

# The 2020 Nobel Prize in Physics

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The **2020 Nobel Prize in Physics**, which was announced on 6th October, 2020 was divided, one half awarded 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.*" Click [here](#) for the press release.

**Sir Roger Penrose FRS**, is an English mathematical physicist, mathematician, and philosopher of science and the Emeritus Rouse Ball Professor of Mathematics at the University of Oxford, an emeritus fellow of Wadham College, Oxford, and an honorary fellow of St John's College, Cambridge. **Reinhard Genzel** is Professor at the University of California, Berkeley, USA, and Director of the Max Planck Institute for Extraterrestrial Physics (MPE), Garching, Germany; and **Andrea M. Ghez**, is the Distinguished Professor of Physics & Astronomy and Head of University of California, Los Angeles's (UCLA) Galactic Center Group.

## 1. Sir Roger Penrose

### 1.1. Early years and mathematics

Sir Roger Penrose is one of the greatest figures of modern-day science. He started his scientific career as an algebraic geometer at the University of Cambridge supervised by William Hodge and John Todd. He dabbled in physics too and took Dirac's Quantum Mechanics and Bondi's course on relativity but it was conversations with Dennis Sciama, one of the fathers of modern cosmology, that really got him excited about the prospect of doing physics.

Beginning in 1959, Penrose published a series of important papers on cosmology. His unique mathematical perspective allowed him to approach relativity in an entirely new way. One of Penrose's major breakthroughs was his introduction of twistor theory, a remarkable mathematical theory combining powerful algebraic and geometric methods in an attempt to unite relativity and quantum theory.

Einstein's equations are devilishly difficult to solve without lots of simplifying assumptions. Penrose focused instead on what he could learn from the topological, causal, and conformal properties of spacetime. In 1960 he published the landmark paper, "[A spinor approach to general relativity](#)", providing an elegant and detailed exposition of the mathematical apparatus of gravitation theory, with emphasis on the geometrical theory of the Riemann tensor.

## **1.2. Penrose and Hawking**

In 1963 Penrose introduced his method for representing the global causal structure of spacetime with simple diagrams and in 1964, he showed that singularities were an unavoidable outcome of gravitational collapse. This profound result was extended and codified in work with Sciama's best-known student, [Stephen Hawking](#).

In 1965 Penrose published his first singularity theorem, which treated the specific problem of singularities in black holes. The theorem demonstrated that, given certain initial conditions on a collapsing star, a singularity would inevitably occur. Such singularities had been known previously only in certain specialized models e.g., models of stellar collapse that assumed perfect spherical symmetry. Penrose's theorem established that singularities are in fact a general feature of collapse. The following year, Hawking announced his own singularity theorem by applying Penrose's theorem to cosmology and proved the existence of a singularity not in a collapsing star, but at the beginning of the universe.

Hawking's theorem advanced cosmology in much the same way Penrose's theorem had advanced black-hole physics. It showed that singularities follow from rather general assumptions, whereas previously they had been known only for certain specific cosmological models, primarily those with perfect homogeneity. Their definitive success came in 1970 when they jointly proved a singularity theorem much more powerful than any of the theorems they had created individually. The theorem was a watershed in cosmology because it asserted that a Big Bang singularity must occur in any universe with certain very fundamental properties, such as positivity of the energy density of matter.

Earlier work by Lifshitz and Khalatnikov had indicated that the singularities in some models like the Friedmann models did not originate with a proper singularity. But the theorem of Hawking and Penrose showed that this belief was almost certainly erroneous.

In proving their theorem, Hawking and Penrose employed mathematical techniques that had been developed in the theory of differential topology but had never been successfully applied to Einstein's equations. Previous work had focused on rigorous solutions of Einstein's equations for each particular model, a method that necessitated making significant simplifying assumptions about the universe. Hawking and Penrose instead investigated the possible solutions to Einstein's equations assuming certain inequalities.

Before this paper it wasn't clear if singularities were in some sense contrived; the end result of evolution from an unnaturally symmetric initial configuration too perfect to occur in the real world. Penrose showed that they were instead probably generic and unavoidable. Working with inequalities enabled Hawking and Penrose to side-step many complexities and still come up with a significant result.

The same mathematical techniques later enabled them to prove the well-known area theorem for black holes and several other astonishing results. The most notable one among them is that a black hole radiates as a blackbody with a temperature inversely proportional to its mass.

## **2. Andrea Ghez and Reinhard Genzel**

### 2.1. Overview of their Work

Just as the moon revolves around the Earth and the Earth revolves around the sun, our star; the sun revolves around our black hole, Sagittarius A\*! Andrea Ghez and Reinhard Genzel helped create images of the black hole at the centre of our galaxy. They made precise measurements of the stars orbiting close to our black hole, with Ghez using the Keck Observatory in Hawaii and Genzel using the Very Large Telescope in Chile. By precisely measuring the trajectories of stars orbiting our black hole they were able to peer closer and closer to its event horizon.

The centre of the Milky Way is a great laboratory for fundamental physics, harbouring 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 certain distance from the centre should be 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, one led by Genzel at MPE and the other by Ghez at 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.

## **2.2. Overcoming technical challenges**

Distinguishing individual stars in orbit in the very crowded region at the Galactic centre requires excellent spatial resolution. However, there is obscuration by interstellar dust in the centre of the Milky Way that inhibits observation at optical wavelengths. Less than about one photon per billion penetrates 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). At these longer wavelengths, the mean-free path of photons is much larger. This reduces 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. The challenge now 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 in the 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. The exposures were added with the stack of shifted images providing a sharper and deeper image, ultimately limited by diffraction.

The short exposure times involved in speckle imaging limited the monitoring to only the brightest stars. Lengthy surveys were required to extract a robust determination of the projected velocity. These limitations were overcome when adaptive optics, first envisioned by the legendary Director of the

Palomar Observatory, Horace Babcock, became available to Ghez's and Genzel's teams.

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 then 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 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. 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.

## **2.3. Observations**

They discovered a compact object in the Galactic centre of one of the stars. Genzel's group labelled it as S2 and it was called S02 by the team led by Ghez. It was shown to have a very short orbiting period around Sgr A\*, just under 16 years. For comparison, it takes over 200 million years for the Sun to complete a full orbit around the Galactic centre! The groundbreaking 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 astronomical units (1 astronomical unit or AU is roughly the distance from Earth to Sun).

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. These can be naturally ascribed to variations in the accretion flow towards a massive black hole. The measurements have provided exquisite kinematic evidence for a compact object in the Galactic centre. Some of the other important information these measurements provide are:

1. A sub-percent error estimate of the distance to the Galactic centre.
2. Detection of the relativistic corrections needed to model the orbit of the star to the supermassive black hole.

The team was also able to detect the relativistic precession of the orbit. 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.

### **3. Conclusion, remarks and comments on the prize**

The undoubted heroes of today's Nobel Prize in Physics are Black Holes, objects once so mysterious that giants like [Einstein](#) and Eddington berated its existence. 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 majestic conceptual breakthrough, technological advances have enabled probing closer and closer to the black hole event horizon. The terrific measurements by [LIGO](#), the exquisite observations by Genzel and Ghez, and the remarkable picture of the centre of M87 taken by the Event Horizon Telescope are all compatible with the existence of supermassive black holes.

This prize also marks the second consecutive year when astrophysics/cosmology drew the top honours, a far cry from a time when the committee refused to consider it as part of physics and giants like Hubble, [Eddington](#), Oppenheimer, Burbidges, Rubin, and Hoyle went unrecognised. It recognises the mettle of fine theoretical cosmologists like Penrose and Peebles (who won the laurel last year). The Nobel Prize to Andrea Ghez is extra special because she is only the 4th woman to win the Nobel prize in Physics and highlights the Nobel committee's poor record with recognising women, people of colour, and other minorities. One can't also resist pointing out the ludicrous nature of the committee's stubbornness to restrict the prize to three persons in an era where science is more of a collaborative enterprise than one white man show.

Physical cosmology, with its interplay between observations and theory, is a tremendous success story that over the past half-century has changed the way we view our universe. Once, cosmology was a subject full of unfounded speculations and little data but now it is an exact mathematical science, where accurate observations play a key role. The era of discovery is not over. As the measurements become more precise, new and unexpected phenomena are likely to be discovered, and physical cosmology will have more surprises in store, and giants like Penrose and Peebles are the ones who have paved the way.

The Nobel Prize to Roger Penrose is the icing on the cake on what has been a trailblazing career of a giant

who revolutionised vast swathes of mathematics and initiated the greatest discoveries in classical general relativity and greatly enlarged our understanding of space-time by powerful analysis of its possible structure and by the invention of mathematical tools designed to allow an entirely new framework for the description of physical phenomena. One can't resist shedding a few tears for Stephen Hawking, who would've surely split today's prize if he had lived to see the day. One can only hope that more pioneering mathematical physicists like Witten too get a nod because as Penrose and Peebles show, outstanding theorists play a crucial role in germinating fields that flourish years after the ideas were originally seeded and are truly of the greatest benefit to mankind!!

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