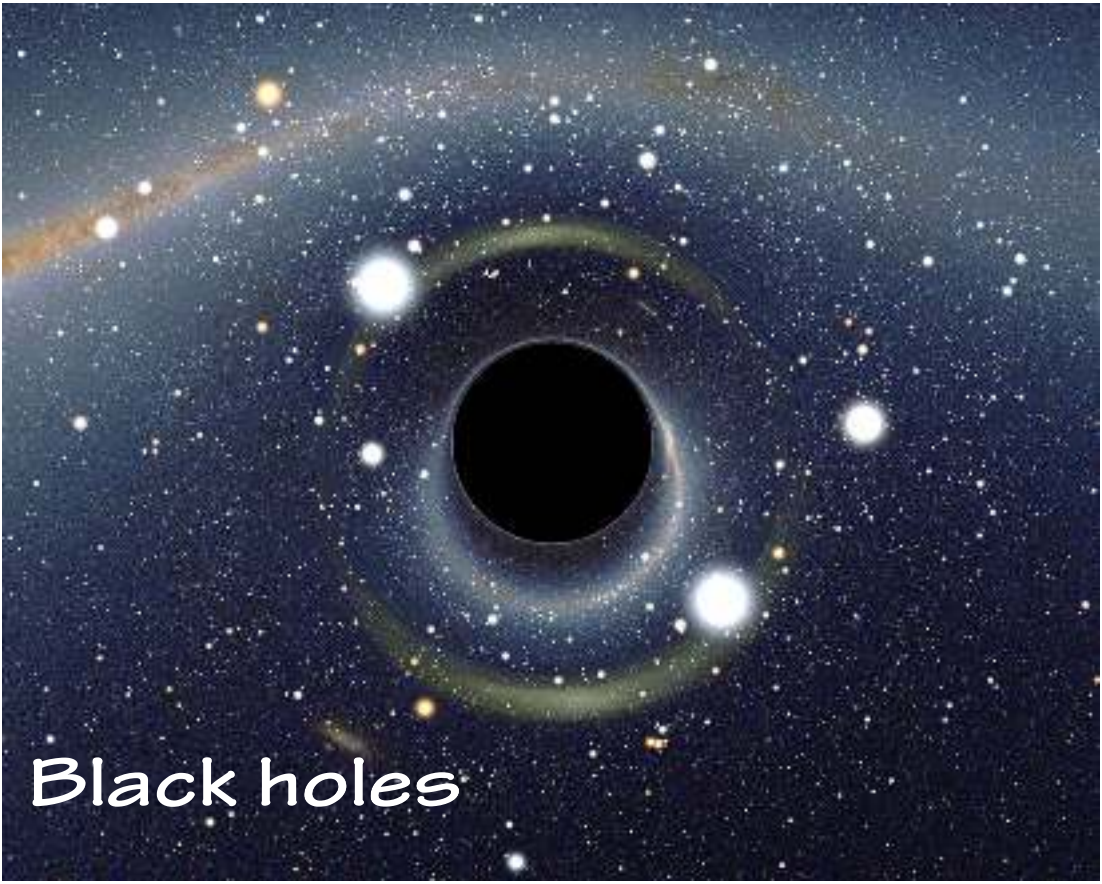
The Universe in my pocket



TUIMP
No. 17
THE UNIVERSE IN MY POCKET

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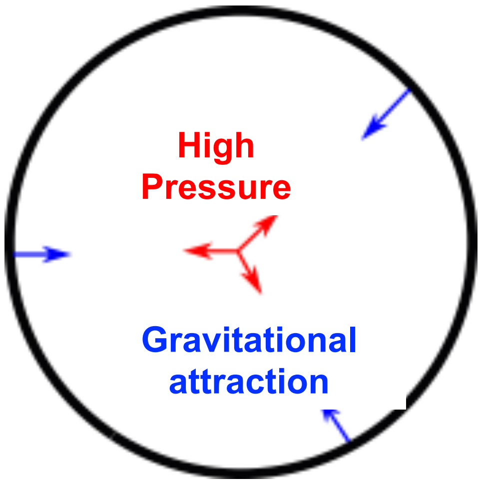
The tremendous pressure at the center of a star pushes outwards like steam in a pot of boiling water.

Gravity tends to make the outer parts of the star fall towards its centre, just as an apple falls from a tree due to the Earth's attraction.



A star is in equilibrium between the outward action of thermal pressure and the inward action of gravity.

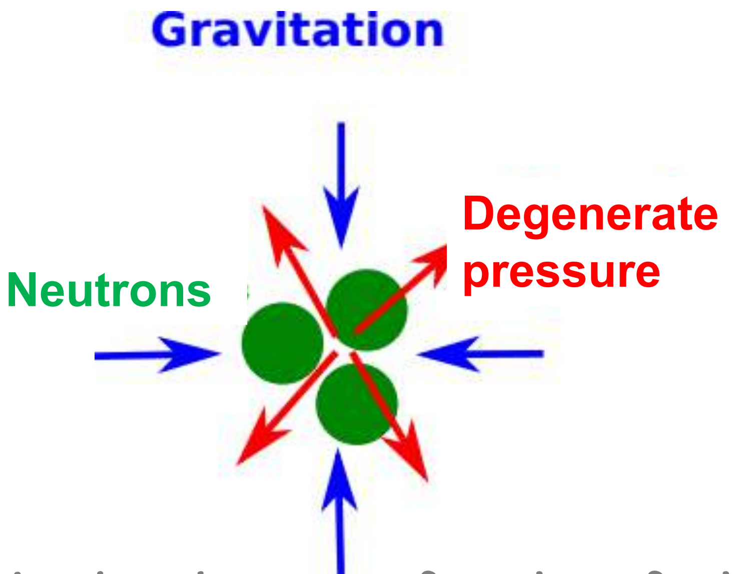
The balance of a star

A star is balanced between two opposing tendencies.

The nuclear reactions at the centre of the star (fusion of hydrogen into helium, fusion of helium into carbon etc. see TUIMP 14) heat the matter and thus give it a very high pressure which tends to expand the star (like water vapour under the lid of a heated pan).

Gravity causes the outer parts of the star to be pulled towards its centre, which tends to contract the star.

These two tendencies exactly balance one another for most of the star's life. But what happens when the star's internal fuel is exhausted?

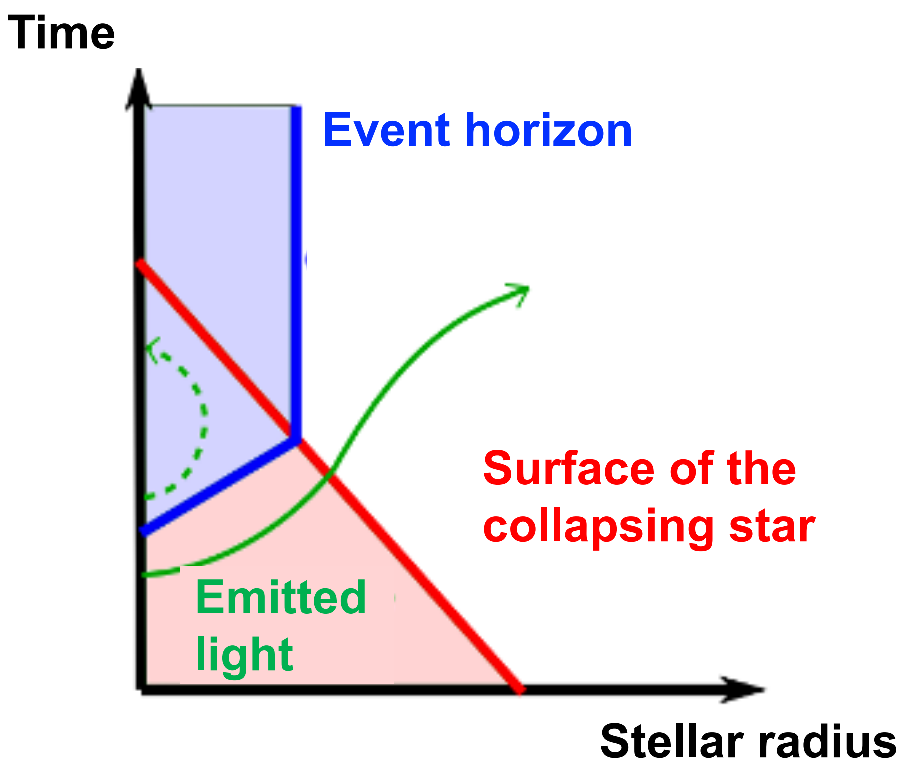


In the absence of nuclear fuel, gravity causes the star to collapse, which leads to a very strong compression of the star's matter. Quantum mechanics then reveals a new form of pressure known as degeneracy, which increases as the compression increases. A new adversary thus develops to confront gravity, after the thermal pressure is no longer sufficient to support the star. However, if the star is massive enough, gravity eventually wins out, and the collapse continues until a black hole is formed.

End of life of a massive star

When all the fuel has been used up in the core of the star, the pressure-gravity balance is broken. Gravity prevails when the thermal pressure is no longer high enough to support the weight of the star. The star then collapses in on itself.

If the star is massive (more than about 10 solar masses) it continues to collapse until an exotic form of pressure called 'neutron degeneracy pressure' appears and fights against the collapse. Eventually the star explodes as a supernova, blowing away the outer layers of the star. If the remaining stellar core has about two solar masses, the core will remain as a neutron star. But if the core has a larger mass, then not even the neutron degeneracy can provide enough pressure to counteract the gravity and the star will collapse into a black hole.

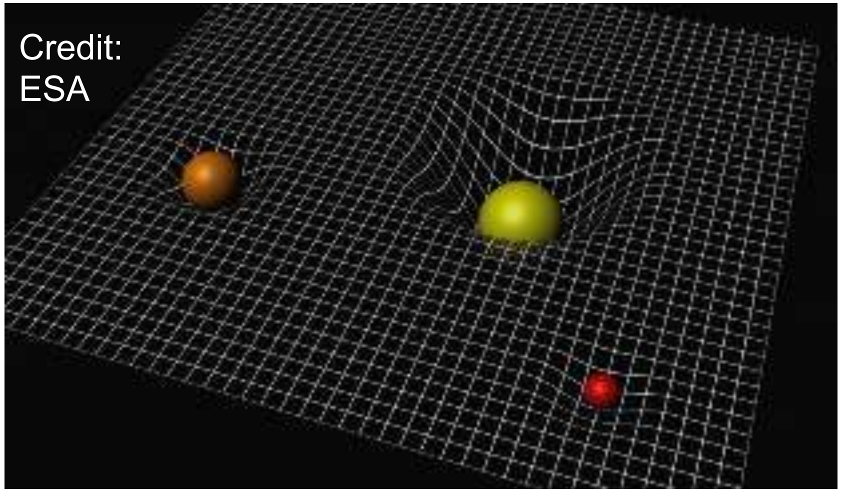


This diagram represents the size of the collapsing star (red part of the diagram, which decreases with time from bottom to top). At a certain stage of the collapse, the event horizon appears and grows to its final size (blue part of the diagram). Light emitted outside the horizon can escape (green solid line trajectory), but light emitted below the horizon (green dashed line trajectory) is trapped there. The black hole is the blue part of the diagram.

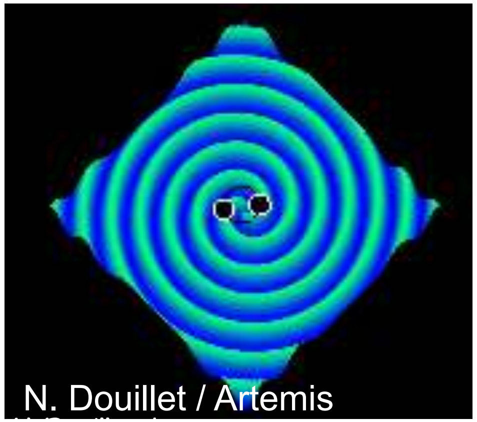
Formation of a black hole

Imagine a photon (a particle of light) emitted from the centre of the collapsing star. Initially, this photon can escape from the star.

However, at a very late stage in the collapse of the star, although the photon starts to move away, it will soon be forced back towards the centre of the star. Why? Because a new structure of space-time is born, called the event horizon. This signals the creation of the black hole. The light emitted inside the event horizon is subject to such extreme gravity that it is trapped inside the horizon. A black hole is 'black' in the sense that light cannot escape from it.



The presence of massive objects distorts space-time in their vicinity. If these objects are static, this deformation will not evolve.



If these objects are black holes rotating around each other, the deformation propagates like ripples on the surface of a pond into which a stone has been thrown, but travelling at the speed of light: These are gravitational waves. The figure above shows the emission of these waves by a pair of black holes rotating around each other.

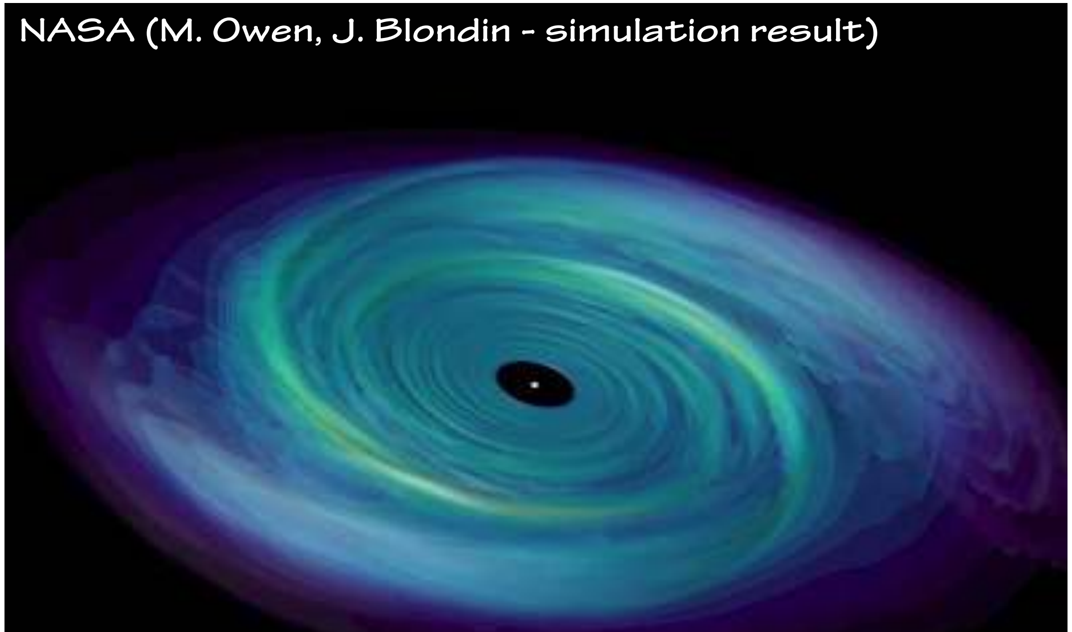
Gravitational waves

Black holes can exist in pairs: the two members of the pair will then orbit around one other and emit gravitational waves.

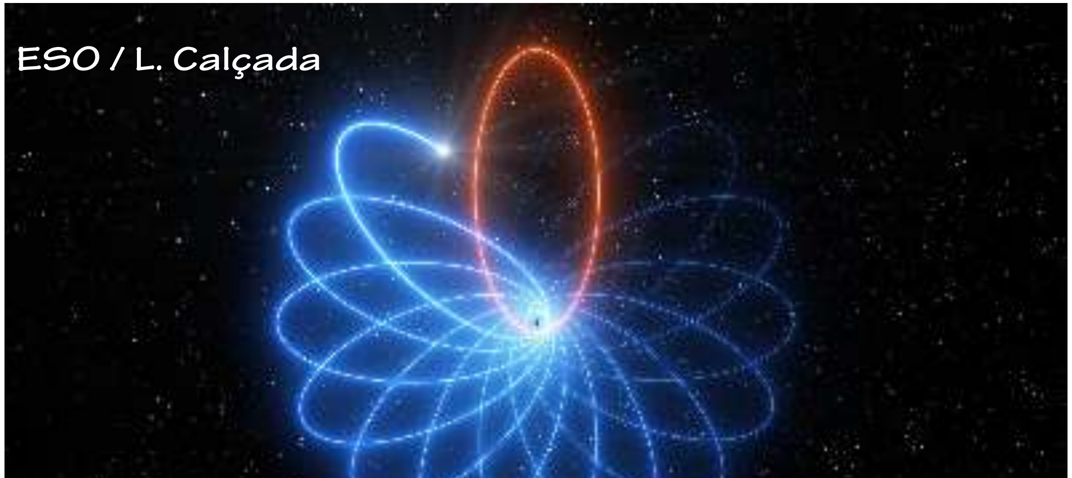
Imagine a layer of jelly with a raspberry on top: the berry will slightly deform the surface of the jelly. Another raspberry placed next to it adds its own deformation. If you rotate the raspberries around each other, deformation lines will spread through the jelly.

Similarly, gravitational waves are ripples of deformation in space-time caused by moving black holes.

Such ripples were first detected on Earth in 2016. They provide a very valuable means of determining the properties of black holes. The 2017 Nobel Physics Prize was awarded for this detection.



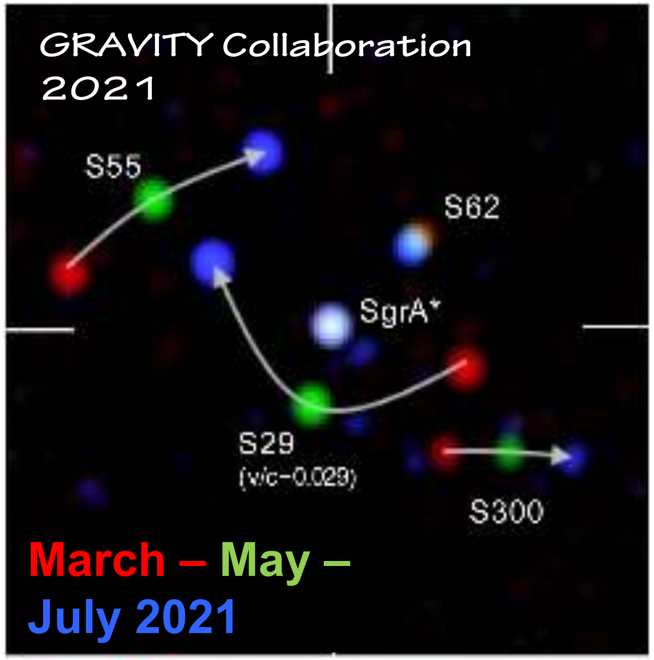
Accretion disc: Matter revolves around a black hole, emitting light.



Artist's view of the orbit of a star around a black hole. The gradual shift of the orbit is caused by the extremely strong gravity of the black hole.

Black holes and surrounding matter

Although a black hole is black, the same cannot be said for the matter surrounding it. A black hole is not a great cosmic vacuum sweeper: matter will orbit the black hole and create an accretion disc. These discs emit copious radiation at all wavelengths, which marks the presence of the black hole.
Moreover, stars can orbit a black hole, and their trajectories will also show the presence of the compact object. Like gravitational waves, the light emitted in the vicinity of a black hole and the orbits of nearby stars are useful probes for studying the black hole properties.



Motion of four stars in the vicinity of the supermassive black hole SgrA* in the centre of the Milky Way. The central white point corres-ponds to the radiation from the accretion disc surrounding SgrA*.

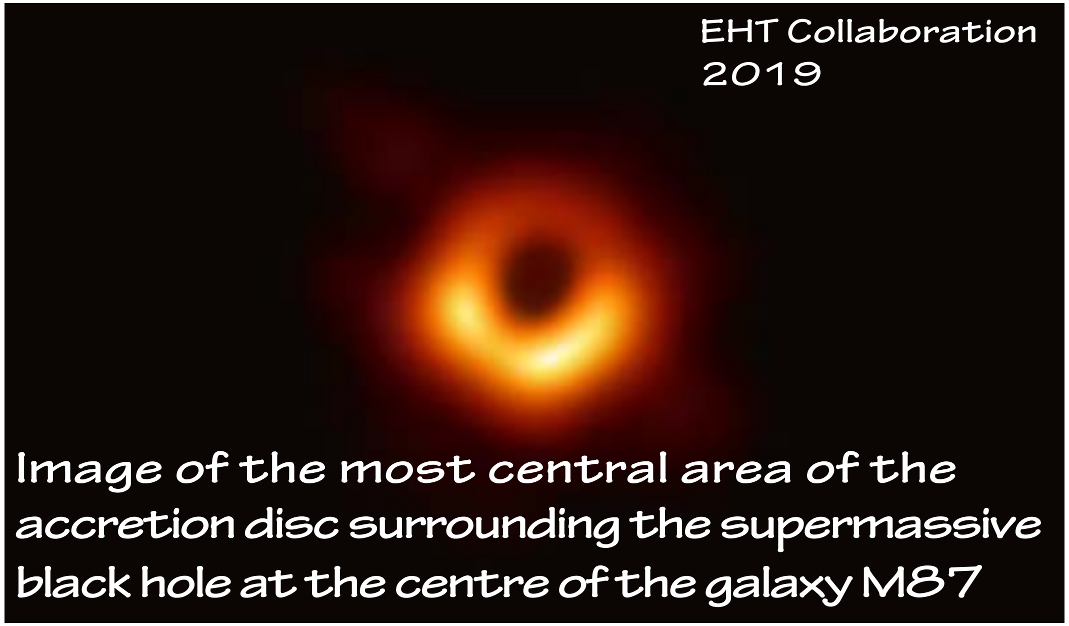


Image of the most central area of the accretion disc surrounding the supermassive black hole at the centre of the galaxy M87

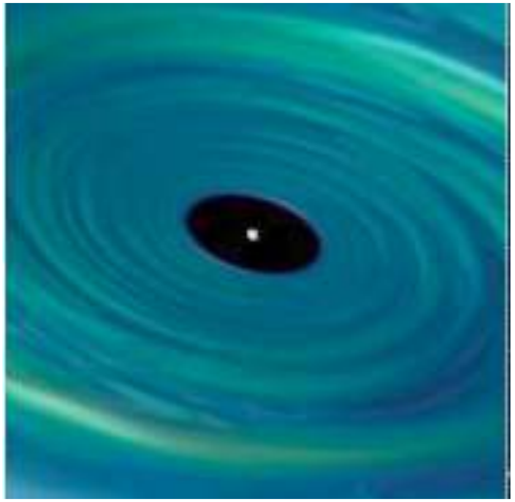
Supermassive black holes

In addition to black holes created by the collapse of massive stars, there are 'supermassive' black holes at the centres of galaxies.

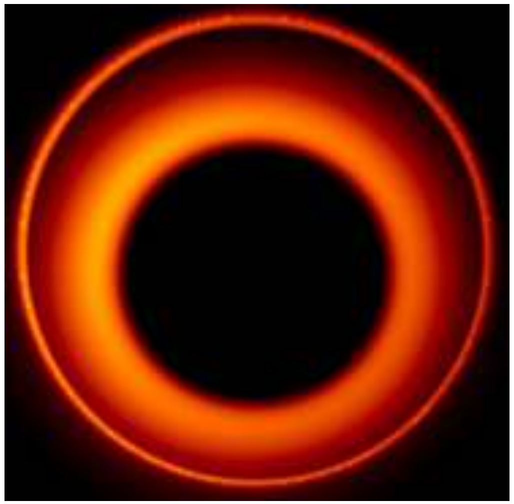
The 2020 Nobel Prize was awarded for the study of the orbits of stars occupying the most central region of our Milky Way, revealing the existence of a mass 4 million times the mass of the Sun, gathered in a region no larger than our Solar System.

Further observations of the Messier 87 galaxy in 2019 provided the first image of the immediate vicinity of another supermassive black hole, bringing strong support for the existence of these extremely massive objects.

QUIZ



Which of these images is the result of an observation?



Answer on the back

Simulation of a accretion disc surrounding a black hole (Owen & Blondin, 2005).

Observed image of the accretion disc at the centre of the galaxy M87 (EHT Collaboration 2019).

Simulation of the sky background of the Milky Way with a black hole in the foreground (Riazuelo 2009).

Answer

Simulation of an accretion disc surrounding a black hole at the centre of the galaxy M87 (Vincent et al. 2019).

Simulation of an accretion disc surrounding a wormhole in the centre of the Milky Way (Lamy et al. 2018).

The Universe in my pocket N° 17

This booklet was written in 2022 by Frédéric Vincent from Paris Observatory (France) and reviewed by Eric Gourgoulhon, also from Paris Observatory and Stan Kurtz (UNAM, Mexico).

Cover image: simulation by Alain Riazuelo (Paris Institute of Astrophysics) of a Milky Way sky background with a black hole in the foreground.

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Translation: Stan Kurtz