Black Holes and the Swampland

Niccolò Cribiori

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

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String Theory at MPP

- **Permanent members**: Ralph Blumenhagen, Dieter Lüst, Stephan Stieberger.
- **Postdocs**: Niccolò Cribiori, Saskia Demulder, Alessandra Gnecchi, Marco Scalisi.
- **PhD students**: Andreas Bischof, Davide de Biasio, Julian Freigang, Christian Kneissl, Andriana Makridou, Pouria Mazloumi, Thomas Raml, Alejandro Rodriguez.
- **Secretary**: Annette Sturm.
- **+ Master Students**

Introduction

- Black Holes (BHs) are physical objects

  Nobel prizes '17, '20; First ever picture of event horizon '19

- Important window on quantum gravity

- We do not know the theory behind quantum gravity

- Can we use BHs as a tool to understand it?

Figure: Event Horizon Telescope

Dual nature of Black Holes

- BHs are spacetime geometries.

  Solution of General Relativity: metric with horizon

- BHs are thermodinamical objects. They have

$$\text{Temperature} = \text{Surface gravity}$$

$$\text{Entropy} = \text{Area of the horizon}$$

Black Holes, microscopically

- We know how to describe BHs in string theory.

  However, few and very unrealistic.

- For those, precise matching with Hawking's semiclassical picture in the appropriate limit. [Strominger, Vafa '96]

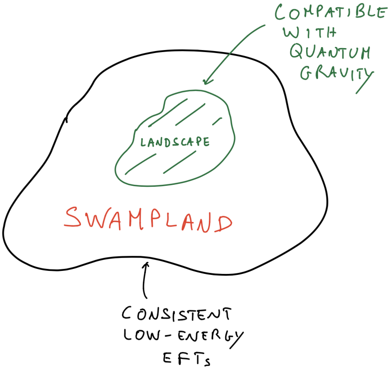
- Given our limited understanding of string theory, how to go beyond?

The swampland approach to quantum gravity

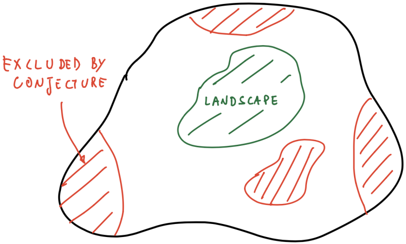
Swampland program

[Vafa '05]

- Not everything goes in quantum gravity
- Encode defining properties of quantum gravity into sharp statements/principles: **swampland conjectures**
- Theories not obeying them are in the swampland. They are **NOT** good effective field theories.
- Complementary to derivation from string theory (top-down)



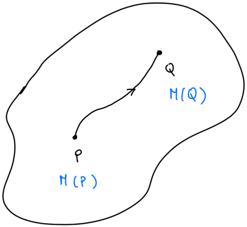
Ideally



In practice

The moduli space

- In a given effective field theory, scalar fields are coordinates of a manifold called **moduli space**.
- This can be endowed with a metric, which can be used to calculate distances.
- Physical quantities are functions of the scalars
  E.g. masses, couplings,. . . , **temperature**, **entropy**



The distance conjecture

[Ooguri, Vafa '06]

Conjecture:

As the distance between two points in moduli space $d(P, Q) \to \infty$*, an infinte tower of states with mass*

$$M \sim M_0 e^{-\lambda d(P,Q)}, \qquad \lambda > 0$$

enters the effective theory.

- The EFT breaks down since an infinite number of external light states enter.

Q: What happens to BHs solutions when temperature and entropy are very small/large?

A: Not clear yet [NC, Dierigl, Gnecchi, Lüst, Scalisi, in progress], but it seems that large/small temperature limits can be **dual**.

This **duality** would be a general property of quantum gravity.

It might be a (remnant of a) string duality seen with EFT glasses.

Black holes and the swampland:

large/small temperature and entropy regimes

Black holes: geometry

- Solutions of General Relativity

$$ds^2 = -f(r,\alpha)dt^2 + f(r,\alpha)^{-1}dr^2 + r^2 dS_2^2, \qquad \alpha = S, T, \dots$$

with horizon r_H, such that $f(r_H) = 0$.

- Add scalars: warped geometry

$$f(r,\alpha) \to e^{2U(\phi)} f(r,\alpha)$$

Black holes: thermodynamics

- Entropy given by the horizon Area

$$S = \frac{A}{4}$$

- Temperature given by the surface gravity

$$T = \frac{\kappa}{2\pi} = \frac{1}{4\pi} f'(r_H)$$

- Extremality parameter

$$c = 2ST$$

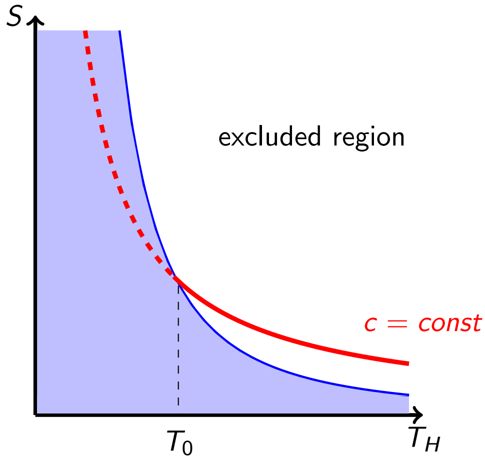
Extremal BH: $c = 0$

The strategy

- We look at BH solutions in supergravity, since they include scalars and have a moduli space

- We are particularly interested in non-extremal solutions

- We study limits in S, T parameter space by mapping them into limits in moduli space


S
excluded region
c = const
T0
TH

One special scalar

In EFTs from string compactifications, one scalar field governs the size of the compact manifold.
It is called **volume** and is related to the Kaluza-Klein scale.

For 4D EFTs, we have

$$M_{KK} \sim \frac{1}{Vol^{\frac{1}{6}}}$$

In a BH solution, we invert $T = T(Vol)$ and $S = S(Vol)$, to get

$$Vol = Vol(T, S)$$

We can map large/small T, S limit into limit in moduli space, where swampland conjectures apply.

Limits and duality

Two interesting limits are:

- $T \to \infty$ (and $S \to 0$)

$$Vol \to \infty, \qquad m_{KK} \to 0$$

- $T \to 0$ (then $S \to \infty$)

$$Vol \to 0, \qquad m_{KK} \to \infty$$

Related by

$$T \to 1/T \qquad \textbf{temperature duality}$$

In each direction we have a light tower of states: KK or winding.
Related works [Agrawal, Gukov, Obied, Vafa, '20; Blumenhagen, Kneißl, Makridou '21].

Conclusion

- Black holes teach lessons about quantum gravity.
- The swampland program is a systematic bottom-up approach to quantum gravity.
- We can apply it to BH solutions to learn new properties of quantum gravity.
- These properties should be general and can improve our understanding.

Thank you!

Extra slides

An argument: Circle compactification

$$ds^2 = e^{2\alpha\phi} g_{\mu\nu} dx^\mu dx^\nu + e^{2\beta\phi} dy^2, \qquad R \sim e^{\beta\phi}$$

Field theory

$$M^2 = \left(\frac{n}{R}\right)^2$$

- As $\phi \to \pm\infty$, different behaviour.

An argument: Circle compactification

$$ds^2 = e^{2\alpha\phi} g_{\mu\nu} dx^\mu dx^\nu + e^{2\beta\phi} dy^2, \qquad R \sim e^{\beta\phi}$$

String theory

$$M^2 = \left(\frac{n}{R}\right)^2 + \left(\frac{wR}{\alpha'}\right)^2$$

- As $\phi \to \pm\infty$, there is **always** one exponentially light tower.
- Genuinely stringy. No analogous in field theory.
- Suggesting distance conjecture

$$M(\phi + \Delta\phi) \sim M(\phi) e^{-\alpha|\Delta\phi|}$$