

Abstract

Black holes provide one of the only naturally occurring extreme environments in which the predictions of general relativity and quantum mechanics no longer apply. When applied to the minuscule scale where quantum mechanics operates, general relativity breaks down and produces impossible infinities. This paper examines why the theories of general relativity and quantum mechanics are unable to explain the phenomena that occur in the presence of a black hole, and how this motivates new theories of quantum gravity that could explain these extreme instances where general relativity and quantum mechanics break down. This manuscript details the formation and growth of black holes themselves, and what makes them such a marvel of the natural world. It then discusses the classical prediction of black hole singularities, the implications of the Heisenberg Uncertainty Principle, and Hawking Radiation and the resulting information paradox. It then focuses on the emerging theories of quantum gravity such as String Theory and Loop Quantum Gravity and how they each try to reconcile quantum mechanics with gravitational phenomena. While neither theory has been experimentally confirmed, both demonstrate the ways in which quantum effects could modify our view of spacetime. Understanding these approaches may provide insight into how gravity can ultimately be incorporated into a quantum framework and contribute to a more complete description of the fundamental laws of the universe.

Why quantum theory and general relativity alone are insufficient to describe black holes and how this motivates the development of new theories of quantum gravity

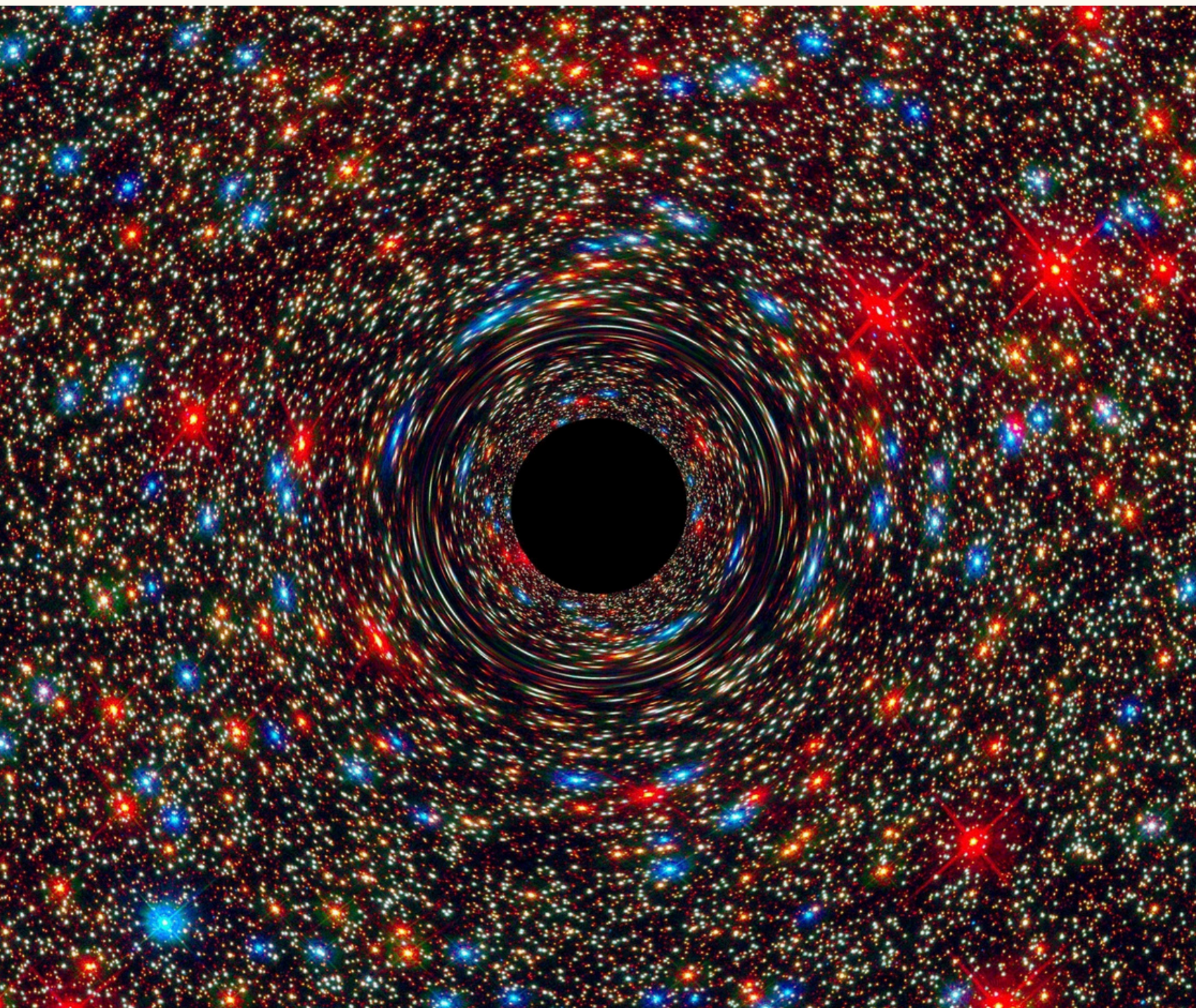
Leif Peters-Barnes

Introduction

The two primary theories of physics are marvels of the intellectual capabilities of humans; however, they are unable to work together to form one seamless theory of everything[1]. General Relativity successfully describes gravity and large-scale spacetime, while Quantum Mechanics describes the microscopic phenomena that underlie them. Separately, these two theories are highly successful and have shaped physics for over a century. However, any attempt to reconcile the two theories to form a single, seamless theory of physics is futile. This mismatch between the two theories becomes visible in extreme environments, such as in the presence of a black hole[2][3], and raises the question: why are quantum theory and general relativity insufficient to describe black holes on their own, and how does this motivate the development of new theories of quantum gravity?

Methods

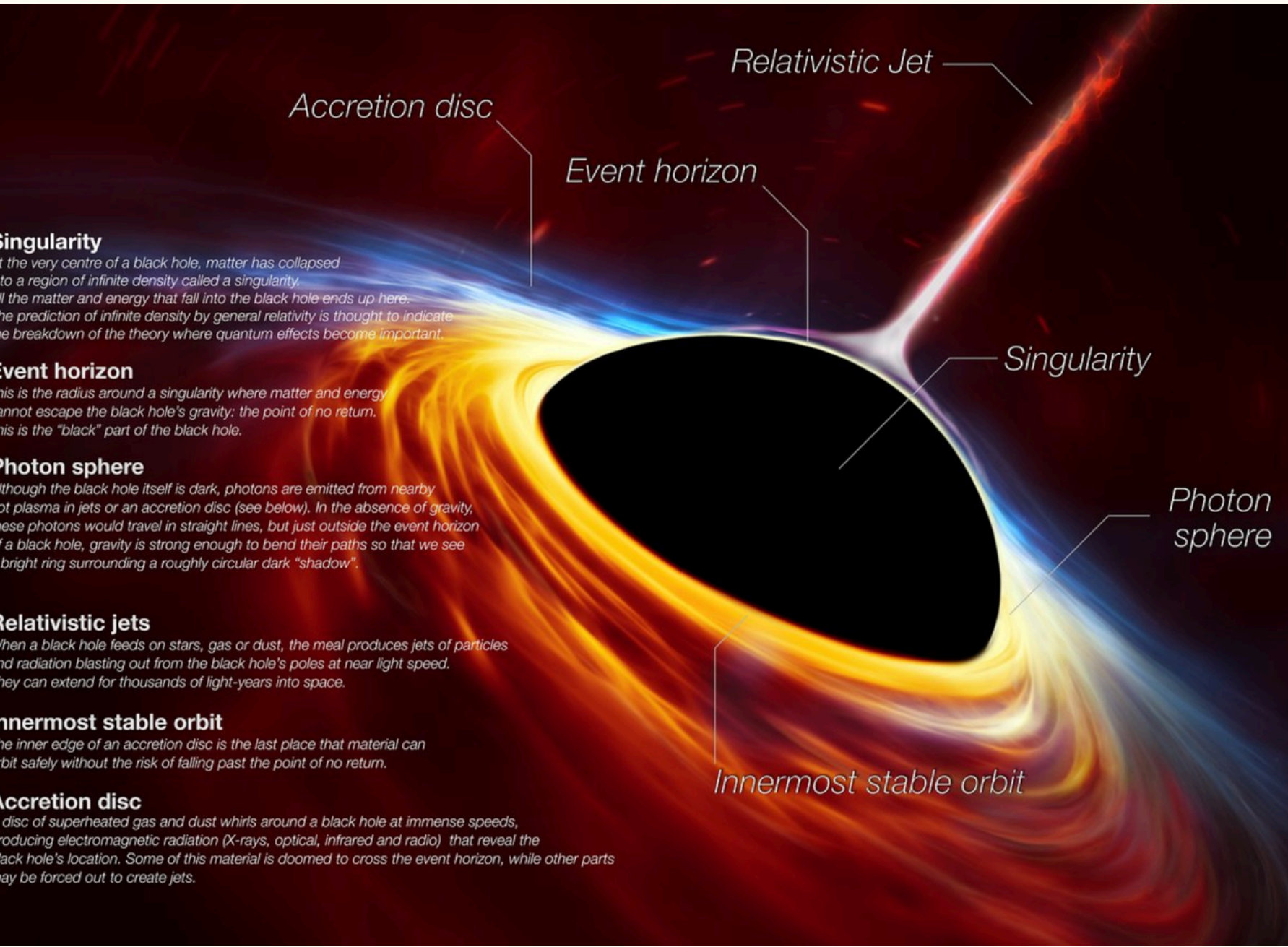
For my research, I collected information from a collection of papers published by astrophysicists around the world and formed a literature review in an attempt to break down the components of quantum mechanics and general relativity and simplify them to make them more accessible and easier to understand. I chose the specific papers based on each section of my paper concerning black holes, quantum mechanics, general relativity, and new theories of quantum gravity.



NASA, ESA, and D. Coe, J. Anderson, and R. van der Marel (STScI)

Results

The sources referenced collectively demonstrate that black holes expose important limitations in quantum mechanics and general relativity. Singularities, quantum uncertainty, Hawking radiation, and the information paradox show that the two theories cannot fully describe extreme black-hole conditions[2-4]. In response to the mismatch that occurs between quantum mechanics and general relativity, scientists have worked to develop new theories that aim to successfully fuse the two theories together into a single framework, and these theories are known as theories of quantum gravity. Some of the leading theories of quantum gravity include String Theory and Loop Quantum Gravity[5][6]. Neither of these theories, nor other emerging theories of quantum gravity, has been proven, but they share the common goal of explaining the phenomena that current theories cannot.



ESO, ESA/Hubble, M. Kornmesser/N. Bartma

References

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[5]Ashtekar, A., & Bianchi, E. (2021). A short review of loop quantum gravity. Reports on Progress in Physics, 84(4), 042001. <https://arxiv.org/pdf/2104.04394>

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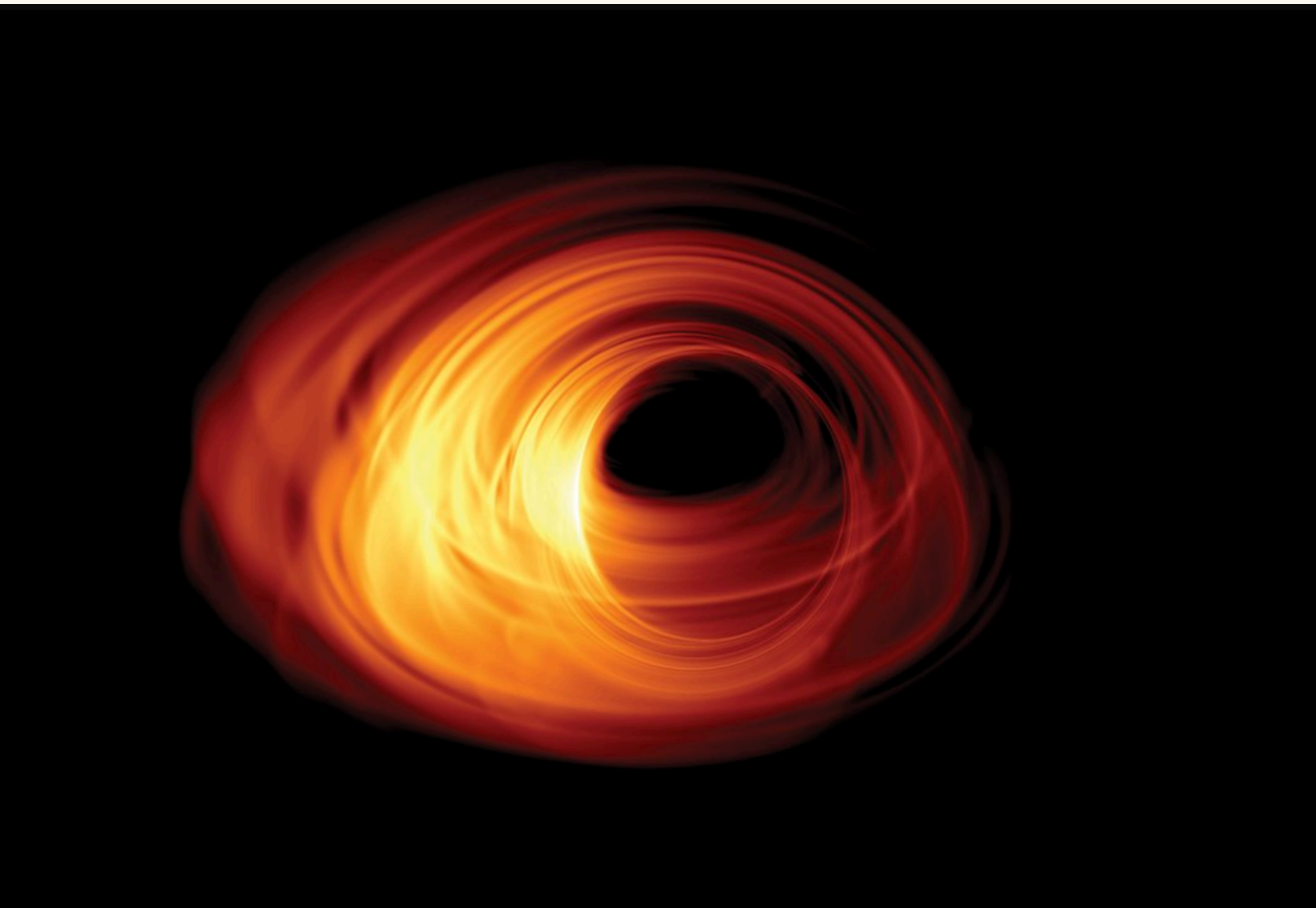
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Discussion

These results suggest that the problem is not that general relativity or quantum mechanics is individually incorrect, but that neither provides a complete framework for describing situations where quantum effects and extreme gravity occur simultaneously. Black holes therefore provide a natural environment for studying this incompatibility and demonstrate why a theory of quantum gravity may be necessary.

Conclusion

The study of black holes illustrates one of the most significant limitations in modern physics: the inability of general relativity and quantum mechanics to describe the same physical system under extreme circumstances successfully. Developments in new theories of quantum gravity, such as string theory and Loop Quantum Gravity, have aimed to build on existing theories rather than replace them. They aim to expand our knowledge, explain why general relativity and quantum mechanics break down, and develop a model of gravity in terms of quantum mechanics[5-7]. Ultimately, black holes stand as one of the most important boundaries of modern physics, providing a natural roadblock to the existing theories we have now. Resolving the contradictions between general relativity and quantum mechanics could provide a deeper understanding of spacetime, matter, gravity, and information. Whether through string theory, loop quantum gravity or a theory that has yet to be developed, finding a consistent description of quantum gravity could represent a major step toward a more complete understanding of the fundamental laws governing the universe.



Credit: Bronzwaer/Davelaar/Moscibrodzka/Falcke/Radboud University