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COSMIC CONCEPTS: THE END OF MATTER?

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What is a black hole? Today's lecture pertains exclusively to astrophysical black holes, which are part of scientific fact and not merely science fiction. A black hole is a region of space where the attraction due to gravity is so strong that nothing, not even light, can escape from within.

How fast is fast enough when it comes to escape from gravity? How fast a spacecraft needs to travel in order to escape the gravitational pull from a planet depends on how massive the planet is: more mass means more speed is needed to escape and a denser more compact planet also means a higher speed is needed to overcome the pull of gravity. This speed is well defined by these two properties: the mass of the planet and the distance separating the centre of the planet's mass from the spacecraft and is known as the escape velocity. It does not depend on the mass of the spacecraft, so irrespective of its payload, the spacecraft will need to acquire a speed of 11 km/s or 25,000 mph if it is to escape without further propulsion from Earth's gravitational field.

What is an event horizon? This is a mathematical surface surrounding a black hole from which you would need a escape velocity equal to the speed of light to be able to escape its gravitational pull. As mentioned in the first lecture in this series, in accordance with Einstein's pronouncement, it is not possible for anything in our Universe to be able to travel at a speed faster than the speed of light therefore anything and everything that is within this event horizon surface remains that way and cannot escape.

Who first thought of the concept of black holes? The first conceptual basis for objects resembling black holes considerably pre-dated Einstein and came from the late 18th century from the Rev John Michell, a Rector in Yorkshire. He published his thinking on "Dark Stars" in the Proceedings of the Royal Society in 1783. What Mitchell envisaged for his Dark Stars was that if a star were sufficiently massive and gravity affected starlight then the gravitational force could be sufficient to hold back the particles of light completely and prevent them from leaving.

Is there a black hole at the centre of our Galaxy? Yes! In fact, the mass of the black hole at the centre of the Milky Way has a mass nearly 4 million times that of our Sun. This has been measured by two independent groups who have each made time-lapse observations of the motions of stars very close to the Galactic centre over many successive occasions. Having established the types of stars that are orbiting and hence their masses, these groups have calculated their orbital trajectories and hence determined the mass of the light-less, yet gravitationally attracting, presence which they are orbiting around. The distance of this black hole from the solar system is about 26,000 light-years so we are considerably distant from it. It is thought that essentially every large galaxy has a black hole at its centre, and that many of these black holes have masses approaching billions of that of our Sun. These are termed super-massive black holes.

Are there any black holes closer than that one? Yes – millions of them! However, these black holes are much lower mass, and are typically formed when a massive star (say, a few tens times the mass of our Sun) end their normal stellar evolution and explode as a supernova. The masses of these black holes are therefore orders of magnitude less than that of those of the super-massive black holes at the centres of giant galaxies. This has a very useful consequence which is that the relevant dynamical processes in the lower-mass black holes are speeded up relative to those in the super-massive black holes and thus they are fruitful phenomena to investigate in detail as we seek to understand the influence of black holes on their surroundings.

Can we see a black hole, or its event horizon? Not directly no, because light cannot escape from within.

However, we can observe matter that is being attracted towards a black hole, or ejected from it, for example as accretion discs or jets of plasma respectively. In April 2019, the Event Horizon Telescope team, combining signals from telescopes located on many nations, made a very high-resolution image showing effectively the silhouette or shadow of the event horizon of the super-massive black hole at the centre of the M87 radio galaxy from which its famous jets emanate.

How is it that jets of plasma can be squirted out from near black holes? It's important to appreciate that these jets are launched from *outside* of the event horizon of the black hole, but the black hole and its compact mass are crucial ingredients for how the jet is launched. So too is the nature of the matter that the black holes are sucking towards it, both the rate at which it is being attracted to the black hole and how fast it is orbiting around the black hole.

Can you actually measure the velocity with which plasma jets are squirted away from black holes? Yes! If you have a signal that you can detect with a telescope, for example emission lines from proton and electron pairs (also known as excited hydrogen atoms), and appropriate instrumentation for those telescopes then it is possible to make accurate measurements of these. The Global Jet Watch observatories have done this for the "micro-quasar" in our Galaxy called SS433. By making time-lapse spectroscopic measurements of the successively launched jet plasma, and the application of appropriate analysis and equations, then these velocity vectors can be determined and tested. On the basis of our observations and analysis, we calculated what the shape of the jet trace would be on the sky at a particular date in the future, when radio observations with the ALMA telescope were scheduled. And our prediction agreed with the radio observation!

What are the benefits of studying black holes? By studying black holes, we are studying extremes of physics parameter space that simply couldn't be replicated here on Earth. Thus, our understanding of physics is deepened by exploring such regimes. Further, by investigating their behaviour we can understand how black holes influence their surroundings which in the case of the super-massive black holes includes the formation and evolution of the surrounding "host" galaxy itself. The earnest and careful pursuit of pure science, such as the behaviour of black holes, can lead to important spin-offs. An example of this is the work of the Australian radio astronomer, John O'Sullivan, on interference suppression algorithms to assist the detection of signals from merging black holes at radio wavelengths. This work directly led to the 802.11 WiFi protocol which many of us now use for connecting to the internet.

Further reading and references:
"Black holes and Time Warps", Kip Thorne, W. W. Norton & Company, 1995
"A Very Short Introduction to Black Holes", Katherine Blundell, Oxford University Press, 2015
https://eventhorizontelescope.org
https://www.GlobalJetWatch.net