The 2020 Nobel Prize in Physics

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Black holes are chunks of space-time from which even light cannot escape. The idea of objects whose escape velocity equalled the speed of light emerged as early as in the eighteenth century. What discoveries then prompted the Nobel Prize in Physics of 2020?

Half of the prize was for Roger Penrose's use of innovative topological methods and ground-breaking intuition as applied to massive gravitational collapse, and the consequent discovery that the formation of singularities was an inevitable consequence (see the accompanying articles). The other half of the prize was for the findings of Reinhard Genzel and Andrea Ghez which is the first *direct* evidence for a cosmic black hole, and indeed, for any black hole at all.

Clergyman scholar John Michell in 1783, and also French polymath Pierre-Simon Laplace in 1796, had independently considered the idea of objects that were massive enough to have escape velocities equal to the speed of light (Montgomery et al 2009). Such objects would therefore trap everything, including light. The implied quantitative relationship between the size (radius) and mass of a spherical body was also derived, viz., $R = 2GM/c^2$. With the size thus proportional to the mass, it was apparent that, say, a marble-sized body, would need to have as much as all of the Earth's mass squeezed into it. The implied densities seemed impossible. Therefore, for any such objects to be plausible, i.e., to have reasonable densities, they would have to be enormous and therefore cosmic; they were called "dark stars".

The mathematical relationship that was derived between size and mass for these dark stars, was in fact formally consistent with the Schwarzschild "singularity" solution to the general relativity field equations that Karl Schwarzschild (1916) obtained soon after Einstein propounded the theory of general relativity (GR). The physical interpretation of the two singularities that Schwarzschild obtained remained murky, however, and they were therefore perceived as unphysical.

The prediction of the precession of Mercury's perihelion by GR was completely consistent with the measured precession. The predicted gravitational bending of light was also consistent with the measured bending of starlight in Eddington's famous eclipse experiment of 1919 (Dyson et al 1923). Nevertheless, the idea of the Schwarzschild solution to the very same GR equations was not perceived as acceptable, because inherent to this solution was the singularity - the point where the densities and the curvature of space-time are infinite and where the laws of physics, including GR, fail.

Chandrasekhar (1931) demonstrated that the electron degeneracy pressure that follows from Pauli's exclusion principle would not be sufficient to counter self-gravity for stars that had spent their fuel, if their masses were above the White Dwarf threshold that he derived (approximately a solar mass). This conclusion logically led to the idea of unstoppable collapse, which Chandrasekhar articulated as, "…and one is left with speculating on other possibilities". Subsequently, Oppenheimer and Snyder (1939) investigated solutions of the gravitational field equations for such spent massive stars until final collapse. They assumed spherical symmetry and zero pressure in the derivation, and found that an external observer sees the star asymptotically shrinking to its gravitational radius, i.e., $2GM/c^2$. They correctly interpreted the surface at this radius as an information hori-

The position of the centre of the Milky Way on the sky in a picture taken from Ladakh, India. The Milky Way is seen with the dark patches across it that are due to dust obscuration. The "teapot"-shaped Sagittarius constellation is marked by dashed lines, and the position of the Galactic Centre is at the edge of this constellation marked by a circle. The planets Mars and Saturn are also seen. [Picture taken by Dorje Angchuk]

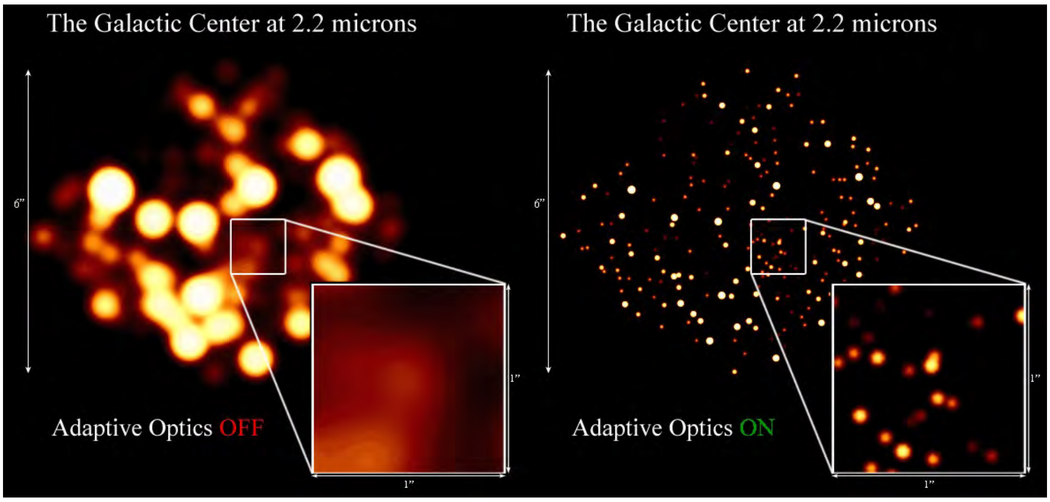
zon, saying that a star at collapse will close itself off from any communication with a distant observer, who will only sense its gravitational field. However, Einstein (1939) himself propounded that Schwarzschild singularities do not exist in physical reality. They were still thought of as artefacts, of perhaps the assumptions made, or that quantum physical effects would prevent collapse to a singularity.

Then came the transformative discovery in the early 1960's of cosmic objects called quasars (Schmidt 1963) - i.e., "quasi stellar" objects. Quasars appeared exactly like stars in visible-light images, i.e., as sharp point-sources of light. Their spectra, however, were quite unlike stars. While typical stellar spectra showed a roughly black-body continuum interspersed with absorption lines depending on atmospheric composition and temperature of the star, quasar spectra had very different continua and were dominated by strong emission lines, which were quite unrecognizable at first. It was soon realized that they were indeed well-known atomic lines but with an over 15% systematic shift to lower frequencies. If interpreted as due to the expansion of the Universe, the implied distances were over 2 billion light-years. This meant that their luminosity was enormous, at least a hundred times the sum-total of the stellar light from a typical galaxy. If the fact that stellar processes fell drastically short in producing such high luminosities were not enough, there was another, even more staggering observation. The light from quasars varied on fast time-scales - months or even days. The light-travel-time argument therefore implied that the enormous luminosity originated from a very small volume. The argument is as follows: due to the finite speed of light, photons from the far-surface of a luminous cosmic object reach Earth significantly after those from the near-surface. Therefore, if such an object is seen to vary on Earth, it cannot be larger than the distance light travels within the time it took for the light to vary. Variability of quasars over a few days implied that the luminosity seen was originating from a region of a 1000 astronomical units (AU=Earth-Sun distance) or less. The enormous but persistent luminosity would result in enormous radiation pressure that required the source to have a mass of a million solar masses so as to not exceed the Eddington limit - clearly implying what we would now call a supermassive black hole. As Salpeter (1964) and, independently, Zel'dovich & Novikov (1965) suggested, the 'horizon' of such an object would be of the appropriate scale from which a significant fraction of the rest-mass energy of matter swirling into it could be released.

Thus the discovery of quasars made "Schwarzschild throats" real. They spurred a re-examination of gravitational collapse in the general relativity framework, and indeed, Roger Penrose's Nobel Prize-winning research.

Advances in quasar research soon revealed that they actually occurred in the hearts of galaxies, and that they had originally appeared as stellar pinpoints of light only because their optical luminosity overwhelmed the stellar light from their hosts, unseen earlier because of dynamic range limitations. Furthermore, a whole panoply of galaxies with over-luminous cores were discovered. Some showed bipolar jets of plasma, most easily visible at radio frequencies, squirted out of the center of the galaxy and reaching out to several hundred kilo parsecs into intergalactic space. Some of the jets were launched at bulk-relativistic speeds. While these "active galactic nuclei" showed a whole range in the luminosities, the speeds of Keplerian gas clouds and the kinetic power of the plasma jets, it became clear that the primary driver for all of them were supermassive black holes.

Initially, it was quite a common perception that such "active galaxies" were "pathological". Lynden-Bell (1969) made a compelling argument, however, that supermassive black holes occurred in the centres of all galaxies, including the Milky Way. The latter proposition was taken further by Lynden-Bell & Rees (1971).



The increase in sharpness of the images brought about by adaptive optics which corrects for the blurring effects of the earth's turbulent atmosphere. The left and the right panel show infra-red images of identical portions of the sky at the centre of the Milky Way, plotted with identical spatial scales. Careful examination reveals the that the panel on the right (with adaptive optics turned on) shows the same stars as on the left, but also many additional fainter stars which are not visible in the left panel because of the blurring. [Created by Prof. Andrea Ghez and her research team at UCLA from data sets obtained with the W. M. Keck Telescopes.]

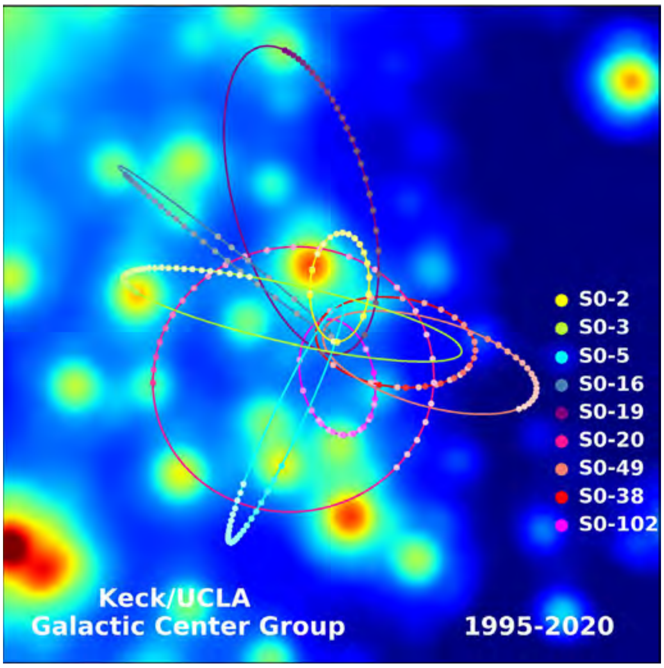
The evidence remained circumstantial, however, because there were at least three challenges to obtaining direct dynamical evidence for black holes. Such dynamical evidence required knowledge of the kinematics of stars in the vicinity of black holes, and most purported extragalactic (outside the Milky Way) supermassive black holes were too far away to observe individual stars around them. Second, the centre of the Milky Way itself, at the edge of the constellation Sagittarius, is shrouded with dust. Third, even the sharpest images possible with state-of-the-art technology fell short for the centre of the Milky Way, which is 26,000 light-years away from Earth. This is because the rays of light from the objects of interest have to pass through the turbulent atmosphere before reaching the telescopes. The turbulence results in very fast refractive index changes, which make the light rays from the cosmos move around very quickly in the detector (the twinkling of stars), which, in turn, blurs the image. Radio frequencies can penetrate the dust shroud and are also unaffected by atmospheric turbulence, and indeed a highly compact non-thermal radio emitter of size at most 0.4~AU has been found there called Sagittarius A* (Lu et al 2018). Nonetheless, any stars that might provide dynamical evidence for a black hole, are too faint to be detectable.

In the '80s, however, infrared telescopes and detectors were gaining ground, and infrared radiation could penetrate the dust shroud around the centre of the Milky Way. Using infrared spectroscopy, Lacy et al (1982) discovered ionized gas clouds there with high velocity dispersion. If they were Keplerian-driven, the presence of a central dark massive object of 3 million solar masses was implied. This was tantalizing but still was not direct evidence, since gas-clouds could also be driven by non-gravitational forces. Ultimately, measurements of stellar velocities were needed.

Again, with infrared spectroscopy, Reinhard Genzel et al (1996) measured over 200 stellar velocities in the line-of-sight using Doppler shifts of the the Helium emission line at 2.11μm, which implied an object with similar mass as above, within half a light-year of the dynamical centre of the Milky Way.

This result was still a step away from definitive dynamical evidence, which really needed the 3-dimensional velocity vector measurements for these stars - i.e., line-of-sight speeds from spectroscopic Doppler shifts, and speeds in the sky plane from the measurement of positional shifts of the stars with time. Measuring such shifts requires extremely sharp images, with a resolution of about 50 milliarcseconds. This is roughly equivalent to reading a newspaper from 15 km away.

The technique of "speckle imaging" was the breakthrough. It involves very short exposures (of a fraction of a second), so that the stars can be imaged at a rate faster



The heart of the Milky Way. The image is about 46 light-days on the side taken in 2015. The background is a false-colour image in the infrared, i.e., the colours represent different intensities of infrared emission, and the circular splotches are real images of stars. The coloured circles represent the positions of the stars averaged over a year, plotted to have increasing colour saturation with increasing time. The elliptical curves are the best-fit simultaneous orbital solutions. [Created by Prof. Andrea Ghez and her research team at UCLA from data sets obtained with the W. M. Keck Telescopes.]

than the changes in atmospheric refractive index moves the stellar images around on the detector. The technique requires a large photon collecting area for the short exposures and/or highly sensitive detectors. The large diameter of the newly commissioned Keck Telescope on Mauna Kea in Hawaii was ideally suited for Andrea Ghez to lead a new investigation of the centre of the Milky Way. Genzel and team also began speckle-imaging with the European telescopes in La Silla, Chile. Over 40 stars tracked by Eckart & Genzel (1997) and 90 stars by Ghez et al (1998) and her team showed speeds of the stars upto 1400 km s^{-1} and clear dynamical evidence for the driving central object to be a black hole of over 2million solar masses in size.

A decade later, both teams were able to ramp up the sharpness of their images hugely by using the technique of 'adaptive optics' on the Keck Observatory telescope and the Very Large Telescope, respectively. This technique involves using a reference star near the target in the sky or an artificial 'star' created by a laser beam to measure the distortions in the wavefront from the target star created by the atmospheric turbulence. The distortions are then corrected for in real time by compensatory deformations at the telescope. The increased sharpness not only enabled higher precision position measurements of the stars, but brought more (fainter) stars into view, and enabled spectroscopy of the stellar Br-γ absorption line to obtain their line-of-sight speeds via Doppler shifts. Thus, zooming into the very centre of the Milky Way and obtaining the 3-dimensional velocity vector for many more stars was made possible. A more precise mass for the central black hole of 4 million solar masses was obtained, and the case for a real supermassive black hole was thus solidified beyond doubt. The fact that two independent teams obtained consistent results using independent telescopes and instrumentation made the discoveries highly robust.

What's next? In 2015 the LIGO collaboration not only detected the first gravitational waves (Abbot et al 2016), but also discovered the second piece of direct evidence for black holes by detecting two coalescing black holes that formed a third black hole. In 2019, the Event Horizon Telescope imaged the silhouette of a supermassive black hole (Event Horizon Telescope Collaboration 2019), again fully consistent with the predictions of general relativity. The continuing high-precision measurements by the teams of Ghez and Genzel (Do+2019, Hees et al 2020, GRAVITY 2020) have enabled researchers to go beyond just determining the Keplerian orbits of the stars around the supermassive black hole; they are now measuring deviations from Newtonian physics, and indeed searching for deviations (or the lack thereof) from predictions of general relativity. One of the stars that has been monitored since 1995 has an orbital period of 16 years and has revealed deviation from Newtonian predictions at the position of closest approach to the black hole, which can be understood as a combination of special relativistic Doppler shift and gravitational redshift. No deviation from general relativity has been measured so far. The centre of the Milky Way is clearly a very promising laboratory to test the predictions of general relativity. It also offers a unique opportunity to investigate the physics of star formation and evolution in a strong-gravity environment.

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