On October 5th, 2020, Royal Swedish Academy of Sciences declared that the Nobel Prize in Physics would be awarded to Sir Roger Penrose of University of Oxford, Prof Reinhard Genzel of Max Planck Institute of Extraterrestrial Physics and Prof Andrea Ghez of University of California Los Angeles for their theoretical and observational work on black holes. In the prize motivation the Academy mentioned that Roger Penrose, in 1965, theoretically showed that black hole formation is a robust prediction of general theory of relativity [1].

Andrea Ghez made groundbreaking observations of stars orbiting the Milky Way's center that suggested that a supermassive compact object resides there [1].

The idea of black hole fascinated people from different faculties starting from the professional physicists to the common people. Black hole forms because gravitational force affect light. Any gravitating object attracts light. If the gravitational force due to some object is so strong that light cannot escape then black hole forms. Mathematically this concept is connected to the existence of spacetime singularities and formation of trapped surface, known as event horizon, within the framework of general theory of relativity. The first hint of such possibility came when Karl Schwarzschild, in 1916, solved Einstein’s equation for a spherical mass M that does not spin. With his elegant and beautiful calculations Schwarzschild obtained the spacetime metric around the mass and found that some terms in his solutions either vanish or diverge at \( r=0 \) and \( r=2GM/c^2 \) (known as Schwarzschild radius) giving rise to singularities in spacetime. As Schwarzschild was ill, he sent his results to Einstein who presented
those results at the meeting of Prussian Academy of Sciences on 13 January 1916. Even though Einstein was fully aware of the work of Schwarzschild, he was not comfortable with those results. In 1939, Einstein wrote a paper in Annals of Mathematics [2]. In the last paragraph of the article Einstein wrote, “The essential result of this investigation is a clear understanding as to why the ‘Schwarzschild singularities’ do not exist in physical reality.... The ‘Schwarzschild singularity’ does not appear for the reason that matter can not be concentrated arbitrarily. And this is due to the fact that otherwise the constituting particles would reach the velocity of light [2].” However during 1930s astrophysicists were busy in resolving one important issue related to the stellar evolution. In 1931, Subramanian Chandrasekhar showed that the low to medium mass stars like Sun will end their life as white dwarf where the system is supported by electron degeneracy pressure against further gravitational collapse. The maximum mass of the white dwarf will be 1.4 times the mass of the sun, known as Chandrasekhar limit [3]. In 1939, J. R. Oppenheimer and G. M. Volkoff, using the general theory of relativity, found that stars in the mass range (0.7 - 3) times the solar mass will end their life as neutron star where the star is supported by neutron degeneracy pressure against further gravitational collapse [4]. Therefore, astrophysicists asked what would happen to a star which has mass, say 50 solar mass? Oppenheimer and his student Hartland Snyder gave an answer using general theory of relativity [5]. They concluded for a sufficiently massive spherically symmetric star: *When all the thermonuclear sources of energy are exhausted, a sufficiently heavy star will collapse ... the radius of the star approaches asymptotically its gravitational radius; light from the star is progressively reddened, and can escape over a progressively narrower range of angles ... The total time of collapse for an observer co-moving with the stellar matter is finite...* [5]. Somehow this work did not get much attention. Also a group of astrophysicists were skeptical about the final conclusion of the paper. It was thought that it could be due to the assumption of spherical symmetry. Therefore, the question of gravitational collapse, its connection to the space-time singularity and trapped surface remained unanswered. Oppenheimer joined Manhattan project and, later became the director of Institute of Advanced Study, Princeton, but never went back to research in gravitational collapse.

After a gap of almost twenty years, research on gravitational collapse started again with the discovery of quasars, pulsars and compact x-ray sources. In 1960, Roy Kerr, a mathematician from New Zealand, discovered an exact solution of Einstein’s equations for a rotating massive object and determined the metric for the space-time around the rotating mass [6]. This is known as Kerr metric which describes the space-time around a rotating black hole.

In the same year Roger Penrose, a mathematician and philosopher of science, introduced a new approach, known as spinor approach to general relativity. It was actually a topological approach to describe the spacetime. At that time this was completely new to the relativists. Along with that he started describing the space-time associated with some phenomena in his observations on gravitational collapse without assumptions of symmetry, Roger Penrose concluded that deviation from spherical symmetry cannot prevent space-time singularities from arising, and in the process he challenged the applicability of the existing laws of Physics. Later, in 1970, working jointly with Stephen Hawking, he gave black hole formalism a strong basis with a mathematical theory that had a consequential effect in big bang cosmology. Here, the very basis of the work of Penrose was Raychaudhuri equation. Raychaudhuri equation was discovered by Amal Kumar Raychaudhuri, a professor at Presidency College, Calcutta (now Kolkata) in 1955 just one month after the death of Einstein. In his paper, “Relativistic cosmology I” published in Physical Review, Raychaudhuri showed that the space-time singularities are inevitable in general theory of relativity. In fact this very paper formed the basis of the work of Stephen Hawking as well.

**Indian connection to Roger Penrose’s spinor approach to general relativity**

In his observations on gravitational collapse without assumptions of symmetry, Roger Penrose concluded that deviation from spherical symmetry cannot prevent space-time singularities from arising, and in the process he challenged the applicability of the existing laws of Physics. Later, in 1970, working jointly with Stephen Hawking, he gave black hole formalism a strong basis with a mathematical theory that had a consequential effect in big bang cosmology. Here, the very basis of the work of Penrose was Raychaudhuri equation. Raychaudhuri equation was discovered by Amal Kumar Raychaudhuri, a professor at Presidency College, Calcutta (now Kolkata) in 1955 just one month after the death of Einstein. In his paper, “Relativistic cosmology I” published in Physical Review, Raychaudhuri showed that the space-time singularities are inevitable in general theory of relativity. In fact this very paper formed the basis of the work of Stephen Hawking as well.

![Roger Penrose](image_url)
graphically which is known as Penrose diagram. With his new formalism Penrose investigated the possible formation of space-time singularity in gravitational collapse. In his paper titled, “Gravitational collapse and space-time singularities” published in Physical Review Letters in 1965 Penrose discussed gravitational collapse without assumptions of symmetry [7]. He concluded: “deviation from spherical symmetry can not prevent space-time singularities from arising [7].” Physically space-time singularity means a region in which space and time have become so locally distorted that present laws of physics are no longer applicable. The work of Penrose had many important consequences. Later, in 1970, Penrose and Hawking proved a theorem which gave the mathematical theory of black hole formalism a strong basis. His work also has far reaching consequences in big bang cosmology. At this point it is important to mention that the very basis of the work of Penrose was Raychaudhuri equation. Raychaudhuri equation was discovered by Amal Kumar Raychaudhuri, a professor at Presidency College, Calcutta (now Kolkata) in 1955 just one month after the death of Einstein. In his paper, “Relativistic cosmology I” published in Physical Review, Raychaudhuri showed that the space-time singularities are inevitable in general theory of relativity [8]. In fact this paper formed the basis of the work Stephen Hawking as well.

Once Penrose theoretically confirmed the existence of black holes the next question naturally arises how to detect them. As light can not escape a black hole, we can not see a black hole through astronomical observation directly. But the presence of a black hole can be sensed by observing its influence on the environment of the region where it resides. This idea led to the detailed observational study of active galactic nuclei (AGN) which were discovered by the radio astronomers in early fifties. AGN are distant galaxies with their centres more luminous (~ $10^{44}$ ergs/s) than the rest of the galaxy. The total luminosity of a galaxy like Milky Way is ~ $10^{44}$ ergs/s. Astronomers argued that the such enormous amount of energy release is possible if there is a supermassive (~ $10^7$ times the mass of the sun) black hole at the center of the galaxy. As far as our own galaxy Milky Way is concerned, radio astronomers Bruce Balick and Robert Brown, in 1974, concluded that there is a bright compact supermassive object at the center of Milky Way and it is known as Sagittarius A*. Since then rigorous study was going on to find the exact nature of the object.

Reinhard Genzel and Andrea Ghez independently studied the motion of stars moving around the Sagittarius A*. The idea was to study the orbit and the periastron passage of a star. From such observations one can measure the mass and the compactness of Sagittarius A*. Andrea Ghez and her team studied the star S0-2 astrometrically (1995–2007) and spectroscopically (2000 – 2007) in the near-IR region using Keck 10m telescope in Hawaii while Reinhard Genzel and his team followed the same star over last 26 years using the Very Large Telescope (VLT) at
European Southern Observatory (ESO), Chile. To study the orbits they introduced two new techniques—speckle imaging technique and adaptive optics. Using such techniques they could remove the blur in the image due to the turbulence in the Earth’s atmosphere. Finally, in 2008, they reported that S0-2 has a period of 15.56 years (note that the Sun completes one revolution around Sagittarius A* in 200 million years!!), during its periastron passage it was just 120 AU away from Sagittarius A* and moved with a speed approximately 7650 km/s [9, 10]. From these observations they concluded that the mass of Sagittarius A* is four million times the mass of the Sun and it is contained within a region of size of our solar system. Therefore Sagittarius A* is definitely a black hole. Thus it took more than hundred years for the concept of black hole to get its final recognition which was a long due.

References
5. J. R. Oppenheimer and H. Snyder, Physical Review, 1939, 56, 455

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