BLACK HOLES: THE MEETING OF GRAVITY AND QUANTUM PHYSICS

We know that black holes exist through a mix of complex mathematics and astrophysics but linking mathematical ideas to what we can observe in the Universe is no easy task. **Dr Daniel Terno** and his team at **Macquarie University** in Sydney, Australia, are building a framework of characteristics that can be used to search for black holes in the Universe, but their findings may challenge our understanding of the fundamental laws of physics.

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Field of research
Quantum Physics

Research project
Using quantum theory to understand the gravitational traits of black hole physics, and how this can help us link up mathematical theory and physical proof

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PROFILE

TALK LIKE A...

BLACK HOLE PHYSICIST

Apparent horizon — the last surface from which the light that is aimed outwards still bends backwards

Event horizon — the boundary of the region from which nothing can ever escape

General relativity — a theory of gravitation which describes gravity as geometry and relates its curvature to masses and their motion

Mathematical black hole (MBH) — the definition of a black hole provided by mathematical relativity – the region of space where everything that is hidden by the event horizon

Astrophysical black hole (ABH) — ultra dense, very massive dark objects observed by astrophysicists

Physical black hole (PBH) — a region of space from which nothing can escape now (regardless of what will happen in the future)

Quantum mechanics — a theory in physics that describes the properties of atoms and subatomic particles

Quantum physics — the study of matter and energy at the most fundamental level, where matter behaves both like particles and waves

Singularity — the point at which space and time become meaningless and tidal forces may become infinite

Ultra-compact object (UCO) — an object with sufficient density and mass to cause light to circle around it

A scientist's definition of a black hole depends on their discipline. While there are elegant mathematics pointing towards certain conditions, these properties cannot be physically observed. This means that astrophysicists have to use a different set of conditions to understand what they observe and calculate – but quantum physicist Associate Professor Daniel Terno, based at Macquarie University, is not convinced they are looking at the same thing, or if mathematically defined black holes even exist at all.

Daniel and his team are studying ultra-compact objects (UCOs), which include black holes. Specifically, they are exploring what properties UCOs would need to have to be defined as black holes, and how this can be solved with quantum mechanics. Their findings will help link observable properties of physical black holes (PBHs) to different competing mathematical descriptions. Finding which one is correct may require rethinking our assumptions about the basic laws of physics.

History of black hole research

In the early 20th century, Einstein came up with one of the most important scientific theories in existence: general relativity. This theory gives an understanding of how gravity can warp time and space. A few years later, physicist Karl Schwarzschild

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provided solutions to the equations of general relativity, but only by including some unusual by-products. When not dismissed outright, they hinted at ultra-dense spots throughout the Universe that did not obey normal physical laws. "Work by many people over the following decades found that these solutions did actually make sense and may describe something important," says Daniel.

It was these mathematical equations that first suggested that black holes exist, but it was in the 1970s that the first physical evidence for their existence became apparent, based on studying gravitational waves. However, linking this physical evidence with the existing physical theories led to the emergence of paradoxes that scientists struggle to solve.

Differing definitions

"A mathematical black hole (MBH) is a solution to the Einstein equation of general relativity that includes two important features: an event horizon and a singularity," says Daniel. An event horizon is the threshold between the inside and the outside of the black hole – the point at which gravity is so strong, even light cannot escape. Related to this is the singularity, which is a condition where gravity is so intense that spacetime itself breaks down and becomes infinite, so any definitions related to time and space become irrelevant.

Finding evidence for event horizons is incredibly challenging. "There is no way that a mortal observer can detect the event horizon," says Daniel. "We may even live inside one." However, we can possibly detect the side-effects of an event horizon, related to the trapping of light. According to mathematics, when light travels close to a black hole, there will be a certain point where light on one side will keep on moving outwards, whereas light on the other side will be trapped and non-observable. This boundary is called the apparent horizon and is what defines a physical black hole (PBH) – one that is observable. "According to classical physics, the apparent horizon

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sits within the event horizon, so a PBH sits inside an MBH," says Daniel. "However, while we can observe a PBH, we cannot say for certain whether it has an event horizon and singularity." Because these traits of MBHs are non-observable, our only 'proof' of their existence comes from mathematical equations that are not guaranteed to be correct.

Ultra-compact objects

"An ultra-compact object (UCO) is any object with a high enough density to bend light to such a degree that it circles around the object," says Daniel. "Black holes are a type of UCO." Daniel's team has been studying UCOs to pinpoint the set of conditions that make PBHs different from MBHs. Most importantly, their research suggests that black holes need 'exotic' material – a term used to describe types of quantum matter that are not fully understood – to form.

"After the work of Steven Hawking, we know that quantum mechanics allows the apparent horizon to be outside the event horizon," says Daniel. "Given our research suggests black holes need quantum consideration, this hints that the MBH model is limited and that PBHs may not have event horizons at all." This has big implications for our understanding of black holes and the laws of the Universe. The introduction of quantum physics requires a whole new set of rules which are not currently accounted for in mathematical proofs.

Maths and methods

"An important aspect of this project is clarifying the logical structure, and being cautious about the assumptions that are involved," says Daniel. "We start from basic premises – for instance, the minimal definitions of black holes, without worrying about event horizons and singularities – and then think about how we can identify these conditions in the Universe."

The project work involves many meetings, reading up on new research and techniques, and constantly looking out for assumptions to challenge. "Very often, when the results don't add up, we realise something was overlooked, often due to almost imperceptible beliefs that things work in a certain way even if they don't," says Daniel. "I have learned that the most important tool of a theorist is a wastebasket. Most calculations end up discarded. But, after a lot of panning, occasionally you get a few specks of gold."

Daniel's team has made significant headway, so far. "We understand how the spacetime near the apparent horizon of a freshly-formed, perfectly spherical PBH should behave," he says. "One surprising result is that a PBH can only lose mass, and not gain it. Another result is that the formation of wormholes, connecting distant regions of the Universe, becomes virtually impossible."

Next, Daniel's team wants to calculate how PBHs produce gravitational waves and understand the characteristics of these waves. The researchers also aim to dig deeper into the quantum mechanics required for properly understanding black holes, and how this affects how matter behaves.

ABOUT *QUANTUM PHYSICS*

Quantum physics is a complex but increasingly relevant field of science. Daniel explains more about its importance and what makes it so rewarding.

"As far as we know, the most basic rules of physics are quantum. Gravity is what shapes our world and our Universe. Deep down, everything is quantum. My research allows me to see how these fundamental laws affect us but also how apparently tiny quantum effects can be harnessed by technology. Everything under the quantum umbrella is amazing in its own way and lets me get a little closer to appreciating how the Universe works.

Over the last few decades, the 'weird' side of quantum mechanics has moved from theory and thought experiments to a tool of new technology. This second quantum revolution has already impacted communications and remote sensing and is likely to affect computing – perhaps helping us solve hard problems and, more immediately, helping us design and simulate new materials. There is rising investment in quantum mechanics and its importance in technology will only increase, alongside rising demand for scientists and engineers who can understand and utilise it.

Almost nothing can be calculated exactly, even in pure science, so numerical simulations are essential. While claims of quantum theory's 'weirdness' may be overblown, our normal everyday intuitions are not very helpful. Mathematics and clear thought processes can help you acquire new intuitions for understanding the field."

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Explore careers in *physics*

- Universities often offer relevant outreach activities. For instance, the Santos Science Experience operates across many Australian universities and research institutions, including Macquarie University, providing fascinating science activities for Year 9 and 10 students: **www.scienceexperience.com.au/about-the-program**
- Macquarie University holds an annual Astronomy Open Night, including physics magic shows, planetarium experiences and robotics demonstrations: **www.mq.edu.au/faculty-of-science-and-engineering/departments-and-schools/school-of-mathematical-and-physical-sciences/news-and-events/events/astronomy-open-night-2021**
- The Sydney Quantum Academy aims to "build Australia's quantum economy" and runs outreach programmes and internships for undergraduates: **www.sydneyquantum.org**

Pathway from school to *physics*

Daniel says that mathematics is a "non-negotiable" component of any STEM career. He also recommends learning coding and data handling as crucial skills.

For school subjects, Daniel suggests physics and astronomy as the most immediately applicable, followed by chemistry and biology. He emphasises all are interlinked and believes an understanding of different STEM fields can help draw connections and fuel inspiration.

Be prepared for your education pathway to be ongoing. As Daniel says, "Learning never stops!"

How did Daniel become *a quantum physicist?*

My dad was a car mechanic who became a telecom engineer, and my mum was a physicist and, later, computer programmer in the USSR. My dad taught me about codes and transistors, and my mum about black holes and the Big Bang. My mother gave me my first lesson in coding and helped with my first numerical calculations for science projects.

As a youngster, I loved reading and history. I was good with maths, surprisingly ok with chemistry, and very clumsy at actually building stuff! It looked like becoming a theoretical physicist was quite inevitable.

As an undergraduate, I worked on a project with my future supervisor, Asher Peres, on one classical chaotic system. It was a lot of fun and even led to my first scientific publication. After a period in the army, I joined Asher in the emerging field of quantum information. As I learned more, I realised that I like relativistic physics, and pushed my PhD research towards the relativistic side of quantum information theory. Since then, some combination of relativity and quantum mechanics has been a constant theme in my research.

I have had two strange eureka moments – both related to sports accidents. Failing to bench press a weight led to a moment of clarity on relativistic quantum information, while missing a head kick in Thai boxing sparring helped me understand black hole collapse!

My career highlights cover steps forward in understanding quantum physics. They range from helping develop relativistic quantum information, to designing pioneering experiments using quantum technology, to my current project understanding how to derive the existence of black holes.

Understanding what observed ultra-compact objects really are is my main focus for the next few years. In general, I also want to learn more areas of physics. This is an over-ambitious goal, but I want to work more on complex systems and to understand their behaviour. This covers about one third of modern physics, so I'm definitely not going to be bored for the next few years – or at least until artificial intelligence takes over!

Daniel's *top tips*

1. **Ask yourself what you want and why you want it.** Then, think about what you would be ready to risk and willing to sacrifice to succeed.

2. **Try to get a taste of more challenging science and experience in research as early as possible.** Keep in mind that you will fail many times, and it will be painful, but this is an experience common to even the most accomplished physicists.

Meet *Pravin*

Pravin Dahal works closely with Daniel, using quantum physics to understand black holes.

Growing up, my parents wanted me to be a doctor or an engineer. In later years of school, I grew interested in pure science, especially physics and mathematics.

For me, the purpose of life is to pursue the path of truth and understand the Universe. During my education, I realised that being a physics researcher would assist in achieving this purpose.

The path to working with Daniel was somewhat accidental, although the aim was not. After finishing my master's degree in physics in Nepal, I was unsuccessful in securing a PhD position in the USA. I then applied to Australia and got an offer there. As Australia is not a familiar destination for Nepalese PhD candidates, getting a PhD position was difficult and getting scholarships was even more challenging. I genuinely believe that I got lucky!

Our research into the nature of massive compact objects in our Universe involves a combination of study, calculation and critical thinking. Thought influences calculation, while calculation influences thought, and this process continues until one obtains a consistent result. Communication with the group and taking feedback from them is an essential part of scientific research practice.

I am also working independently to see if black holes could be alternatively characterised, which could assist in uncovering their new features. In simple terms, I am just adding yet another definition of the black hole boundary to the long list of definitions, in the hope that we can understand it more.

Talking physics outdoors

Pravin's *top tip*

Your passion, limitations and some luck lead you to a career path. Spend most of your time developing whatever skills you find interesting and useful, whether academic or not. The skills you acquire will become the purpose of your life in the future.