Lane (no weekends in Manhattan for me either!) and going through Peter's piles of papers and notes to see whether there is anything worth salvaging. Peter called it ”archeology” and it was lots of fun! One of my papers actually originated from such ”excavation”.

• Martin ”superspace-ing” my random physics question.

• Warren explaining things and worrying whether he gets his argument ”backwards”.

After Stony Brook:

Postdoc positions:

- 1996-1998: Leuven
- 1999-2000: Utrecht
- 2000-2001: Princeton

Faculty jobs:

- 2001-2003: Princeton, Assistant Professor
- 2003-now : Amsterdam, Associate Professor

One of the strong points in getting an education at Stony Brook is that one acquires a strong background on all topics of theoretical physics.

Most of my PhD work was on QFT topics. The topic I will discuss today however is about gravity.

Black holes and Holography

Defining questions in gravity for the last 30 years have been:

• Why does a black hole have entropy proportional to its horizon area?

• Is there information loss because of black holes?

• How does one resolve spacetime singularities, such as those inside black holes or in Big Bang cosmologies?

Recently, the AdS/CFT correspondence motivated a new idea in black holes physics, the fuzzball proposal which, if true, it would provide answers to these questions.

According to this proposal, associated with any black hole there are an exponential number of horizon-free non-singular solutions that look like the black hole asymptotically but generically differ from it up to the horizon scale.

These solutions represent the “microstates” of the black hole; the original black hole provides only the “average” description of the system.

This proposal would resolve black hole puzzles because:

• The entropy of the black hole would be of standard statistical origin. The physics of black holes would then be no different than that of a distant star, with temperature and entropy being of statistical origin.

• There are no horizons and therefore no information loss. Incomimg matter would escape back to infinity at late times.

• Spacetime is non-singular. The black hole singularity is an artifact of the coarse-grained description.

In this talk I will describe the origin of this proposal and progress towards promoting this interesting idea to physical quantitative model.

This talk is based on:

- KS, Marika Taylor, PRL (2007)
- Ingmar Kanitscheider, KS, Marika Taylor, JHEP (2007)
- Ingmar Kanitscheider, KS, Marika Taylor, 0704.0690

So let's starts from the beginning ...

Since the entropy of a black hole is proportional to the horizon area, the number of degrees of freedom of a black hole should be proportional to its horizon area.

And since black holes are the densest objects around we conclude that *the maximal number of degrees of freedom that can fit in a region bounded by area A is proportional to the area A*.

This is *drastically* different from Quantum Field Theory where the number of degrees of freedom is proportional to the volume rather than the surface area.

These considerations motivate the ['t Hooft ('93), Susskind ('94)]

Holographic principle

Any quantum $(d+1)$-dimensional gravitational theory should have a description in terms of a d-dimensional quantum field theory without gravity.

It is useful to think of the quantum field theory as "living" at the boundary of the spacetime region under consideration.

We will refer to the gravitational theory as the "*bulk*" theory, and the field theory as the "*boundary*" theory.

The AdS/CFT correspondence

A concrete realization of holography emerged about 10 years ago. According to this duality gravity in Asymptotically Anti-de Sitter $(d+1)$-spacetimes is dual to a QFT living at the d-dimensional conformal boundary of the spacetime. [Maladacena (1997)]

This is meant to be an exact equivalence between the two theories.

We won't need the details of the correspondence in this talk except for the main headline:

Quantum field theory data, such as the the vacuum structure and correlation functions, are encoded in the asymptotics of the bulk solution.

Back to black holes now ...

The entropy of a class of supersymmetric black holes has been understood in string theory using D-branes. [Strominger, Vafa] (1996)

The basic idea is simple:

Supersymmetric states (generically) exists for all values of the parameters of the underlying theory. Changing the gravitational strength one interpolates between the description of the system as a black hole and a description in terms of bound states of D-branes. Counting the degeneracy of the bound states one arrives exactly at the Bekenstein-Hawking entropy formula.

This argument shows that the gravitational entropy has statistical origin.

It does not explain however what *are* the gravitational microstates (in the regime where gravity is valid) nor answers the question of whether their dynamics is unitary.

Although the dynamics of D-branes is unitary, the Strominger-Vafa argument involves an extrapolation.

Next comes the AdS/CFT correspondence ...

Focusing on the near horizon region of these black holes one finds that the geometry becomes asymptotically AdS and the degeneracy of the D-brane bound states is the degeneracy of supersymmetric states of the dual CFT.

Since AdS/CFT is an exact equivalence of two theories and the boundary theory is unitary, the dynamics of the black hole microstates is unitary.

Although this in principle settles the issue of ”information loss” (i.e. there is no information loss) it still does not explain what is the gravitational nature of the black hole microstates, nor shows where does Hawking's original argument goes wrong.

But AdS/CFT correspondence predicts more ... [KS, Taylor (2006)]

Given any stable state of the dual QFT, characterized by a set of vacuum expectation values (vevs) of gauge invariant operators, there should exist a dual non-singular asymptotically AdS geometry encoding these vevs in its asymptotics. If the original state is pure, the dual geometry should be horizon-free.

So associated with any black hole microstate there must exist a horizon-free non-singular geometry. This is the fuzzball proposal!

Most of these geometries however would either contain regions of high curvature or be too similar with each other to be distinguishable within supergravity – one would need to incorporate string theory corrections.

The most basic questions are:

• Can one find enough such geometries for each black hole?

• What properties should such geometries have to be associated with black hole microstates?

• Can one show quantitatively how black hole properties emerge upon coarse-graining?

Answering these questions in full generality is currently out of reach.

However, one may focus on the simplest possible non-trivial set up. This is the so-called D1-D5 system. This is a simpler cousin of the system studied by Strominger and Vafa.

For this system an exponential number of horizon-free non-singular solutions was found by Lunin, Mathur (2001). This provided enough solutions to account for a fraction of the black hole entropy.

We recently completed this program by finding all such solutions [Taylor] (2005) [Kanitscheider, KS, Taylor] (2007).

The fuzzball metrics are of the form

$$ds^2 = -f(r,\theta,\phi)dt^2 + g(r,\theta,\phi)(dr^2 + r^2 d\Omega_2^2).$$

In the black hole solution, $f(r,\theta,\phi) = g^{-1}(r,\theta,\phi) = F(r)$, where $F(r)$ vanishes at the horizon, and diverges at the singularity.

In the fuzzball solutions, $f(r,\theta,\phi)$ is always positive and finite, so there is no horizon and no singularity.

• Near where the horizon would have been f is very small, so geodesics follow almost the same path as in the black hole.

• $f \longrightarrow F$ for large r, so the fuzzball has the same mass (and charges) as the black hole, and there are families of choices of f.

To understand the relation between these geometries and the CFT states that account for the black hole entropy we advocated and developed AdS/CFT methods. [KS, Taylor] (2006) [Kanitscheider, KS, Taylor] (2007).

We find that each horizon free geometry is indeed dual to a CFT state, which provides very strong evidence for the fuzzball proposal.

So at least for certain black holes we have a precise matching between horizon free geometries and field theory states.

The next step would be to show how the black hole properties emerge upon coarse-graining over these geometries ...

This in exciting period where fundamental questions are being answered.

Despite substantial progress many big questions remain . . . to keep us busy till

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Thank you!