Superstring theory

The most famous candidate for a theory of quantum gravity is string theory. The quantum theory of the strings from string theory allowed physicists to find the graviton, the quantum ('particle') of the gravitational field. But to what extent can string theory provide a theory for quantum gravity that actually matches the observational evidence? Let us begin our tour, the second stage in this series, through the good, the bad and the ugly of string theory!

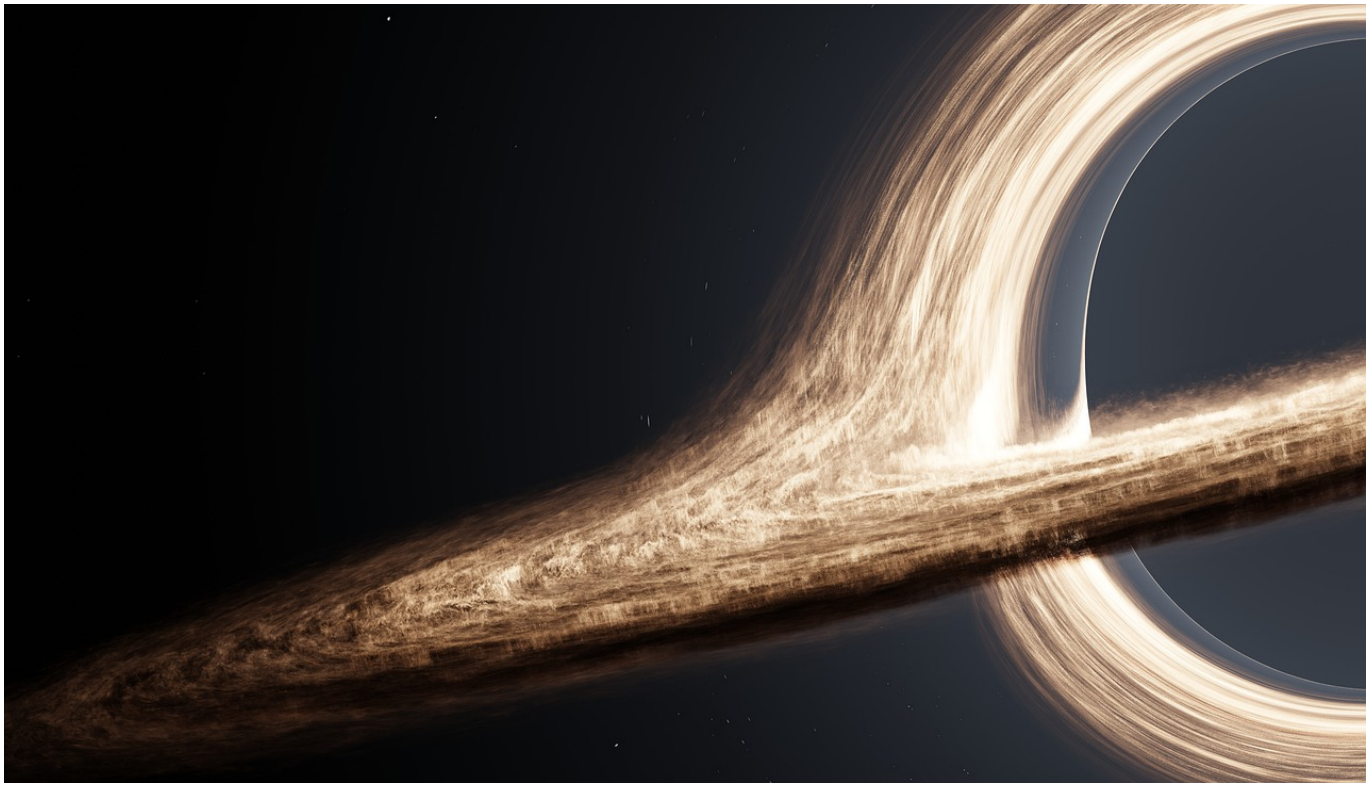


Figure 1. Can strings tell us something about black holes? Image by Adis Resic.

The good: black hole entropy

In the introductory piece of this series we established that black holes are a great place to start if we want to explore the realm of quantum gravity. We noted that, broadly speaking, there are two mysteries concerning them: the origin of the black hole entropy and the

recuperation of information of matter falling into the black hole horizon.

Black holes have thermodynamic properties like temperature and entropy. This suggests that statistical laws underlie them. Especially interesting is the fact that a black hole's macrostate (i.e. what we see of it 'from a distance') might be a result of a counting of microscopic states. In a gas, the temperature (which is the way we describe the gas's macrostate) is given by the average kinetic energy of all microscopic particles constituting the gas. But what could the 'microscopic particles' be for a black hole? String theory has an answer: D-branes. D-branes are extended objects upon which the strings end. In 1996, Andrew Strominger and Cumrun Vafa managed to theoretically construct a (very) specific example of 5-dimensional black holes in string theory in which they were able to count the microstates of that 5d black hole in terms of D-branes. They showed that, approximately, the D-brane microstates reproduced the black hole entropy. Since then, more general (and more realistic) solutions were found including rotating black hole and 4d black hole microstate countings. If you are interested in the details, a conceptual overview was given by *de Haro et al.*

This is a great success for string theory! The effectiveness of these computations – where many previous attempts had failed – shows that there may be something fundamentally true about string theory as a theory of quantum gravity.

The bad: Supersymmetry

Our world hosts two types of particles: bosons and fermions. Fermions, on the one hand, are the matter particles like electrons, protons etc., which make up atoms, molecules and ultimately you and me. Bosons, on the other hand, are force-carrying particles, like the photon, that mediate the forces between particles.

Importantly, these two types of particles have radically different behavior. For instance, fermions don't like to sit on top of each other. Much like the electrons' charge, their attitude towards one another is rather negative. This notion was first introduced by the Austrian physicist Wolgang Pauli and the effect bears his name, that is, the Pauli exclusion principle. On the other side of the spectrum we have the bosons, who enjoy each other's company and gather plentifully.

How is this all related to string theory? Well, string theory is a priori a theory of bosonic

strings, meaning that it can only describe the force-carrying particles. That is why originally we were able to find the elusive graviton! In order to also describe fermions, string theory needed a new tool: supersymmetry.

Supersymmetry is a symmetry between bosonic and fermionic particles. Supersymmetry relates each particle to its respective supersymmetric partner called a *sparticle*. If we apply this idea to string theory, the resulting theory after adding fermionic strings, is what is known today as *superstring theory.*

Supersymmetry applied to the standard model of particle physics also contributed to major resolutions to some open questions. These, for instance, include a solution to the hierarchy problem and also provide a unification of the seemingly very different interaction strengths of the Standard model.

So after all these goodies, why is supersymmetry in the 'bad' section? Well until now no sparticles have been found in nature. Very detailed searches for supersymmetry have been done by the ATLAS and CMS collaborations at the Large Hadron Collider but they have yet not found the expected sparticles. Is supersymmetry ruled out? Well, not yet – better tests could still find sparticles – but given these studies it makes the realization of supersymmetry in our universe more and more unlikely.

The ugly: swamps and the landscape

It is a strange but mathematically well established fact that in order for superstring theory to be consistent it needs 10 spacetime dimensions, meaning 6 extra spatial dimensions on top of the 3 spatial and 1 time dimensions that we experience in our everyday life. This seems like a pretty fatal and obvious flaw, but there might be a solution: the extra dimensions might be curled up into tiny loops and other forms. Hence effectively we would only 'notice' the 4 'big' spacetime dimensions. This is analogous to the shape of a pencil, where, if we are far enough away from it, we become unaware of the two-dimensional tube form of the pencil and only identify a one-dimensional line.

There are multiple ways we can curl up these 6 extra dimensions. These affect how the strings can wrap around and move in these dimensions. This in turn greatly constraints the possible interactions and excitations that the string can have in the 4 'visible' dimensions.

Ultimately this tells us something about the universe that would be possible as a result of the geometry of the extra dimensions. Does this mean that we can simply take a specific geometry and see whether the emergent physics resemble our universe? Technically, yes! But there is one hurdle: there are estimates on the number of possible geometries for the extra dimensions and they are of order 10^{500} – 500-digit numbers! The collection of possible geometries is called the *string landscape.*

This brings us to the ugly problem with superstring theory. From the studies so far it seems likely that most universes do not resemble our own and in fact lead to inconsistent 4-dimensional physics. These we call the *swamps* of the landscape. In particular, the cosmological constant is often found to have the wrong sign, which contradicts our current observations.

Thus, the landscape itself is 'ugly', but also the part that remains – the 'dry land' – is still way too large to be easily investigated, and in fact is so large that string theory loses some predictive power: essentially any outcome you want to find, can be found somewhere in the landscape.

Good, bad or ugly?

Given the good, the bad and the ugly of superstring theory what should we do? Throw it away or live with the problems it has? Like any physical theory we need to study it further. Even successful theories like quantum mechanics have not been fully understood, and this is certainly also true for the finer details of string theory. This is what science is all about: trying to push the boundary between known and unknown.