Is our universe inside a black hole?

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Physicists have postulated that according to General Relativity Theory our universe might exist inside a black hole. However, they have no clear observational or experimental technique to determine if this is true or not. One reason is that black holes themselves are such mysterious objects. In this article I explore what we know about black holes and compare it with similar things that we know about the universe. While the question appears to remain open, I favour a negative answer to the title question. This paradox may be just one more of the multitude of mysteries that pervade the universe and our place within it.

Our universe is curiously enigmatic in a multitude of ways.[1,2] One example is that the leading contemporary theory for its origin, the inflationary Lambda Cold Dark Matter (big bang) Model, is built on (among other things) three main components—inflation, dark matter, and dark energy—of which we have "no direct evidence or fundamental understanding".[3] A bizarre alternative theory that has emerged out of this intellectual wilderness is that we might be living inside a black hole. Experts promoting this idea include award-winning physicist and TV science guru Professor Brian Cox, together with CERN colleague Dr James Beacham,[4] Spanish cosmologist Professor Enrique Gaztanaga, who published his Black Hole Universe (BHU) Theory in an article entitled "How the Big Bang ends up inside a Black Hole,"[3] and the Perimeter Institute for Theoretical Physics in their 2015 cover story in *Scientific American*, "The Black Hole at the Birth of the Universe".[5]

Cox and Beacham based their arguments upon (i) thermodynamics and probability, which create a paradox in big bang theory, and (ii) the Schwarzschild radius of the observable universe approximately coincides with its Hubble radius, and this might resolve the paradox by placing us inside a black hole. Gaztanaga's theory posits the origin of our universe in the dissolution of a prior universe that existed inside its own gravitational radius (i.e. already inside a black hole) which collapsed down to a matter density equivalent to that of atomic nuclei, and then 'bounced' back into an expanding phase, which we now see happening around us today. The Perimeter Institute argument is based on the holographic principle and argues that a single black hole creation event in a four-dimensional universe could have given birth to our three-dimensional universe.

What are we to make of all this? I explore the idea in this article, but without expecting to offer much that is new. In 1980 Nobel Prize winning American cosmologist Joseph Peebles wrote a textbook entitled *The Large-Scale Structure of the Universe*, which was reprinted in 2020 on the grounds that it was still the "essential introduction to this vital area of research." However, in the [original] preface Peebles had said:

> "… the links between theory and observation … [which] is the main point of the subject … is not treated at length because I think there are too many options, all apparently viable but none particularly compelling. It seems likely that the game of inventing scenarios will go through several more iterations before a secure picture emerges."[6]

Clearly, this 'game of inventing scenarios' to explain the universe is still going strong more than four decades later, and a 'secure picture' is still very far from 'emerging' any time soon!

What do we know about black holes?

In 1915, in the trenches on the Russian Front during World War I, German physicist Karl Schwarzschild read Einstein's newly published General Relativity Theory (GRT). He soon discovered an exact solution (which Einstein had failed to do) that predicted the potential existence of black holes in any non-rotating point or spherical mass.[7] No-one knew about black holes at the time, so this prediction remained hidden within the mathematics. Schwarzschild's equation contained two points where the result became 'singular' (went to infinity); one was at zero radius (i.e. where all the matter is squashed up into zero volume of 4-dimensional spacetime),[8] and the other was at a radius that he called the 'characteristic gravitational radius' for that mass, and this is now called the *Schwarzschild radius*.[7]

In 1939, Robert Oppenheimer and Hartland Snyder calculated that when a large star has used up all its thermonuclear fuel it could collapse indefinitely inside this 'gravitational radius',[9] but such a collapsed object had not yet been identified with any known astronomical entity. In 1956 Wolfgang Rindler introduced the term 'event horizon' to describe the perimeter marked out by the gravitational radius,[10] and during the 1960s the collapsed object became known as a 'black hole.'[11]

In 1965 Roger Penrose took Schwarzschild's solution together with Oppenheimer and Snyder's 'collapsed star' theory and generalized them to non-spherical initial mass

conditions.[12] For this work he was awarded a half-share in the 2020 Nobel Prize in physics "for the discovery that black hole formation is a robust prediction of the general theory of relativity".[13] In 1972 the first black hole Cygnus X-1 was identified from its X-ray emissions and its gravitational effects on a companion star.[14]

Schwarzschild's equation applies only to a stationary object, but it is expected that most real black holes will have angular momentum (spin), and in 1963 Roy Kerr found an exact solution that applies to a spinning mass.[15] A spinning black hole has a more complex boundary than a stationary one because it drags the surrounding spacetime with it,[16] but all of this happens inside the Schwarzschild radius. It also has a ring singularity at its centre rather than a single point singularity.

The other half of the 2020 Nobel Prize in physics was awarded to Reinhard Genzel and Andrea Ghez for their astronomical observations over many years, beginning in the 1990s, which established the existence of a supermassive black hole (SMBH) known as Sagittarius A* at the centre of our galaxy.

In 2015 the first gravitational wave signals were detected, emanating from the merger of two black holes,[17] and in 2019 astronomers produced the first ever image of an SMBH at the centre of galaxy M87*, followed in 2022 by a similar image of Sagittarius A* at the centre of the Milky Way.[18]

Despite this progress, black holes remain weird objects and experts cannot agree on what they are or how to describe them properly.[19–21] Being black, we cannot see them against the blackness of interstellar space, and when near to other things they enfold themselves in optical illusions caused by their intense gravitational fields.[22,23] Anything that enters them is lost to both our sight and understanding, yet everything about them seems to agree quite precisely with the mathematics of GRT.

There are some things that experts have agreed on, and to make this discussion succinct I based it on just three of these. First, black holes conserve the energy of everything that goes into making them, so non-rotating black holes can be characterized by their mass.[24] Our sun is used as the standard for measuring the mass of other celestial objects and is called a 'solar mass,' with the symbol $M_{\odot}$. Second, experts agree that the most fundamental description of the simplest black hole is given by Schwarzschild's exact solution to the field equations in GRT. The Schwarzschild radius is considered to be the "proper distance measure" in studies of black holes and their interactions with other celestial bodies,[25] and the astronomy literature contains numerous and repeated references to it.[26,27] And third, Schwarzschild's solution puts all the mass at the centre of the black hole in a single point of infinite density and zero volume (technically called a 'singularity'), and it places an 'event horizon' around the perimeter at a distance called the 'Schwarzschild radius', which is directly proportional to the contained mass.

Black hole theory

We now know from GRT and Schwarzschild's solution to it that black holes are a consequence of the unique relationship that exists between energy and the geometry of 4-dimensional spacetime which holds it in existence. The presence of energy distorts the geometry of spacetime, and the greater the *energy density* the greater the distortion. This distortion is described as 'spacetime curvature' and it can be measured as a 'radius of curvature.' This unique relationship was unknown before Einstein published his GRT in 1915, and its consequences and implications are still being actively investigated today.

GRT can be summarized in the following equation:

$$\mathrm{G} = \frac{8\pi G}{c^4}\mathrm{T}$$

where G describes the geometry of spacetime, G is the Newtonian gravitational constant, c is the speed of light in vacuum, and T describes the energy content of the universe. However, both G and T are complex mathematical functions, so the only people that usually study GRT are expert mathematicians, but others can still follow the logic of the arguments if they are expressed in simple terms as I have tried to do in this article.

The Schwarzschild radius (r_s) can be derived from GRT as follows:

$$r_s = \frac{2GM}{c^2}$$

where G is the gravitational constant, M is the object's mass, and c is the speed of light in vacuum.[28] We can simplify this expression as follows:

$$r_s = aM$$

where a is a constant ($\frac{2G}{c^2}$). This means that there is a simple linear relationship between a black hole's radius and its mass. For example, if the sun were to be squashed down until it collapsed into a black hole, it would have a radius of about 3 km, and if a star that was 10 times the mass of the sun was likewise squashed to the point of collapse, the resulting black hole would have a radius of about 30 km (i.e. 10 times larger).

Most people think of black holes as very dense objects, but this is not necessarily so. The Schwarzschild radius increases as a simple linear function of mass, but the density of the black hole decreases as an inverse cubic function of the radius.[29] It is unfortunately misleading to refer to the 'density' of a black hole, however, because all the mass that goes into the making of it is concentrated (as energy-equivalent) in the central singularity where spacetime curvature becomes infinite, while the perimeter (the event horizon) marks the point of no return for any object that enters it. It is only for the convenience of comparison with other objects that we use the term 'black hole density' and this limitation should

be kept in mind. Whatever the 'density' might be, however, the significance of the Schwarzschild radius always remains the same—it defines the point at which the escape velocity equals the velocity of light. And since nothing can exceed the velocity of light, nothing can escape from a black hole!

How did our universe end up inside a black hole?

To grasp the cosmological implications of black holes we need to examine them on the scale of the whole universe. We don't exactly know how big the universe is, but we do know that our continuously advancing telescope technology is allowing us to see further than ever before, revealing galaxies upon galaxies without any apparent end.[30,31] There is no reason to believe, therefore, that the universe does not continue like this far beyond our visible horizon.

From the expansion of the universe, we can calculate the Hubble radius of the observable universe as being the sphere marked out by the limits of our observational capacity. From this we can then calculate the mass contained within this sphere and the Schwarzschild equation will give us the radius of its event horizon. Recent estimates of the universe's mass range from 1 to 2 × 10^{53} kg,[32,33] and Claude Mercier combined a variety of methods which produced 1.73 × 10^{53} kg; this gives a Schwarzschild radius of 27 billion light years and an age for the universe of 13.65 billion years.[34]

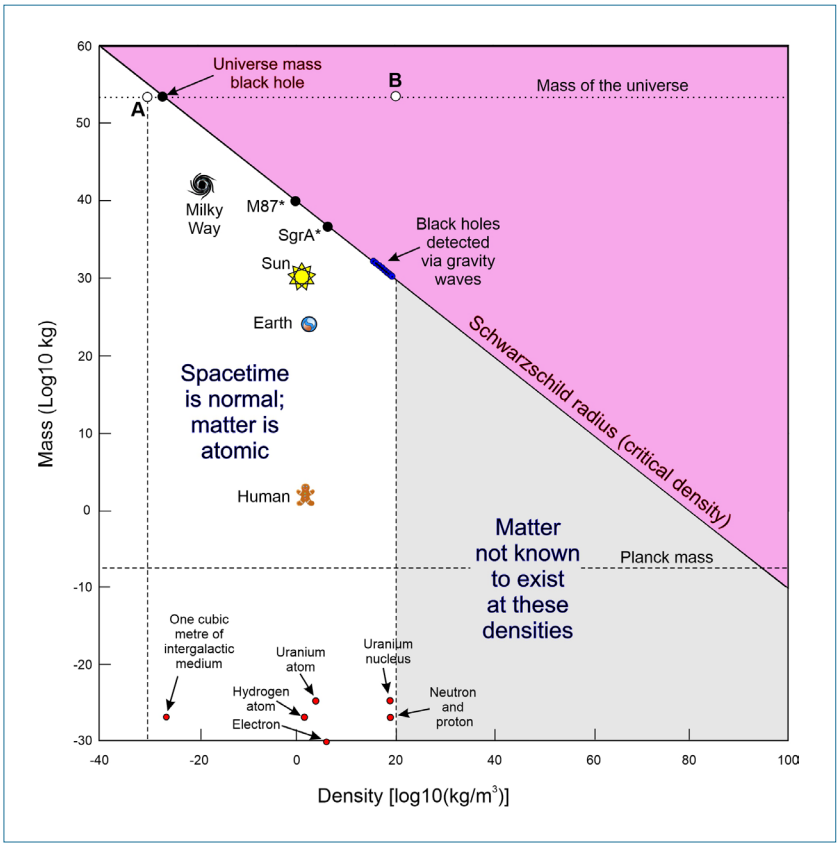

Figure 1. A mass versus density diagram ranging from the smallest to the largest scales in the observable universe. Black holes detected via gravitational waves line up on the diagonal labelled 'Schwarzschild radius (critical density)'; and supermassive black holes M87* and Sagittarius A* are included for comparison. Spacetime is normal and matter is atomic only in the white areas of the graph; areas shaded pink lie beyond event horizons; areas shaded grey are too dense to contain normal atomic matter. The top dotted horizontal line represents the mass of the observable universe (10^{53} kg), which must remain constant in any theory of origin.

Figure 1 puts these numbers into context by plotting mass against density for a selection of observed black holes and extrapolating the Schwarzschild radius line from the smallest- to the largest-known scales. Two well-studied supermassive black holes (M87* and Sagittarius A*) are included to provide extra context. We do not know what a universe-sized black hole would look like (from the inside), so the best we can do is extrapolate what we know about smaller black holes up to the point where the Schwarzschild radius meets the universe's mass.

Only in the white areas of the graph do we find spacetime supporting normal atomic matter. The Milky Way galaxy, the sun, the earth, a human, a cubic metre of intergalactic medium, a single electron, a single neutron (or proton, which has slightly less mass) and a single atom of the smallest naturally occurring element (hydrogen) and the largest (uranium) are included as examples. The pink regions all lie beyond event horizons, and the grey-shaded areas represent an undefined region that would be over-dense because nothing is known to be denser than neutrons, protons, and atomic nuclei.

Everything that we value about life and the universe is made of atoms plus the radiation (e.g. light) that only atomic matter can produce. Atoms consist of very dense nuclei surrounded by varying numbers of shells of electrons, plus lots of 'empty' space.[35] All these things exist only in the white region in figure 1.

The horizontal dotted line at the top of figure 1 represents the mass of the observable universe at 10^{53} kg. The black dot on the diagonal line intersecting it is the black hole equivalent of a universe of this mass. The open circle to the left of it, labelled A, represents a possible universe like ours made of normal atomic matter in normal spacetime. In contrast, the object at position B represents the universe at just above neutron density, which is the 'bounce' point in Black Hole Universe Theory. The lower-down horizontal dashed line,

labelled 'Planck mass', represents the smallest unit of mass defined in Planck units; it appears in theories of quantum gravity and superstring theory, but it is not (yet) relevant to the subject of this article.

Penrose–Hawking black hole expeditions

Stephen Hawking, in his best-selling 1988 book *A Brief History of Time: From the Big Bang to Black Holes*,[36] used a standard method of teaching relativity theory to compare the experiences of two hypothetical observers: one that falls into a black hole, while the other remains a safe distance away. He explained that when a large star uses up its nuclear fuel it collapses to form a black hole, then he continued:

> "Suppose an intrepid astronaut on the surface of the collapsing star, collapsing inward with it, sent a signal every second, according to his watch, to his spaceship orbiting about the star" (p. 87).

The intense gravitational forces would cause time dilation, length contraction, and red shifting of light. The view from the spaceship would see him never actually reaching the event horizon (because of time dilation and length contraction); he would just turn reddish in colour, and progressively dimmer until he faded from view. The astronaut, however, would pass through the event horizon, only to be 'stretched out like spaghetti' and torn apart by the difference in gravitational force between his head and feet!

This would be the case [said Hawking] when considering a stellar-mass black hole, but a happier fate might be possible!

> "However, we believe that there are much larger objects in the universe, like the central regions of galaxies, that can also undergo gravitational collapse to produce black holes; an astronaut on one of those would not be torn apart before the black hole formed. He would not, in fact, feel anything special as he reached the critical radius, and could pass the point of no return without noticing it. However, within just a few hours, as the region continued to collapse, the difference in the gravitational forces on his head and his feet would become so strong that again it would tear him apart" (p. 88).

Roger Penrose went much further and developed a special mapping technique (now called a 'Penrose diagram') which showed that it might be possible for a traveller to pass through the centre of a rotating black hole and emerge into one of several bizarre alternative universes.[37,38]

Many other writers up to the present day have followed Hawking and Penrose in repeating the idea that astronauts might safely enter a black hole (but never return).[23,39–42]

The critical role of the event horizon

Supporters of this Penrose–Hawking theory about humans safely entering an SMBH seem to place their confidence upon little more than the authority of Penrose and Hawking as the award-winning pioneers of our modern understanding of black holes. Everyone agrees that the central singularity is lethal (but perhaps navigable, if Penrose is correct), yet they insist that the event horizon is *not* lethal, so this is what we must examine in more detail.

Wolfgang Rindler (who introduced the term 'event horizon' in 1956) in his 2006 revised textbook entitled *Relativity: Special, General, and Cosmological*, stated that:

> "… nothing very special would occur there … nothing untoward occurs *at* the [event] horizon … this shows the horizon events to be ordinary."[43]

Physicist-philosopher Erik Curiel has used the following thought experiment (based on Rindler, pp. 258–259) to argue that material objects can survive the fall through an event horizon:

> "If all the stars in the Milky Way gradually aggregate towards the galactic center while keeping their proportionate distances from each other, they will all fall within their joint Schwarzschild radius and so form a black hole long before they are forced to collide."[44]

No such celestial event has ever been observed, but something like it might occur when galaxies collide. If a supermassive black hole were to form in this way, a distant observer would see nothing more than an advancing front of darkness (the black hole created by the innermost stars in the collapsing galaxy) as the event horizon grew and engulfed the last star. No one knows how fast the transition to equilibrium takes in a supermassive black hole, but we do know how fast it is in stellar-mass black holes. Two such black holes can merge 'instantaneously' and equilibrate within a few milliseconds,[45,46] while a black hole can 'eat' a neutron star with 'one bite' and reach equilibrium in less than 2 seconds.[47]

No-one knows for sure what happens inside an event horizon, and that is one reason why there is such a diversity of views about them. But we can cut through some of the confusion by focusing on what we do know about how black holes are created.

Black hole creation

The only known way that a black hole can be produced *de novo* is via a core-collapse supernova event of sufficient mass. When a large star burns up all its nuclear fuel and disintegrates in a core-collapse supernova explosion the core may become compressed into one of three known kinds of 'dead star'—a white dwarf, a neutron star, or a black hole. These remnant stages are all 'dead' because their atomic structures have collapsed and can no longer provide thermal resistance against gravity. They are so dense that only quantum fluctuations of subatomic particles provide resistance, and all such resistance disappears in the black hole. Such 'degenerate matter' can only be produced in the hearts of disintegrating large stars and is not known to exist anywhere on Earth or in our solar system.

White dwarf stars exist in a *super-dense* state where only electrons can jiggle about in a very restricted manner among

neutrons and protons to provide enough pressure to prevent further gravitational collapse. Known white dwarf stars have masses in the range of 0.17 to 1.35 $M_\odot$ and densities of about one tonne per cubic centimetre.[48] In neutron stars, electrons are forced to join up with protons to produce neutrons, and nothing but neutrons can jiggle about in an *ultra-dense* state to provide enough pressure to prevent further gravitational collapse. Neutron stars can have masses in the range of 1.4 to 2.35 $M_\odot$, and densities of about a billion tonnes per cubic centimetre. Theoretically, there could also be a 'quark star', which forms when neutrons are crushed even further into quarks and gluons.[49]

In the terminal stage of matter degeneracy—a black hole—the quarks and gluons transmute into energy via Einstein's famous formula $e = mc^2$, where e = energy, m = mass, and c is the velocity of light (~300,000 km/sec). Their energy is conserved in the black hole in the form of the 'infinite curvature of spacetime' at its central 'singularity'. Black holes are not size- or density-limited; the smallest known so far is around 3 $M_\odot$ and the largest known *supermassive* black hole is about 66 billion $M_\odot$.

A core-collapse supernova must produce a vast amount of compression to create a black hole. For a core with the mass of our sun, it would have to be compressed into a volume that is ten thousand trillion times smaller than its original size.[50] And it is this vast amount of compression that causes the structure of atomic matter to collapse well *before* an event horizon forms.

Since we can see nothing inside an event horizon, we must look for answers in the region just outside of it where we *can* make a wide variety of observations. And this is the task that the *Event Horizon Telescope* collaboration has taken up.

The Event Horizon Telescope

The *Event Horizon Telescope* (EHT) is an international collaboration among astronomers in eight different countries using 19 different telescopes that can capture images of black holes using an Earth-sized 'virtual telescope' by integrating images from different locations across the globe. Their first one, published in 2019, looked at the supermassive black hole at the heart of galaxy M87.

This resulted in several important lessons for astrophysicists.[51] Most fundamentally, it clearly demonstrated that event horizons are real and not just 'apparent' (as some theorists claim); also, that they confirm the predictions of Einstein's General Relativity Theory (GRT), and that this one (like most, perhaps) is rotating. Prior estimates of the black hole's mass derived from its gravitational influence on nearby stars ranged from 6.2 to 6.6 billion solar masses, and a more precise figure obtained from this new image came in at 6.5 billion solar masses!

Further work on the supermassive black hole at the centre of our own galaxy, Sagittarius A*, was published in 2022 and

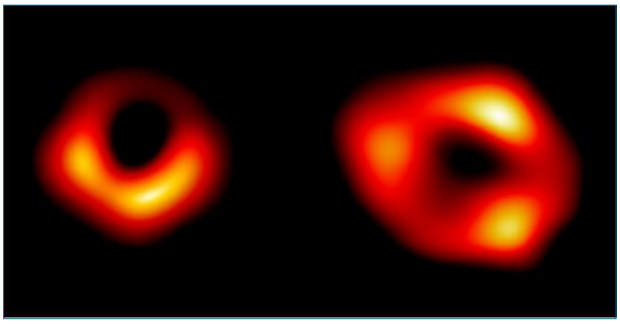

Image (left and right): ESO, Wikimedia / CC BY 4.0

Figure 2. Images of the supermassive black hole in the centre of galaxy M87 (left) and Sagittarius A* in the centre of the Milky Way galaxy (right). Original images from the Event Horizon Telescope website have been passed through a 'hard light' filter to reduce unwanted detail.

came in at 4 million solar masses. Both images are compared in figure 2.

The bright regions in these images represent gas and dust in the accretion rings that is being swept up into the central black holes. The uneven distribution of glowing matter is partly due to the angle of view and partly due to rotation of the central black hole, which drags spacetime around with it. The actual black holes lie within the central dark regions and are surrounded by a distinctive 'shadow region' and a 'photon ring', which further studies have clearly revealed.[52]

Katherine Mack, a theoretical astrophysicist at the Perimeter Institute, has listed four ways a black hole could kill you:

1. *spaghettification*—which is tidal disruption from coming too close to the singularity
2. *fried by accretion disk*—the fiery parts in figure 2 illustrate what happens to *any* material object that comes within gravitational reach, or
3. *zapped by plasma jets* which erupt from both ends of a rotating SMBH
4. *incinerated by firewall*—a theoretical wall of energy that (may) blast out from all over an event horizon.[53]

I am not an expert in any of these fields, so I will not attempt to resolve the matter either way. However, it seems rather obvious to me from figure 1 that everything about life and the universe that we *do* know about exists in 'normal' four-dimensional Minkowski spacetime; it is nearly all made of normal atomic matter, and it produces radiation of various kinds that can only be explained as emanating from known states and energy transitions within normal atomic matter. In contrast, we cannot be sure of anything that lies inside an event horizon except that all its mass is transmuted into energy, which is entirely contained within the singularity at its centre. Importantly, just outside the event horizon of the two SMBHs that we do know about, we *can* see incontrovertible evidence of (i) lethal violence, and (ii) extreme distortion of spacetime. Figure 3 shows three features that next-generation space telescopes should be able to resolve more clearly: (i) the shadow region immediately beyond the event horizon; (ii)

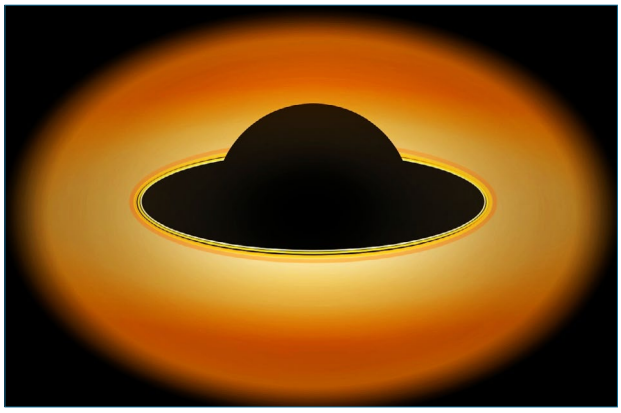

Figure 3. Schematic illustration of structures associated with a rotating supermassive black hole (central black sphere). A shadow region immediately surrounds the black hole, caused by interference effects under extreme spacetime curvature, followed by a series of photon rings resulting from light rays that are trapped into one or more orbits before escaping into the observer's line of sight. The outer orange glow is the accretion disk of compression-heated infalling gas and debris from ruptured celestial objects that came too close to escape. (After figure 12 in Bronzwaer and Falke.[54]).

numerous photon rings at the edge of the shadow; and (iii) a distinction between the outer photon ring and the accretion disk. Nothing about these regions seems to me to be friendly towards visiting astronauts!

Could Einstein have been wrong?

Everything we know about black holes is based upon GRT. Is it possible that Einstein was wrong?

In 1919 Einstein himself addressed this question:

> "The chief attraction of the theory lies in its logical completeness. If a single one of the conclusions drawn from it proves wrong, it must be given up; to modify it without destroying the whole structure seems to be impossible."[55]

He proposed three tests of the theory: the precession of Mercury's orbit around the sun; the gravitational deflection of distant starlight by the sun; the gravitational redshift of light from distant sources. Many physicists since that time have put Einstein's claims to the test, and so far, GRT has passed all of them. Moreover, as technology and instrumentation have improved over the decades, the tests have become more and more stringent and the precision to which GRT still receives the 'pass mark' has advanced greatly.

For example, a recent 16-year study of a double pulsar system has confirmed to unprecedented precision several different predictions of GRT in a strong gravitational field that we were previously unable to test.[56] The effect of gravity on time (time dilation) in the relatively weak gravitational field near the earth's surface has been demonstrated and measured at many different scales; but recently, ultraprecise atomic clock experiments have demonstrated that it still holds true even at microscopic differences in altitude.[57]

Most importantly for the present article, the successful detection of gravity waves emanating from colliding black holes (and neutron stars) proves not just that GRT is correct, but also that Schwarzschild's solution was correct in his 'logically complete' description of the physical nature of the universe. And the awarding of the 2020 Nobel Prize in physics for demonstrating that black holes are a 'robust prediction' of Einstein's GRT would seem to answer the question in the negative—as far as we know today, Einstein was not wrong!

Conclusion

Everyone agrees that black holes are objects in which both variables in the equations of GRT (spacetime geometry, and mass/energy equivalent) have collapsed into a singular point of infinite density and zero volume. But this creates an event horizon at the Schwarzschild radius which prevents us from directly observing what happens inside it, and it is this 'vacuum' in our knowledge that has led to many varied and speculative conjectures.

From a purely physical point of view, figure 1 suggests that the universe we live in exists outside of its 'critical density,' and not inside. Mathematics, however, provides for other possibilities that are not considered here, and those who suggest our universe might be inside a black hole base their confidence on such mathematical considerations.

Alternatively, perhaps this puzzle is just one more enigma in a universe that abounds in mysteries.

According to Prof. Brian Cox, if the universe came into being through a random quantum fluctuation (as many have suggested), then we must choose between the likelihood of (a) it having appeared in a highly ordered primordial state, or (b) it appearing as we see it today in its disordered state. He then said there is an astronomically greater likelihood that it popped into existence as we see it today![4]

A far more reasonable explanation lies in Genesis 1:1, "In the beginning, God created the heavens and the earth."

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