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Scientific Background on the Nobel Prize in Physics 2020

THEORETICAL FOUNDATION FOR BLACK HOLES AND THE SUPERMASSIVE COMPACT OBJECT AT THE GALACTIC CENTRE

The Nobel Committee for Physics

BOX 50005 (LILLA FRESCATIVÄGEN 4 A), SE-104 05 STOCKHOLM, SWEDEN
TEL +46 8 673 95 00, KVA@KVA.SE ⋆ WWW.KVA.SE

Theoretical foundation for black holes and the supermassive compact object at the Galactic centre

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2020

with one half to

Roger Penrose

for the discovery that black hole formation is a robust prediction of the general theory of relativity

and the other half jointly to

Reinhard Genzel and **Andrea Ghez**

for the discovery of a supermassive compact object at the centre of our galaxy

Introduction

This year's Nobel Prize in Physics focuses on black holes, which are among the most enigmatic objects in the Universe. The Prize is awarded for establishing that black holes can form within the theory of general relativity, as well as the discovery of a supermassive compact object, compatible with a black hole, at the centre of our galaxy.

The early history

The first scientists to discuss the possibility of dark objects with an escape velocity larger than the speed of light were the English astronomer and priest John Michell, in 1783, and the French polymath Pierre-Simon Laplace, in works from 1796 and 1799.

In a contribution to *Philosophical Transactions of the Royal Society* (Michell 1783), Michell calculated that a star with the same density as the Sun, but a radius 500 times as large, would have a gravitational pull so strong that light would be trapped and unable to escape. In his *Exposition du Système du Monde* (Laplace 1796), Laplace made a similar suggestion, independently of Michell. He provided the full details in a mathematical treatise from 1799 (Laplace 1799), where he considered a star with the same density as Earth, i.e., four times the density of the Sun. He arrived at a radius 250 times that of the Sun.

The objects contemplated by Michell and Laplace would now be classified as supermassive black holes with masses between that of the compact object at the centre of our galaxy, the subject of this year's Nobel Prize, and the black hole candidate at the centre of M87, recently imaged by the Event Horizon Telescope (EHT).

The calculations of Michell and Laplace were made within the framework of Newtonian mechanics. The results are easily obtained by setting the total energy of a test particle equal to zero, so that it just barely can escape from the dark object. This gives $\frac{1}{2}mv^2 - \frac{GMm}{r} = 0$, from which it follows that a radius smaller than $\frac{2GM}{c^2}$ prevents a particle of light from reaching infinity. In his work from 1799, Laplace explicitly presented just this formula. In his work, Michell had gone even further, with an interest in the new discoveries of binary stars, speculating how one could infer the existence of these dark objects. He wrote:

… we could have no information from light; If any other luminous bodies would happen to revolve around them we might still perhaps from the motions of these revolving bodies infer the existence of the central ones with some degree of probability.

The observations made by the teams led by Reinhard Genzel and Andrea Ghez have allowed them to make precisely this inference, for which they are awarded this year's Nobel Prize in Physics. The theoretical work by Penrose in the other half of this year's Prize was essential for the study of black hole physics, and a great motivation for astronomers in their search for good candidates.

The Schwarzschild metric

On 13 January 1916, less than two months after Einstein completed his theory of general relativity on 18 November 1915, and less than four months before his own death, the German astronomer Karl Schwarzschild published a solution to Einstein's field equations, describing the curved space-time around a spherically symmetric, non-rotating, mass (Schwarzschild 1916). His metric takes the form

$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 - \frac{1}{1-\frac{2GM}{c^2 r}} dr^2 - r^2(d\theta^2 + \sin^2\theta\, d\phi^2).$$

For years to come, only the leading term in a large radius expansion of Schwarzschild's metric was of any practical use in tests of general relativity, such as the Mercury perihelion precession, light bending, or the Pound-Rebka experiment in 1960, confirming gravitational time dilation. Only recently has it become possible to test the metric beyond leading order, but it quickly became clear that the metric had two intriguing features at positions $r = 0$ and $r = \frac{2GM}{c^2}$, where some of its components diverged or vanished. What was their significance?

In the early 1920s, the French mathematician and politician Paul Painlevé (Painlevé 1921), and the Swedish optician Allvar Gullstrand[1] (Gullstrand 1921) independently found what they both believed to be a new and different solution to Einstein's equations. They each argued that their discovery rendered general relativity incomplete. In 1933 the Belgian priest and cosmologist George Lemaître proved that their metric was simply a coordinate transform of the one of Schwarzschild (Lemaître 1933). The confusion over how to interpret the metric persisted for years. Eventually, researchers determined that $r = 0$ corresponds to a true singularity, while the so-called Schwarzschild singularity at $r = R_S = \frac{2GM}{c^2}$ is just an artefact generated by the choice of coordinates. An observer can use local measurements to discern that something dramatic happens at $r = 0$ but not at $r = \frac{2GM}{c^2}$. Only much later, through the work of David Finkelstein in 1958, the importance of different coordinate systems was fully understood (Finkelstein 1958).

We now know that R_S has an important *global* significance as the point of no return, which we call the *event horizon*. Its position precisely coincides with the value proposed long ago by Michell and Laplace, based on Newtonian gravity and the assumption of a particle nature of light. Was it just serendipity that they had found the correct expression as early as the end of the 18th century? Not completely. In special relativity, time dilation in the form of a non-trivial Lorentz factor, gives rise to the relativistic expression for kinetic energy, while gravitational time dilation is associated with potential energy. To obtain the escape velocity, the energy of the test particle moving radially in the Schwarzschild background should be equated with the rest energy of the particle positioned far away from the gravitating mass.

[1] Gullstrand was a long-time member of the Nobel Committee for Physics, and the 1911 Laureate in Medicine or Physiology. Ironically, he argued *against* awarding the prize to Einstein for general relativity.

Taking gravitational time dilation as well as the Lorentz factor into account, the resulting equation is $\left(1-\frac{2GM}{c^2r}\right)^{1/2}\left(1-\frac{v^2}{c^2}\right)^{-1/2}mc^2 = mc^2$, where v is the proper velocity, as measured by an observer at constant radius. This has the same solution as the analogous Newtonian expression. Thus, the two calculations happen to give the same result.

The period 1939-1964

In 1939, the American physicist Robert Oppenheimer, together with his student Hartland Snyder, managed to decipher the implications of Schwarzschild's metric (Oppenheimer & Snyder 1939). They studied the collapse of a spherical cloud of matter, and for the first time realized the full importance of the Schwarzschild radius, which they correctly identified with the presence of a horizon:

The star thus tends to close itself off from any communication with a distant observer; only its gravitational field persists.

A key assumption in the calculation of Oppenheimer and Snyder was spherical symmetry. Many physicists were concerned that without this assumption the endpoint of gravitational collapse could be something entirely different. After all, if the system was not spherically symmetric, how could in-falling matter focus itself to a single point and create a singularity? Could the collapse fail, with matter bouncing back out? Einstein expressed serious doubts about the existence of horizons at about the same time as the work of Oppenheimer and Snyder (Einstein 1939).

Such considerations led the Soviet physicists Evgeny Lifshitz and Isaak Khalatnikov to revisit the calculations, concluding that results like those of Oppenheimer and Snyder did not represent what actually happens in a real physical situation (Lifshitz & Khalatnikov 1963). In fact, they claimed that singularities could not occur under any realistic circumstances in general relativity:

The results presented allow one to draw the important conclusion that the singularity in time is not a necessary property of cosmological models of the general theory of relativity, and that the general case of an arbitrary distribution of matter and gravitational fields does not lead to the appearance of a singularity.

The American physicist John Wheeler is said to have had similar worries, speculating that quantum mechanics might hinder collapse toward a singularity, preventing the formation of this strange object called 'the singularity'. He imagined how the collapsing star would convert itself into gravitational radiation, rapidly evaporating away leaving nothing behind.

A remarkable observational discovery would follow this theoretical development.

The first observational hints for supermassive black holes

The discovery of quasi-stellar objects, abbreviated quasars or QSOs, generated a lot of interest. These were first detected as compact radio sources in all-sky surveys in the late 1950s without optical counterparts. Eventually, in the early 1960s, optical astronomers found visible blue objects associated with these sources, originally thought to be stars in our galaxy. A major breakthrough was achieved when the Dutch astronomer Maarten Schmidt (Schmidt 1963), following the accurate radio location obtained by Hazard, Mackey & Schimmins (1963), identified QSO 3C 273 as being an extragalactic source, with prominent spectral lines indicating a location outside of the Milky Way, at redshift z = 0.158. Both articles were published in the same issue of *Nature* in 1963. This result was very surprising, as the large distance to the point-like source (760 Mpc) implied a luminosity about one thousand times larger than that of our entire galaxy. The first discovery was soon followed by many others, at cosmological distances and with rapid random (non-periodic) time variation of emissions on the scale of days or even hours, indicating a small and powerful source of energy. By 1965, Schmidt had extended the distance range of quasars to very high redshifts, $z > 2$.

Astronomers realized that quasars, rather than being isolated objects in our own galaxy, were in fact located at the centre of distant galaxies, with the rest of the distant galaxy often too faint to detect. The engines behind these "Active Galactic Nuclei " (or AGN) commonly produce 10^{39} W, more than two orders of magnitude larger than the luminosity of all stars in a typical galaxy. This mindboggling realization led to the idea that AGNs could be extremely massive stars, as heavy as several million solar masses, as first contemplated by Hoyle & Fowler (1963). However, it soon became clear that any such giant star would be extremely unstable and short-lived, and therefore could not explain the quasar observations.

The singularity theorem

Schmidt's discovery prompted Wheeler to reconsider the physics of gravitational collapse and he discussed this with Penrose, who began to think about the problem in late 1964.[2] Oppenheimer and Snyder had described the spherically symmetric case where an astronomical body contracts to within its Schwarzschild radius, forming a singularity of infinite density. However, it was far from clear that this could happen in the real world and whether the assumption of spherical symmetry was a prerequisite for gravitational collapse. Penrose was well aware of the rotating solution found by Kerr the year before (Kerr 1963). The solution retained a lot of symmetry and did not exclude the possibility that departures from symmetry could prevent singularities to form.

Penrose set out to analyse the situation *without* the assumption of spherical symmetry, assuming only that the collapsing matter had a positive energy density. To do this, he had to invent new mathematical methods and make use of topology. The key concept that Penrose introduced was that of a *trapped surface*. A trapped surface is a closed two-dimensional surface with the property that all light rays orthogonal to the surface converge when traced toward the future. This is contrary to a spherical surface in flat space, where outward-directed light-rays diverge.

It can be seen that in the spherically symmetric case, any spherical surface with a radius less than the Schwarzschild radius is a trapped surface, which provides a good way to understand the structure of a black hole. Examining the Schwarzschild metric, we find, as illustrated in figure 1, that the radial direction becomes time-like as one passes through the horizon. Time and space switch roles and the direction inwards, towards the origin of spherical coordinates, becomes time. Hence, it is as difficult to get back out of the black hole as it is to go backwards in time.

An even more dramatic consequence of the trapped surface is that the flow of time inevitably will bring any observer towards the origin of the radial coordinate, where time ends. All the matter that formed the black hole resides at this single moment in time, the singularity.

[2] Penrose relates the circumstances of his discovery in two books (Penrose 1989, 2010).

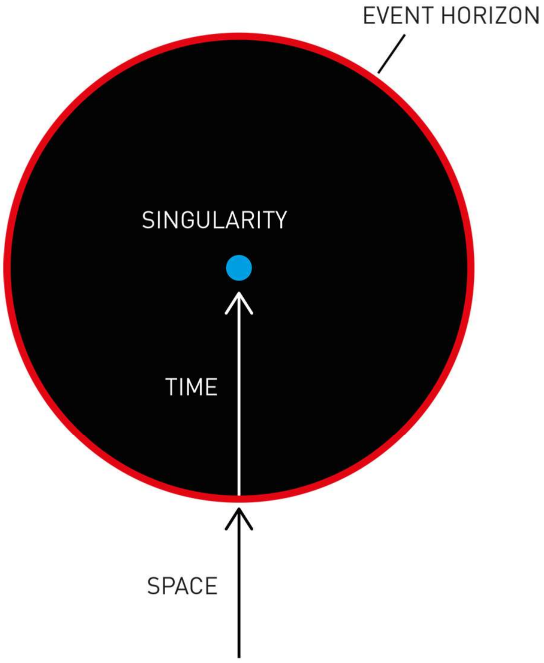

Figure 1. *Schematic diagram showing the interior of a black hole. Inside of the horizon the radial direction is time-like. Time ends at the singularity.*

Such trapped surfaces can also be found in the case of rotating black holes. In fact, the trapped surface remains, regardless of how the solution is perturbed, and its existence is independent of any assumptions about symmetry. After realizing the power of the idea of trapped surfaces, Penrose proceeded to prove that once a trapped surface had formed, it is *impossible,* within the theory of general relativity and with a positive energy density, to prevent the collapse towards a singularity (Penrose 1965). See figure 2.

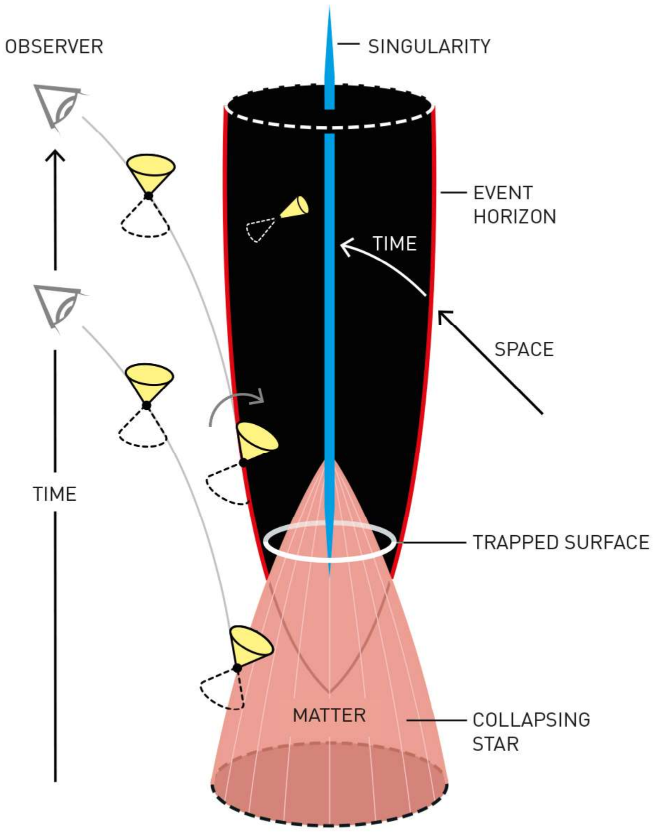

Figure 2. *The diagram is based on Penrose's paper from 1965 and shows the collapse of matter into a black hole. On a trapped surface all light cones are tipped inwards, and the formation of a singularity is inevitable.*

To visualize space-time, Penrose introduced a technique using *conformal transformations* (Penrose 1963). Such transformations can change the scale but they always retain angles. This means that points infinitely far away in space, and events in the infinite past or future, can be brought in from infinity to fit inside a diagram of finite size. If a light ray originally corresponds to a line at 45 degrees, it will remain at the same angle after the conformal transformation. Such diagrams are called *Penrose diagrams*, and they are indispensable tools in the study of curved space-times. A Penrose diagram where a star collapses to form a black hole is shown in figure 3.

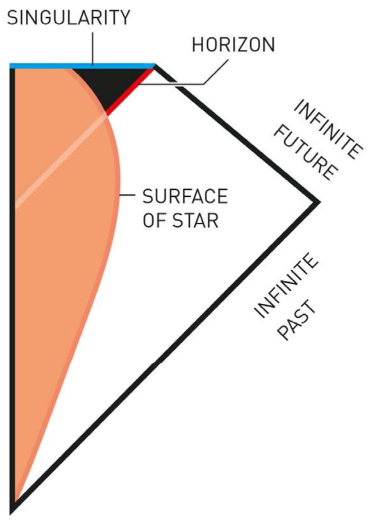

Figure 3. *A Penrose diagram of a star that collapses into a black hole. Time runs upwards and light rays are inclined at 45 degrees.*

Penrose's result is heralded as the first post-Einsteinian result in general relativity. It proves that gravitational collapse cannot be stopped after the trapped surface is formed. One should note that its formation happens at a stage in the collapse when density of matter is not very high. (The supermassive black holes of Michell and Laplace have average densities no higher than those of the Sun or Earth.) A few years later Penrose, together with Stephen Hawking, went further to show that similar results also applied to cosmological singularities (Hawking 1965, Hawking & Penrose 1970). Under reasonable assumptions, a past singularity is inevitable in the Big Bang model. Penrose (1969) wrote a beautiful summary of many of these results. In a review article, Senovilla & Garfinkle (2015) provide a thorough description of the theorem and its historical background.

Penrose's discovery triggered a new era in physics and astronomy. The strange dark objects that Michell and Laplace speculated about were deeply rooted in our modern picture of gravity. It was after Penrose's discoveries that 'black hole' finally stuck as the name for this exotic gravitational anomaly. The American physicist Robert Dicke was the first to use the term during lectures at Princeton in 1960, and Wheeler later helped make it popular (Herdeiro 2018).

Supermassive black holes become the leading model to explain quasars

After the discovery of the extragalactic nature of 3C 273, emission of radiation from accretion of matter onto supermassive black holes became the generally accepted explanation for quasars (Salpeter 1964, Zeldovich & Novikov 1965). This was a plausible extension to the models for X-ray and radio emission from matter falling into (much lighter) stellar-mass black hole candidates, such as the ones observed by the group led by Riccardo Giacconi, the 2002 Nobel Laureate. The gravitational pull must come from an extremely massive object, or else they would exceed the Eddington limiting luminosity, $L = 4\pi GMm_pc/\sigma_T = 1.3 \times 10^{31} \left(\frac{M}{M_\odot}\right) W$ (where m_p is the proton mass, $M_\odot$ the mass of the sun, and σ_T the Thompson cross-section), at which point the radiation pressure would overcome gravity, rendering instabilities, which would blow the object apart. Since the luminosity of 3C 273 is at least 10^{40} W, the enclosed mass must exceed $10^9\ M_\odot$ for the source to achieve equilibrium.

A refined theoretical description of the phenomenon was presented by Donald Lynden-Bell (Lynden-Bell, 1969), who also suggested that many, if not most galaxies, host a heavy black hole at their centre. He asserted that such a supermassive black hole, with a mass as large as 10^6 to $10^9\ M_\odot$, was a quiet remnant of a past active 'quasar phase'. The Milky Way should be no exception, and in a very influential paper two years later, Lynden-Bell and Martin Rees (Lynden-Bell & Rees, 1971) argued for the existence of a supermassive black hole in the Galactic centre and proposed key observations to explore the nature of the compact object. Earlier, Kerr (1963) had generalized the Schwarzschild solution to describe a rotating black hole, adding angular momentum to mass and electric charge (Newman et al. 1965) as the principal physical parameters describing black holes, irrespective of how they were formed.

A critical observable is the innermost stable circular orbit (ISCO), which is at a distance $3R_S$ from a Schwarzschild (non-rotating) black hole. Matter closer than that will therefore fall directly into the black hole, adding to its mass. Furthermore, as matter spirals in to its final destiny, up to between 6% and 42% of its rest-mass energy can be released, depending on the rotational energy and the black hole spin direction with respect to the spiralling in-falling matter. This supermassive black hole hypothesis thus provided a plausible explanation for the high luminosity of quasars.

In 1969, Penrose realized that the rotational energy of a Kerr black hole could be another important source of energy, further elaborating this realization two years later (Penrose & Ford 1971). The mechanism by which this energy is released is far from trivial. In classical mechanics there are a few ways to obtain energy from a rotating body. Projectiles can be shot so that they bounce off the surface, increasing their speed while the rotation of the body decreases. Tidal forces transfer the rotational energy of the Earth to the orbital energy of the moon. A black hole has no hard surface, so how can the energy transfer occur?

Outside of any rotating object, including the Earth, space-time is dragged along with the rotation giving rise to the *Lense-Thirring effect*. The effect is small for Earth, but close to a rotating black hole the effect is dramatic. Just outside of the horizon there is an *ergosphere*, within which it is impossible for an observer to resist the rotation of space-time. If the black hole is rotating, say, in a clockwise direction, the observer will be carried around in a clockwise direction – even if the observer is trying hard to move in the opposite direction.

Penrose found that it is possible to make use of the ergosphere to extract energy. He envisioned how a projectile sent inside of the ergosphere splits into two, with one piece entering through the horizon and the other leaving the ergosphere and escaping from the black hole. Penrose showed that this process can happen in such a way that the escaping piece has a total energy that is *larger* than the energy of the original projectile, with the extra energy extracted from the rotating black hole.

This process seems contrary to the conventional wisdom that nothing can get out of a black hole and that a black hole can only grow in size. The solution to the apparent paradox lies in how to define the size of a black hole. As understood by Stephen Hawking (Hawking 1972), it is *the area of the horizon* of a black hole that never can decrease in size. A Schwarzschild black hole has mass in direct proportion to its area. If the area cannot decrease, neither can the mass. The case of a rotating black hole is more complicated. The Kerr metric leads to $A = 8\pi M\left(M + \sqrt{M^2 - a^2}\right)$, where the parameter a measures the angular momentum of the black hole. Remarkably, the mass can decrease even if the area grows, thus making the Penrose process possible.

Following work of Jacob Bekenstein (Bekenstein 1972), Hawking went on to study the remarkable connection between black hole physics and thermodynamics, with area acting as entropy (Hawking 1975). He discovered that as a consequence of quantum mechanics, black holes have a tiny temperature and are expected to emit radiation. Even though the radiation is far too weak to be measured in the case of astrophysical black holes, the discovery of this process has been of fundamental importance for the development of theories of quantum gravity.

In 1977, Roger Blandford and Roman Znajek used Penrose's insight to construct a realistic model of how the rotation of a black hole could be used to generate power (Blandford & Znajek 1977). If magnetic fields are present, these will be carried along with the ergosphere. In this way, the rotating black hole can act as a gigantic electric dynamo. This process is considered to play an important role for many black holes and their jets.

Early tests of the hypothesis of supermassive black holes in galactic nuclei

The angular resolution of telescopes in the early 1990s was insufficient to spatially resolve objects separated by distances comparable to the size of the Schwarzschild radius of a possible supermassive black hole at the centre of our galaxy, or even much heavier supermassive black holes in other galaxies. However, observations of the orbits of stars and gas can help determine the gravitational potential due to objects at the centre of the galaxy. One can then infer whether a single compact source or dense cluster of known stellar objects, e.g., neutrons stars, white dwarfs or even low-mass black holes, could account for the observations. Black hole mean densities, computed as the ratio of their mass to the volume enclosed within a radius of $3R_S$ (the ISCO), scale inversely with the square of their mass, $\rho = \frac{c^6}{288\pi G^3 M^2}$. For a supermassive black hole weighing $4 \times 10^6 M_{\odot}$, the density is actually only about 40 times larger than that of water. However, when converted to astronomical scales, this amounts to $6 \times 10^{23} M_{\odot} pc^{-3}$ (1 pc = 3.26 light-years), much larger than the density of any known stellar cluster. Globular clusters with a density of $10^5 M_{\odot} pc^{-3}$ are the densest-known long-lived multi-body systems in our galaxy.

Thus, the general observational strategy to identify the existence of supermassive black holes was based on the determination of mass density within the innermost region of galaxies, then comparing this density with known stellar clusters. An additional strategy based on direct imaging would come much later, with the observations of the Event Horizon Telescope reported in 2019.

The study of AGNs became much more accessible with the launch of the Hubble Space Telescope (HST) and its unprecedented angular resolution at optical wavelengths. About 50 nearby AGNs were targeted for observation. Multi-wavelength observations of a powerful jet originating at the nucleus of the nearby elliptical galaxy M87, in the Virgo cluster, were particularly interesting.

Early HST observations (Ford et al. 1994; Harms et al 1994) indicated the presence of a rotating disk in M87 with mass of a few times $10^9 M_{\odot}$, confined within 18 pc from the nucleus. This result was derived from the kinematics of the gas in the disk and the angular scale probed in this case corresponded to about $3 \times 10^4 R_S$. While very suggestive of a central supermassive black hole, the observations could not rule out the possibility that the gravitational potential was due to a dense cluster of stars, too faint for detection.

The first empirical claim that a dense stellar population *could not* account for the kinematic motion around a galactic centre was made by Miyoshi et al. (1995). They made observations of a rotating H_2O maser disc at 0.13 pc from the centre of one of the closest active AGNs, the nucleus of the galaxy NGC 4258 at a distance of 7.3 Mpc. Observations made at the 1.3-cm radio wavelength Very Long Baseline Array (VLBA) showed a thin disk containing H_2O masers surrounding the mildly active nucleus.

Exploiting the power of the very Long Baseline Interferometry (VLBI) technique, they mapped the location and velocity of the masers with an angular resolution better than a milliarcsecond. The rotation curves follow Keplerian orbits around compact central source with a mass of $3.7 \times 10^7 M_{\odot}$, corresponding to a density in excess of a few $\times 10^9 M_{\odot} pc^{-3}$. This density is inconsistent with a long-lived dense cluster of stellar-mass astrophysical sources.

The centre of the Milky Way as a laboratory for fundamental physics

The central few parsecs of the Milky Way harbours a rich cluster of stars and hot gas. These have been used to trace the gravitational potential of the Galactic centre defined by the compact radio source Sagittarius A* (Sgr A*), at a distance of 25,000 light years. If the mass concentration at the very centre of the Galaxy is made of a single supermassive black hole, the typical speeds of the stars at a distance r from the centre should be proportional to $1/r^{1/2}$, i.e., growing for progressively *smaller* radii, as for planets around the Sun.

Such Keplerian orbits should not arise if the mass is due to a spatially extended cluster of stellar-mass objects. With spatially distributed mass, the velocities would increase with distance or be less independent of distance, depending on the density profile of the stellar cluster. Thus, observations of stellar velocities became essential to the exploration of a possible supermassive black hole in the Galactic centre.

Focused observational programs led by Ghez and Genzel

Two observational teams, one led by Genzel at the Max Planck Institute for Extraterrestrial Physics (MPE) and the other by Ghez at the University of California, Los Angeles (UCLA), have been monitoring the motions of stars orbiting the Galactic centre for nearly three decades. Genzel's group used telescopes in Chile operated by the European Southern Observatory (ESO), while Ghez and her colleagues used the Keck Observatory in Hawaii.

Distinguishing individual stars in orbit in the very crowded region at the Galactic centre requires excellent spatial resolution. Obscuration by interstellar dust in the centre of the Milky Way inhibits observation at *optical* wavelengths, with less than about one photon per billion penetrating the dust along the line of sight to Earth. Therefore, the two teams carried out their observations in the *near-infrared* (the astronomical K-band), centred at λ =2.2 μm. At these longer wavelengths the mean-free path of photons is much larger, reducing the attenuation to only about a factor of 10, thus making the observations feasible.

The long measurement time needed to recover the signal and follow the stellar orbits around the Galactic centre rendered space-based observations impractical. Ground-based observations were necessary and the challenge became finding ways to compensate for the blurring that results from changes in Earth's atmosphere during the long measurement time. The technical solutions developed by both teams were key to their successes.

Detection of stellar motions in the Galactic centre

Turbulence in the Earth's atmosphere smears the photon trajectories at time-scales shorter than about one second. To compensate for this, both teams initially developed and used the technique of *speckle imaging* in the near-infrared. Very short exposures, just above a tenth of a second, were acquired with a very sensitive detector. The series of short exposures were spatially shifted to align the pattern of stars and added. The stack of shifted images provided a sharper and deeper image, ultimately limited by diffraction. For K-band observations at the 10-m telescope, the diffraction limit is about 0.05 arcseconds, corresponding to a spatial scale of 2.5 light days at the Galactic centre. Figure 4 (from Ghez et al. 1998) compares an individual image of the Galactic centre with those resolved from speckle imaging at the Keck telescope. The power of the technique to spatially resolve the stars in the central parsec region surrounding Sgr A* is clear.

With high angular resolution the resulting projected velocity vectors of a handful of stars could be determined after a survey over four years on the 3.5-m New Technology Telescope (NTT; Eckart & Genzel 1996, 1997); see figure 5. Genzel's team could also reach the diffraction limit on spatial resolution with the specially constructed SHARP camera. The velocity v of the stars, inferred from the shifts in their positions resolved through diffraction limited images, led to a successful measurement of the $v \propto r^{-1/2}$ behaviour expected for a single massive point source, as shown in figure 6.

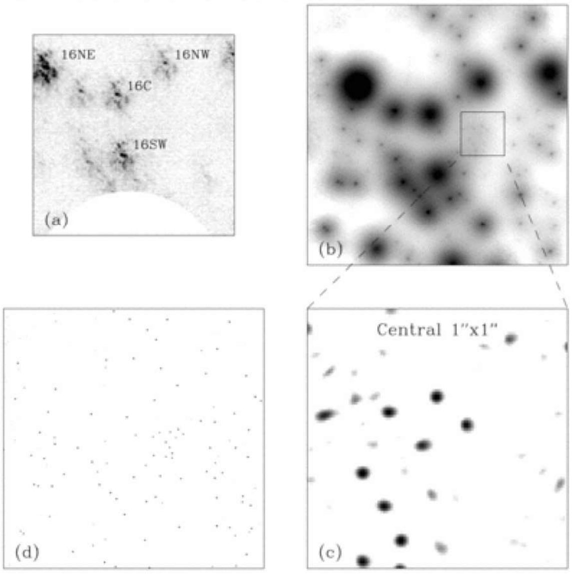

Figure 4. *(a) One of the many short (t_{exp} = 0.13 s) exposures of the stellar cluster surrounding the Galactic centre using the Keck-I 10-m telescope showing the speckle pattern, dominated by one bright speckle. (b) The individual frames are shifted to the same location using a bright reference source. (c) The resulting positions of the stars are shown. (d) The diffraction-limited central 1"x1" stellar region surrounding the compact object. From Ghez et al. (1998).*

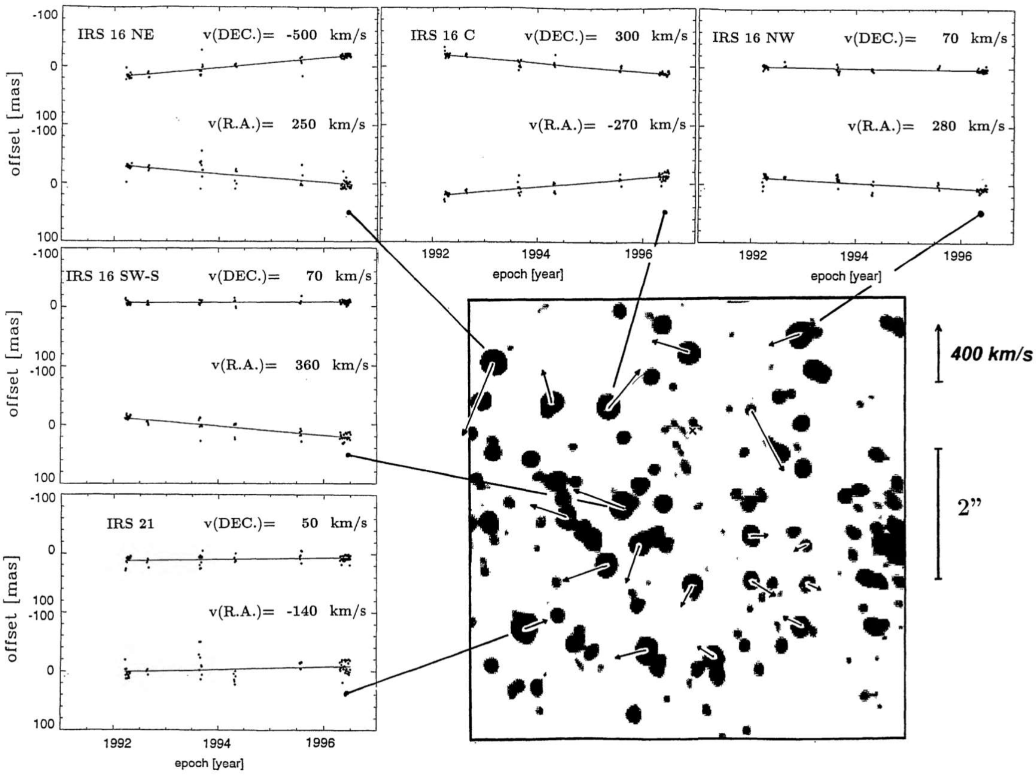

Figure 5. *Proper motions and vectors of selected stars surrounding the central compact radio source Sgr A*, marked with a cross. The measurements were carried out over four years and the offsets were determined with respect to the base epoch in 1994. From Eckart & Genzel (1997).*

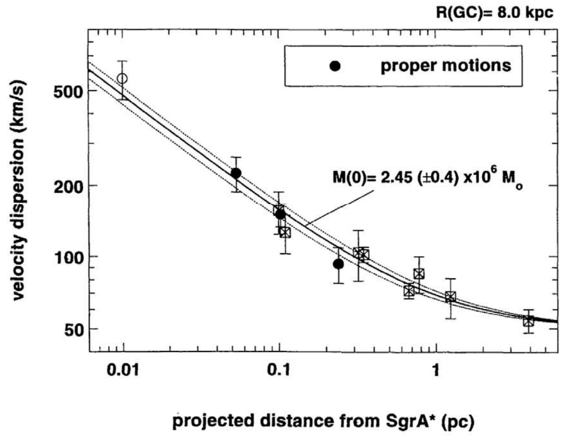

Figure 6. *Projected stellar velocity dispersion as a function of projected distance from Sgr A* from a set of measurements, culminating with the innermost points within 0.2 parsec (circles) obtained from measurements with the SHARP camera on the ESO 3.5-m NTT. The curves indicate the expectations from a supermassive black hole with ~2.5 million solar masses. Adding more recent data from VLT and Keck the mass estimate increased to over 4 million solar masses. From Eckart & Genzel (1997).*

The era of adaptive optics: tracing individual star orbits

The short exposure times involved in speckle imaging limited the monitoring to only the brightest stars, and lengthy surveys were required to extract a robust determination of the projected velocity. These limitations were overcome when adaptive optics, first envisioned by Babcock (1953), became available to Ghez's team at the Keck Observatory (Wizinowich et al 2000) and Genzel's team at the Very Large Telescope (VLT) operated by ESO (Rousset et al 2003).

As shown in figure 7, the adaptive optics technique uses a bright reference object next to the observation target, either a bright star or even an artificial 'star' created by laser excitation of Sodium atoms in the upper atmosphere. A deformable secondary mirror changes shape to compensate for aberrations to the known reference object. The compensation is performed in real time with a feedback loop, thus enabling long exposure time and the creation of much sharper and deeper images, down to the diffraction limit. This technological revolution also allowed for the use of a spectrograph to study the stars, adding two important features: the composition of the stars could be studied and, crucial to the project, radial velocities could be measured in addition to the projected velocities.

At ESO, Genzel's group started a program at the 8-m VLT using adaptive optics imaging with the NACO instrument and spectroscopy with SINFONI. Not only statistical measurements of the stellar motions were made with the new technique, but most importantly, individual stars could be accurately monitored in a manageable time scale.

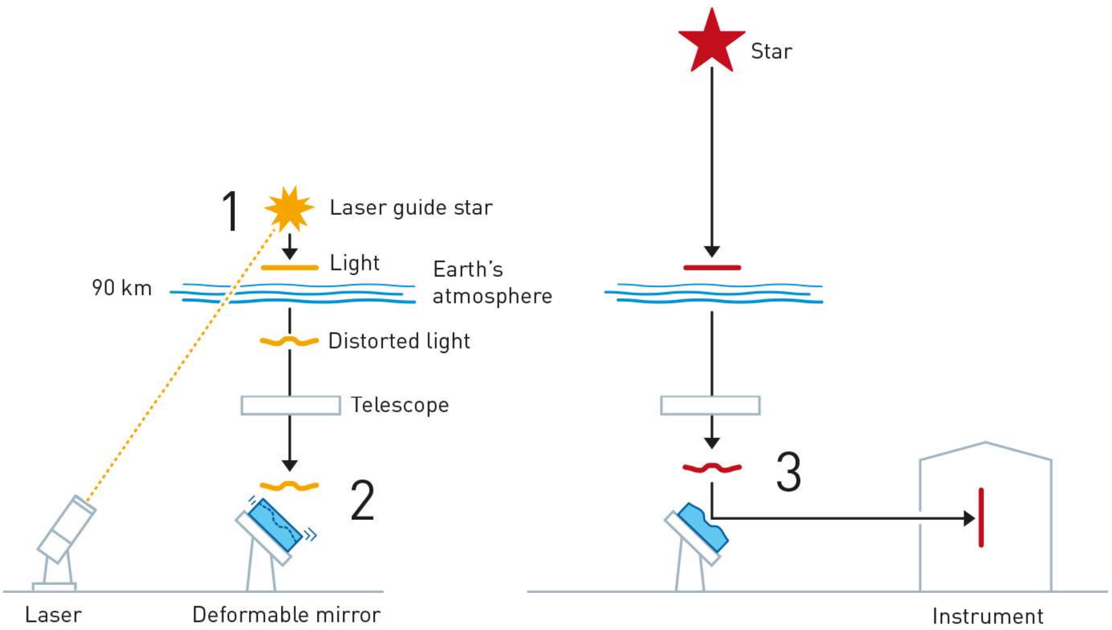

Figure 7. *The principle of adaptive optics. A laser system is used to make artificial guide stars that sense the blurring in the Earth's atmosphere. The images of the bright spots generated by the laser [1] are used in a feedback loop to introduce fast deformations of a secondary mirror [2] that effectively correct for the atmospheric turbulence in the science images [3].*

The discovery of a compact object in the Galactic centre

One of the stars, labelled as S2 by Genzel's group (called S02 by the team led by Ghez), was shown to have a very short orbiting period around Sgr A*, just under 16 years (Schödel et al. 2002, Ghez et al. 2003). For comparison, it takes over 200 million years for the Sun to complete a full orbit around the Galactic centre. This star has a highly elliptical orbit with eccentricity e = 0.88. Its pericentre distance from Sgr A* in the spring of 2002 was a mere 17 light hours, or 1,400 R_s, for a black hole of mass $4 \times 10^6 M_\odot$ (see figure 8). The plane of the orbit has an inclination of about 46° with respect to the plane of the sky.

The agreement between the data from the NTT/VLT and Keck telescopes was excellent. The analysis of the combined data sets showed that the extended mass component (visible stars, stellar remnants and, possibly, dark matter) within the orbit of S2, gave a negligible contribution to the estimation of the central mass (Ghez et al. 2008, Gillessen et al. 2009b). The work of the two teams together established that the Galactic centre contains a highly concentrated mass of ~4 million solar masses within the pericentre of S2, i.e. within 125 AU. This requires a minimum density of $5 \times 10^{15} M_\odot pc^{-3}$. The mass centroid lies within ±2 milliarcseconds of the position of the compact radio source Sgr A*, which itself has an apparent size of <1 AU (Shen et al. 2005, Bower et al. 2006, Doeleman et al. 2008) and lacks detectable proper motion (Reid & Brunthaler, 2004).

A robust interpretation of these observations is that the compact object at the Galactic centre is compatible with being a supermassive black hole. Further support for this conclusion comes from the fact that near-infrared and X-ray flares are observed from the same position, which can be naturally ascribed to variations in the accretion flow towards a massive black hole.

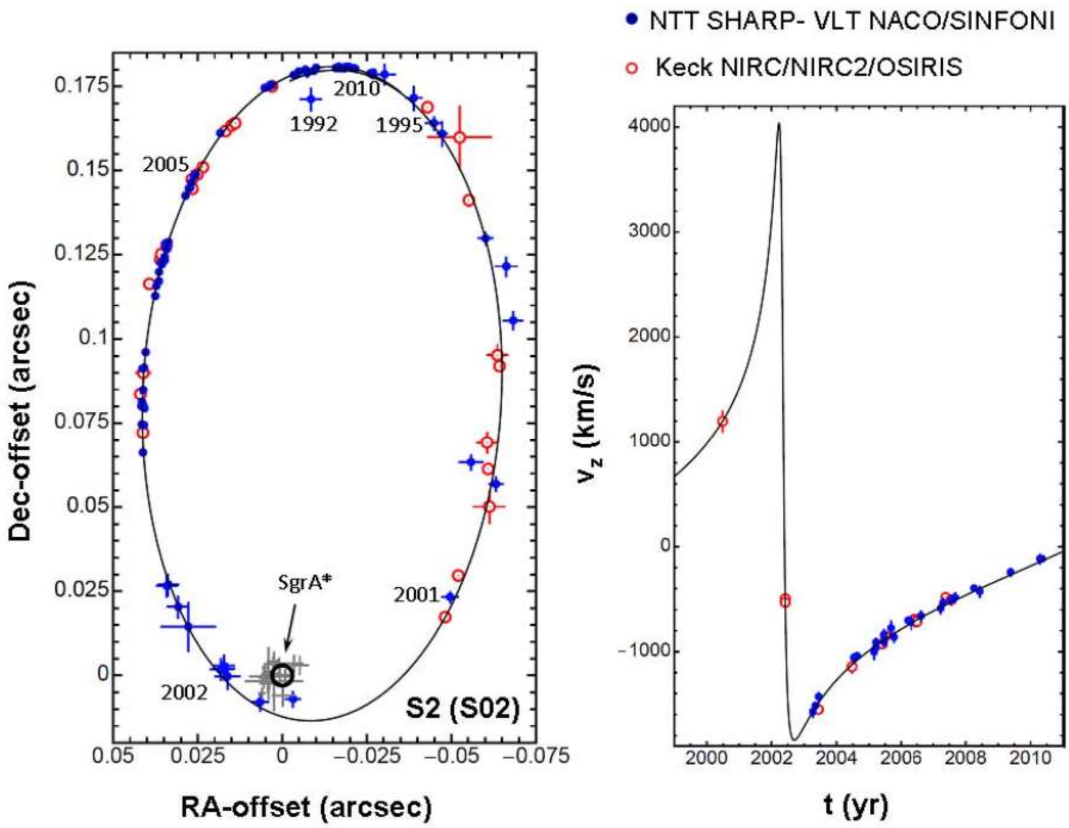

Figure 8. *Orbit of the star S2 (S02) on the sky (left panel) and in radial velocity (right panel). Data from NTT/VLT and Keck are shown. Blue, filled circles, denote the NTT/VLT points and open and filled red circles are the Keck data. The positions are relative to the radio position of Sgr A* (black circle). The grey crosses are the positions of various Sgr A* infrared flares. From Genzel, Eisenhauer & Gillessen (2010).*

Recent updates on Galactic centre results

The ESO/VLT observations using interferometric imaging and astrometry connecting the four VLT telescopes, have now been carried out by the GRAVITY collaboration (Abuter et al., 2018) with Genzel among the leading investigators. GRAVITY has achieved an angular resolution of only 20 micro-arcseconds, about 100 times sharper than the first SHARP speckle imaging results.

Figure 9 summarizes 26 years of imaging the motion of the S2 star around Sgr A* based on observations with ESO telescopes. The upper-right panel shows the spectroscopic observations from both Keck and ESO that were used to measure the radial velocity. The observations are now precise enough that the position of the star can be seen to change between consecutive nights, as indicated in the bottom-right panel. The best fit of the orbit including special and general relativistic effects is shown as a solid line in the plots. Not only have the measurements provided exquisite kinematic evidence for a compact object in the Galactic centre, but also a sub-percent error estimate of the distance to the Galactic centre and a 20σ detection of the relativistic corrections needed to model the orbit of the star to the supermassive black hole. Furthermore, the team was able to detect the relativistic precession of the orbit—a truly remarkable experimental achievement addressing fundamental physics.

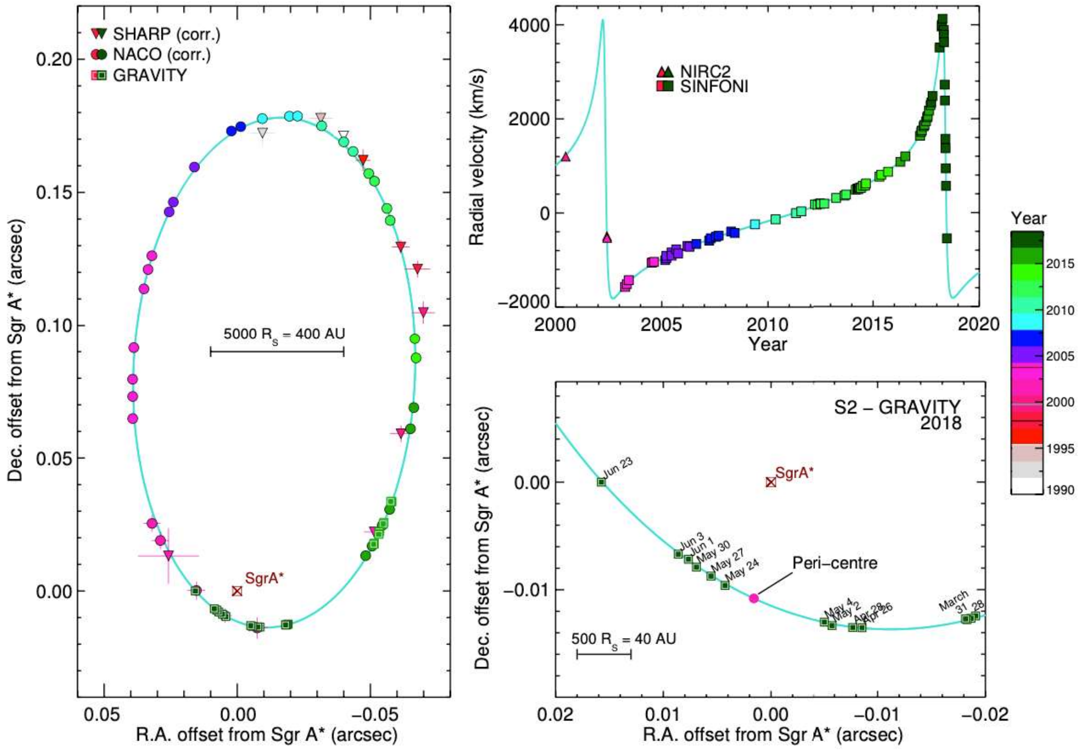

Figure 9. *Summary of the observational results of monitoring the S2–Sgr A* orbit from 1992 to 2018. Left: Projected orbit of the star S2 on the sky (J2000) relative to the position of the compact radio source Sgr A* (brown crossed square at the origin). Triangles and circles (and 1 σ uncertainties) denote the position measurements with SHARP at the NTT and NACO at the VLT, color-coded for time (colour bar on the right side). The cyan curve shows the best-fitting S2 orbit to all these data, including the effects of general and special relativity. The bottom right panel shows a zoom-in around pericentre in 2018. Upper right: Radial velocity of S2 as a function of time (squares: SINFONI/NACO at the VLT; triangles: NIRC2 at Keck). S2 reached pericentre of its orbit at the end of April 2002, and then again on 19 May 2018. The cyan curve shows the best-fitting S2 orbit to all these data, including the effects of General and Special Relativity. From Abuter et al. (2018).*

Detection of motion of heated matter near the innermost stable orbit

The data do not yet allow scrutiny of the compact object closer than several hundred Schwarzschild radii, as shown by the orbit of the S2 star in figure 9. That could change in the future, as deeper observations may reveal stars closer to Sgr A*. However, short infrared flares, about one hour in duration, have been serendipitously discovered over several years (Genzel et al. 2003, Ghez et al. 2003).

These flares originate from the immediate vicinity of the compact object, and the improved angular resolution of GRAVITY potentially allows the use of the flares to trace the innermost region surrounding Sgr A* (Abuter et al. 2018). The sources of the flares appear to orbit around the central object with 30% of the speed of light at a physical distance of only 3–5 R_s, corresponding to the region just outside the innermost stable circular orbit (ISCO) of a Schwarzschild-Kerr black hole of 4 million solar masses. These observations provide additional strong support for the hypothesis that the compact object at the Galactic centre is a supermassive black hole, as predicted by the theory of general relativity.

Summary

Penrose's discovery of the singularity theorem showed that black holes are a robust consequence of the theory of general relativity, forming naturally in very overdense regions.

During the more than half a century that has passed since this conceptual breakthrough, technological advances have enabled probing closer and closer to the black hole event horizon. The observations by LIGO, rewarded the Nobel Prize in 2017, and the exquisite observations by Genzel and Ghez sharing this year's prize, as well as the remarkable picture of the centre of M87 taken by the Event Horizon Telescope, are all compatible with the existence of supermassive black holes.

The extent to which the structure of a black hole surrounded by an event horizon actually match the predictions of general relativity is still an open question. Nature may still have surprises in store.

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