Black Holes

Press Kit

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Cover: The Milky Way spans the sky above Paranal as the VLT peers out towards the Galactic Centre | ESO/Yuri Beletsky

Back cover: Artist's impression of a black hole | ESA/Hubble

Left: Spiral galaxy NGC 253 seen edge-on 13 million light-years away in this image taken with the Wide Field Image at the La Silla Observatory | ESO

Preface

The existence of black holes has been theorised for more than 200 years. Initially just a philosophical idea, there is now strong evidence that most, if not all galaxies contain black holes millions or billions of times heavier than our Sun. Black holes themselves cannot be observed since, by definition, no light can escape them, but astronomers can study the effects of black holes on their surroundings.

What are black holes? How do they form? How can they be studied if nothing can escape them? This guide aims to answer these questions, giving a general overview of the theoretical and observational achievements of the last century in black hole science.

The ESO telescopes and astronomical community have greatly contributed to the investigation of black holes. The place of ESO in the frame of such discoveries will be revealed in this short tour of the past and future of one of the most exciting fields of modern astrophysics.

Overview and History

Lasciate ogni speranza, o voi ch'entrate (Dante Alighieri, *Divina Commedia*)

Abandon all hope, you who enter here (Dante Alighieri, *The Divine Comedy*)

Nothing can escape from a black hole: anything that crosses the boundary known as the event horizon becomes trapped. Even light is not fast enough to escape. The reason that nothing can escape a black hole is its enormous gravitational pull. Black holes a few times more massive than the Sun can form at the ends of the lives of massive stars. When all the sources of nuclear fusion in a star are exhausted, there is nothing to prevent the star from collapsing.

Do black holes exist? You may argue that if they do not emit any radiation it is impossible to detect them. This is indeed true for isolated black holes, but luckily there are black holes that swallow gas, modify the trajectories of nearby stars or have a stable life close to a companion star. The study of the effects that these black holes have on the surrounding gas and stars gives information about the black holes themselves. Observations from Earth and from space are performed at every wavelength: from radio to gamma rays. ESO telescopes have made remarkable discoveries by observing the effect of black holes on their surroundings at ultraviolet, optical and infrared wavelengths.

The concept of an object so massive and dense that nothing can escape from its fatal grip was first proposed at the end of the 18th century, extrapolated from Newton's law of gravity. However the true black hole revolution occurred only with Einstein's theory of general relativity (1915). This theory states that matter curves spacetime. The denser the matter, the larger the curvature. According to Einstein, mass and energy are equivalent, and so even massless phenomena, such as light, are affected by gravity.

The centre of the Milky Way and its supermassive black hole seen in near infrared with the VLT at Paranal | ESO/S. Gillessen et al.

From there the step to black holes is short. By 1916 Karl Schwarzschild had proved that black holes work as a solution to Einstein's equations.

In the past few centuries, black hole physics has made many major breakthroughs:

- In 1784, the eclectic English geologist John Michell, followed in 1796 by the French mathematician Pierre-Simon de Laplace, proposed the existence of so-called dark stars, which would exert a gravitational pull strong enough to lock in light.
- In 1915, Albert Einstein published his first paper on general relativity: *Zur allgemeinen Relativitätstheorie*. Black holes are a direct consequence of general relativity; however Einstein himself did not believe that they could exist.
- A year later, in 1916, the German physicist Karl Schwarzschild proved that black holes are a solution to Einstein's equations in spherical symmetry. Schwarzschild's solution is for a non-rotating black hole, while in 1963, the New Zealand mathematician Roy Kerr found the theoretical solution for rotating black holes.
- The Indian–American astrophysicist Subrahmanyan Chandrasekhar first speculated in 1930 that the fate of massive stars may not be just to cool down, as smaller stars do, but to collapse into something denser (such as white dwarfs and neutron stars).
- In 1939, the American physicists Robert Oppenheimer and Hartland Snyder predicted that black holes could, in principle, form in nature from the collapse of massive stars.
- In 1974, the British theoretical physicist Stephen Hawking considered quantum effects and discovered that quantum black holes are not as black as classical black holes: they emit thermal radiation.

The term "black hole" was coined in 1967 by the American physicist John Arichbald Wheeler.

Black Holes in Theory

In theory, black holes are simple to describe. Just three parameters are sufficient to characterise them fully: mass, angular momentum (describing their rotation) and electric charge. Compared to stars, from which they form, these are very few characteristics, leading physicists to say that "black holes have no hair". Astrophysical black holes are even simpler, as they have no charge: if they were charged, they would be quickly neutralised by the surrounding plasma.

Schwarzschild's solution to Einstein's equations describes a black hole that is not rotating, while Kerr's solution is for rotating black holes. It is reasonable to think that black holes rotate: if they formed from a rotating collapsing star or from the merger of two neutron stars they must have preserved their rotational energy. Moreover they can spin up thanks to successive interactions.

It was once thought that black holes do not emit anything. However, Stephen Hawking pointed out that if quantum effects are taken into account, they can radiate thermal energy and particles. This Hawking radiation carries energy away from the black hole and reduces its mass ($E = mc^2$). Therefore a black hole shrinks until it evaporates. This effect is important for very tiny black holes, but astrophysical black holes are very massive and they would need a time much longer than the age of the Universe to evaporate.

Artist's impression of Cygnus X-1, a black hole 10 000 light-years from Earth and five times the mass of the Sun | ESO, NASA, ESA/Hubble

How Big can a Black Hole be?

In principle there is no limit to the size of a black hole: it can be as light as a feather or as heavy as a few billion Suns! Their size varies accordingly. A black hole with a mass equal to that of the Sun would have a radius of three kilometres. Furthermore the radius of a black hole scales in proportion to its mass. So a typical stellar-mass black hole (ten times the mass of the Sun) would have a radius of thirty kilometres, and a supermassive black hole (e.g., one million solar masses) would have a radius of three million kilometres.

Black holes of different masses have the same basic properties (they all have no hair). They are expected to display different behaviours only because the typical lengths and timescales involved are proportional to the mass and because black holes of different sizes exist in different environments. In the next section we quickly review the different weight classes.

Stellar-mass black holes

A billion stellar-mass black holes exist in our galaxy, the Milky Way, according to standard galactic evolutionary models. Their masses are estimated to be between three and twenty solar masses. Some will be isolated black holes, others black holes lying close to normal stars. Such coupled systems are called black hole X-ray binaries, or microquasars, in cases where they emit a relativistic pair of jets. The bright X-ray emission comes from a disc of gas that is sucked from the normal star and spirals towards the black hole's event horizon, like water spiralling down a plughole.

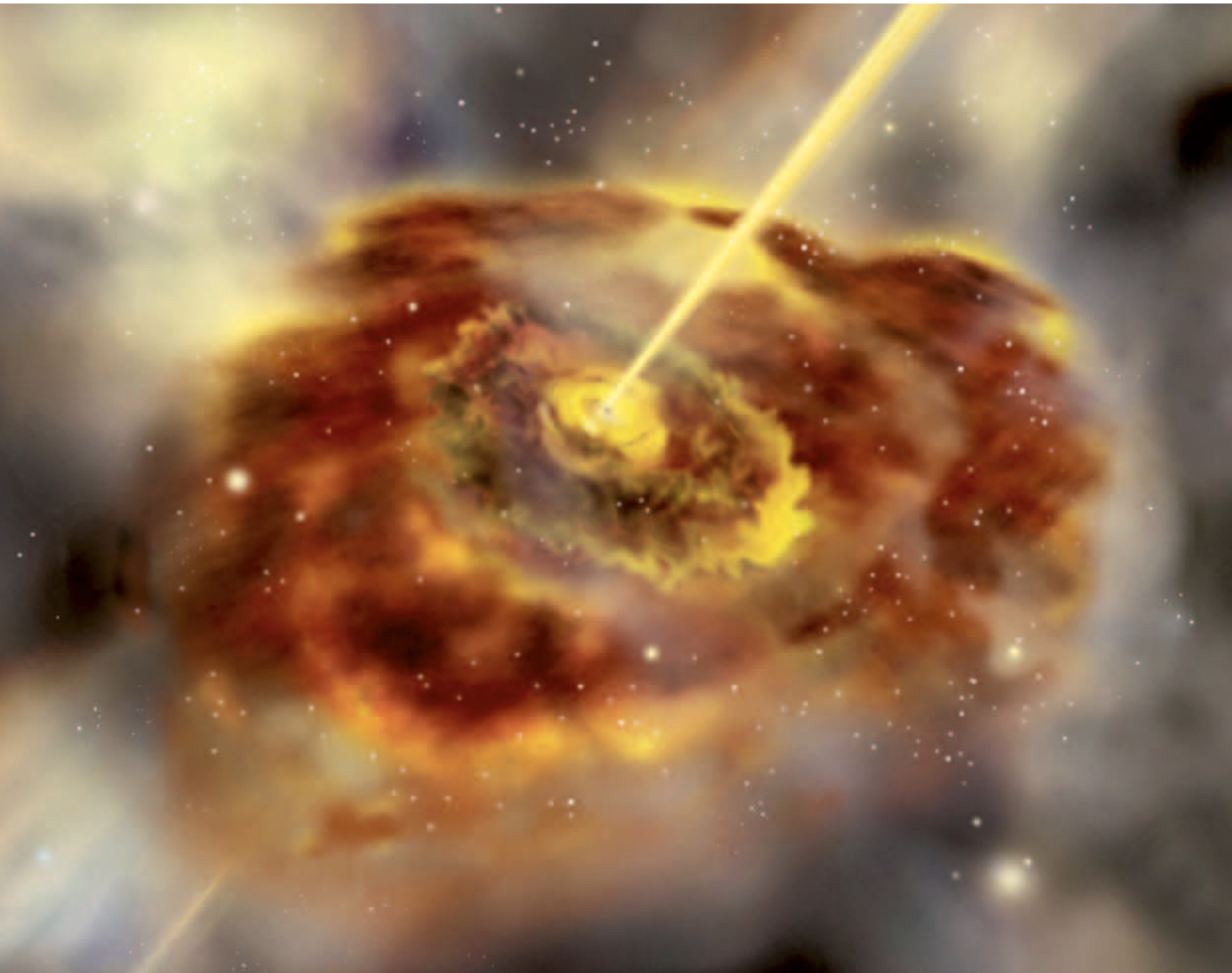
The heavyweights: supermassive black holes

Where do we find supermassive black holes? At the centre of a galaxy! The core of many galaxies is exceedingly luminous, and often across all wavelengths. These brilliant central regions are called Active Galactic Nuclei (AGN). Quasars (QUASi-stellAR radio sources), QSOs (Quasi Stellar Objects) and blazars all belong to this class of objects.

The AGN extend only over a few light-minutes or light-days: they are less than one ten-millionth the size of their host galaxy, but they are hundreds of times brighter than the whole galaxy. The consensus is that AGN are powered by a central supermassive black hole.

Supermassive black holes are not isolated: they sit at the centre of galaxies and they attract the matter in their vicinity with their strong gravitational field. Accretion is the term used to describe this fatal attraction: the gas rotates towards the event horizon, building an accretion disc. While the gas spirals in, its energy is converted into heat and starts to shine brightly, producing the observed extreme luminosities over the entire electromagnetic spectrum. Part of the matter escapes the fate of being gulped down into the black hole, by being carried away in two highly collimated radio jets that emerge close to the inner edge of the disc.

Artist's impression of an Active Galactic Nucleus, with a supermassive black hole emitting two jets of energy and particles | A. Simonnet, Sonoma State University



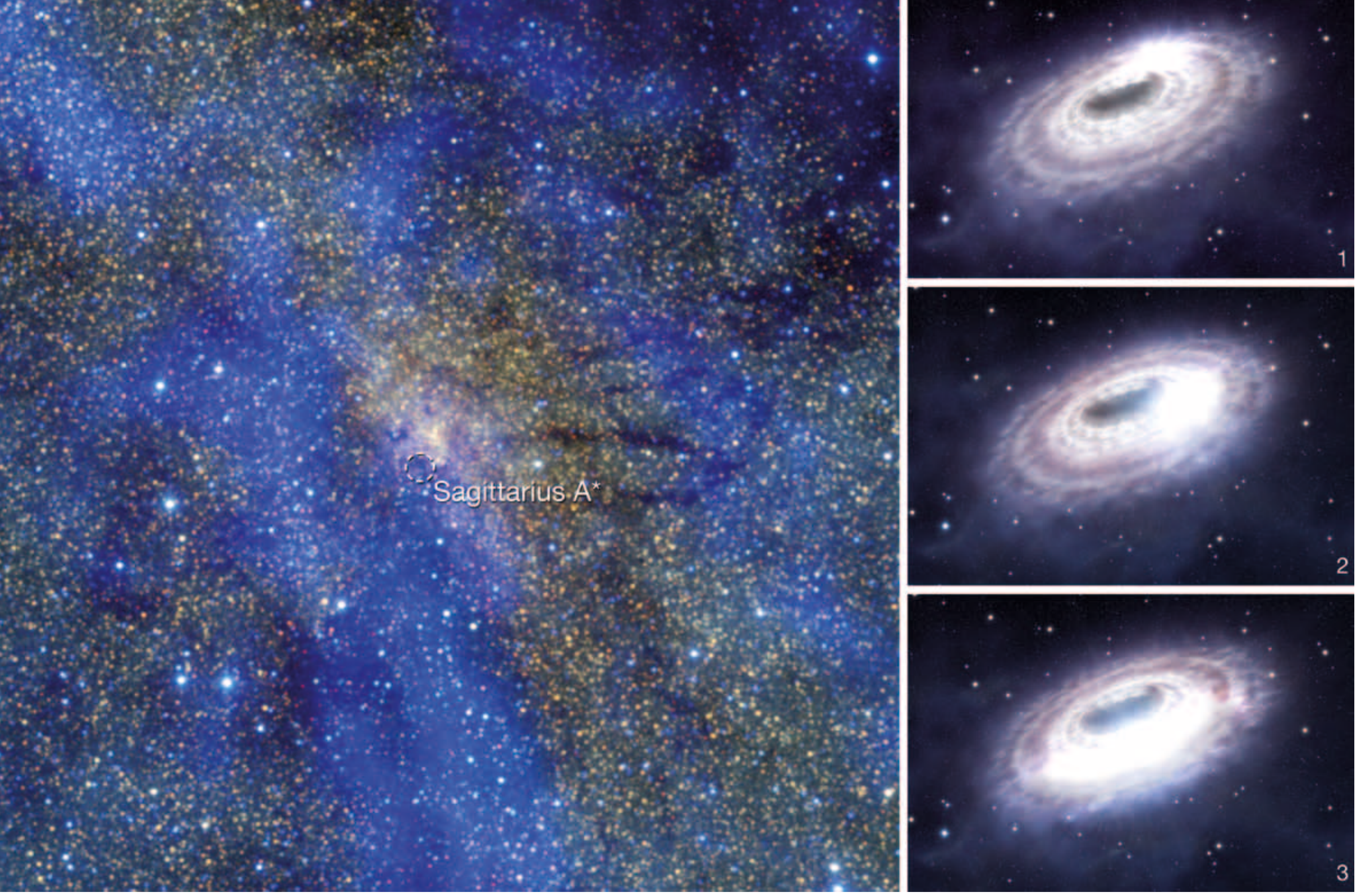
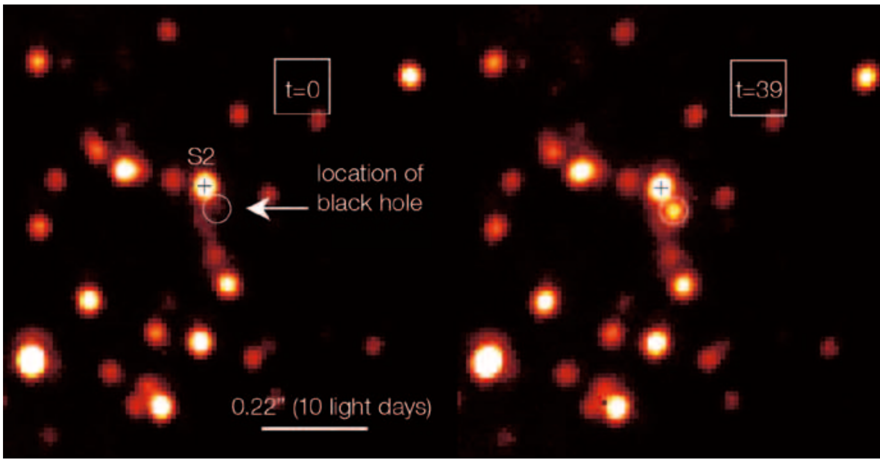


Image of the central region of the Milky Way with an artist's impression of the bright gas surrounding the central black hole | ESO



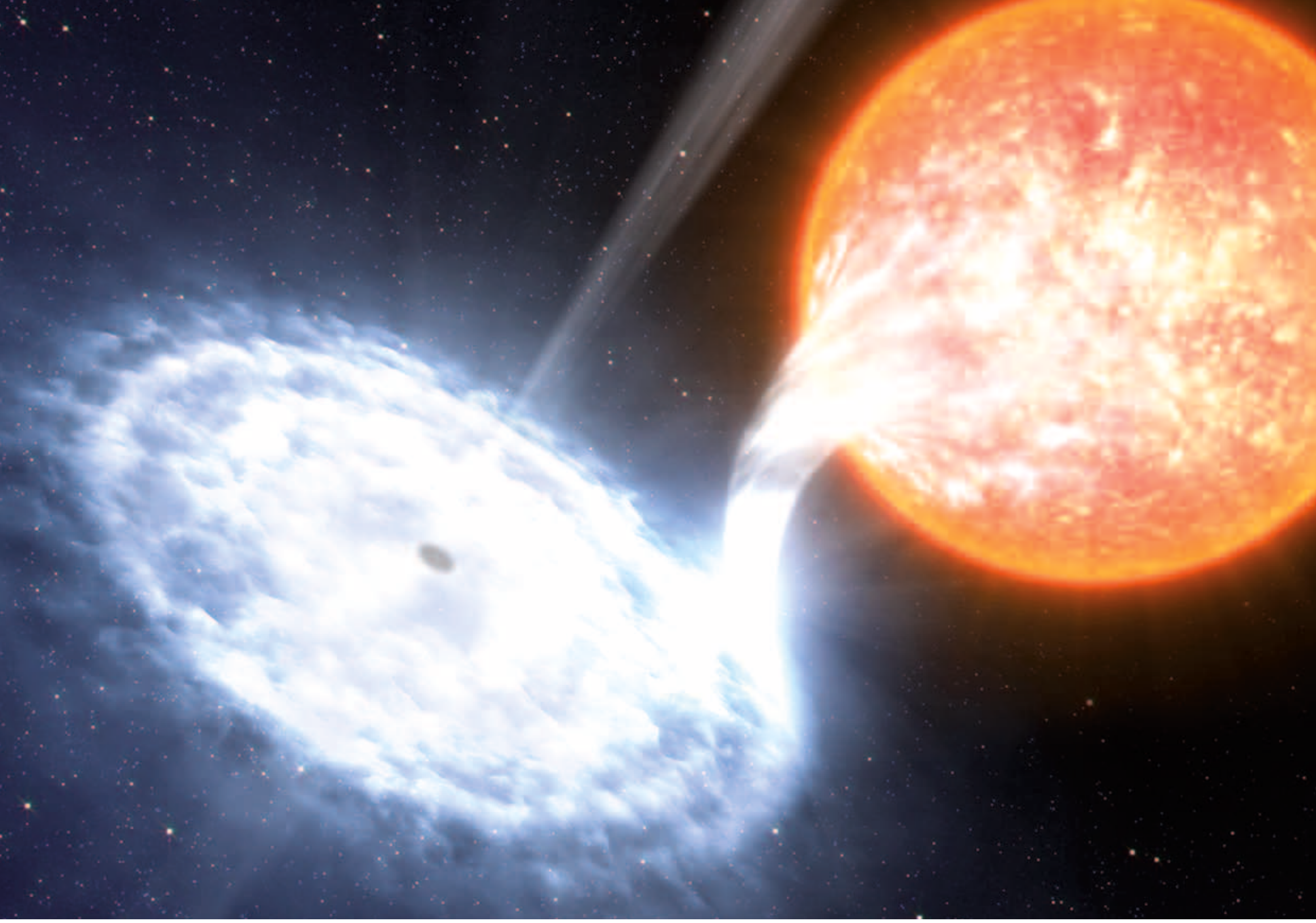
Flare detection from the centre of the Milky Way using adaptive optics on the VLT at Paranal | ESO

In less active galaxies, such as our own Milky Way, the black hole at the centre is starving, as there is not much matter around it. It is therefore much less bright than an AGN.

The best evidence for the existence of supermassive black holes comes from within the Milky Way: thanks to ESO telescopes, astronomers are now convinced that a black hole, with a mass of a few million solar masses and called Sgr A* (Sagittarius A star), sits at the centre of our galaxy, about 27 000 light-years from Earth. The motion of the stars in its vicinity provides the best empirical evidence for the existence of a supermassive black hole (eso0846).

Over the past decade a correlation between the mass of a galaxy and the mass of its central black hole has been observed. For these properties to be related, a number of mechanisms must be at work over nine orders of magnitude in scale, from galaxy environments to the "sphere of influence" of the black hole.

The next generation of telescopes, like ESO's planned European Extremely Large Telescope (E-ELT), will probe scales of less than a few parsecs (~ 10 light-years) in the very central regions of galaxies out to cosmological distances of hundreds of millions of light-years, allowing us to trace the build-up of supermassive central objects in galaxies when the Universe was as young as a quarter of its present age.



Artisit's impression of a black hole inside a binary system | ESO

The enigma of ULXs

Today, more than 200 ULXs are known. ULXs stands for UltraLuminous X-ray sources: they are "ultra" because their apparent X-ray luminosity is above the maximum possible luminosity for stellar-mass black holes. Under normal conditions accretion onto a stellar-mass black hole cannot supply radiation over some limit, known as the Eddington luminosity. This is the limiting case, assuming spherical symmetry, when the gravitational force acting in towards the black hole equals the radiation force acting outwards. Hence the mystery: are ULXs powered by intermediate-mass black holes (100–1000 times more massive than the Sun) or is their high luminosity due to stellar-mass black holes that accrete above the Eddington limit?

Intermediate-mass black holes could represent a link currently missing between stellar-mass black holes and supermassive black holes and they could serve as seeds in the early Universe for the formation of the supermassive black holes that we see today. There is a lot of effort going into the search for intermediate-mass black holes.

Microscopic black holes

The world of black holes is full of surprises: there may be black holes smaller than a flea and lighter than a feather and tiny black holes could one day be produced in the laboratory.

Primordial black holes may have existed during the early stages of the Universe, a few moments after the Big Bang. At that time the temperature and pressure were so gigantic that they could have squeezed matter down to a singularity: however only primordial black holes of about a billion tons could have survived until the present day; the lighter ones would all have evaporated.

The lightest black holes are called elementary black holes, as they would be like elementary particles. With the start-up of the Large Hadron Collider (LHC) these microscopic black holes received a lot of attention as they might be produced during particle collisions at the LHC. However, they would immediately disintegrate again, and would therefore not have time to accrete matter and cause any macroscopic effects.

Colour-composite image of the spiral galaxy NGC 1097 taken by the VLT | ESO

Birth of a Black Hole

The traditional recipe to make a black hole needs a single ingredient: a very massive star at the end of its life. More recently another mechanism has been found, the collision and merger of very dense objects, such as neutron stars.

Black holes that form through these mechanisms usually have masses three to ten times greater than the Sun and they are called stellar-mass black holes. In theory black holes of any size can exist. Supermassive black holes of a million to a billion times the mass of our Sun are found at the centre of (almost) all massive galaxies. How they form is still not fully understood.

The traditional recipe: stellar collapse

The life of a star is a continuous struggle between gravity and pressure radiation. Gravity compresses the star, while the radiation due to nuclear fusion pushes its matter outwards. When the fuel is exhausted, the star stops burning.

If the star doesn't have much mass — like our own Sun — it will become fainter, cooling down as a white dwarf. However if its initial mass is about eight times that of the Sun, it will collapse, bounce back and detonate in a supernova. Neutron stars form in this way. And if the original mass exceeds about 25 solar masses, at the end nothing can counteract gravity and the whole mass is squeezed into a point of zero volume and infinite density. This point is called a singularity. Physicists say that the singularity is not "naked", in the sense that it is surrounded by a boundary, called an event horizon. Hence what is left at the explosive end of the life of a very massive star is a singularity surrounded by an event horizon — a black hole.

Artist's impression of the enormous energy released in a gamma-ray burst, associated with stars as they collapse into black holes | ESO

Image from ESO's Giga-Galaxy Zoom project, displaying the central part of the Milky Way | ESO/S. Guisard

Initial Stellar Mass	Final Stellar Mass	End Product
Less than 8 $M_\odot$	Less than 1.4 $M_\odot$	White dwarf
8–25 $M_\odot$	1.4–3 $M_\odot$	Neutron star
Greater than 20–25 $M_\odot$	Greater than 3 $M_\odot$	Stellar-mass black hole

Tradition and innovation: gamma-ray bursts

In the last decade, a lot of evidence has been collected indicating that the most energetic blasts in the Universe, gamma-ray bursts (GRBs), may be connected to the birth of black holes. Since their discovery in the 1960s, GRBs have posed a challenge to astrophysicists. They are sudden and intense flashes that occur randomly in space and time and they release in a few seconds more energy than the Sun during its whole life. A less energetic X-ray, radio and optical afterglow follows the first emission in the gamma-ray band. The afterglow is extremely useful to investigate the properties of these elusive explosions.

GRBs have been detected in two flavours, both related to the formation of a black hole: long (when the burst is longer than about two seconds) and short.

Bohdan Paczynski and Stanford Woosley were the first astronomers to propose that long GRBs could be connected to stellar collapse. Today, this long-suspected connection (eso9847) is well-established (eso0318). The dominant interpretation suggests that a black hole forms in a hypernova (a rare type of supernova) explosion. Such a newborn black hole is not isolated: it is surrounded by a disc of matter spiralling in and has two jets. The interaction of the jets with the gas expelled in the detonation is thought to be the responsible for the long GRBs.

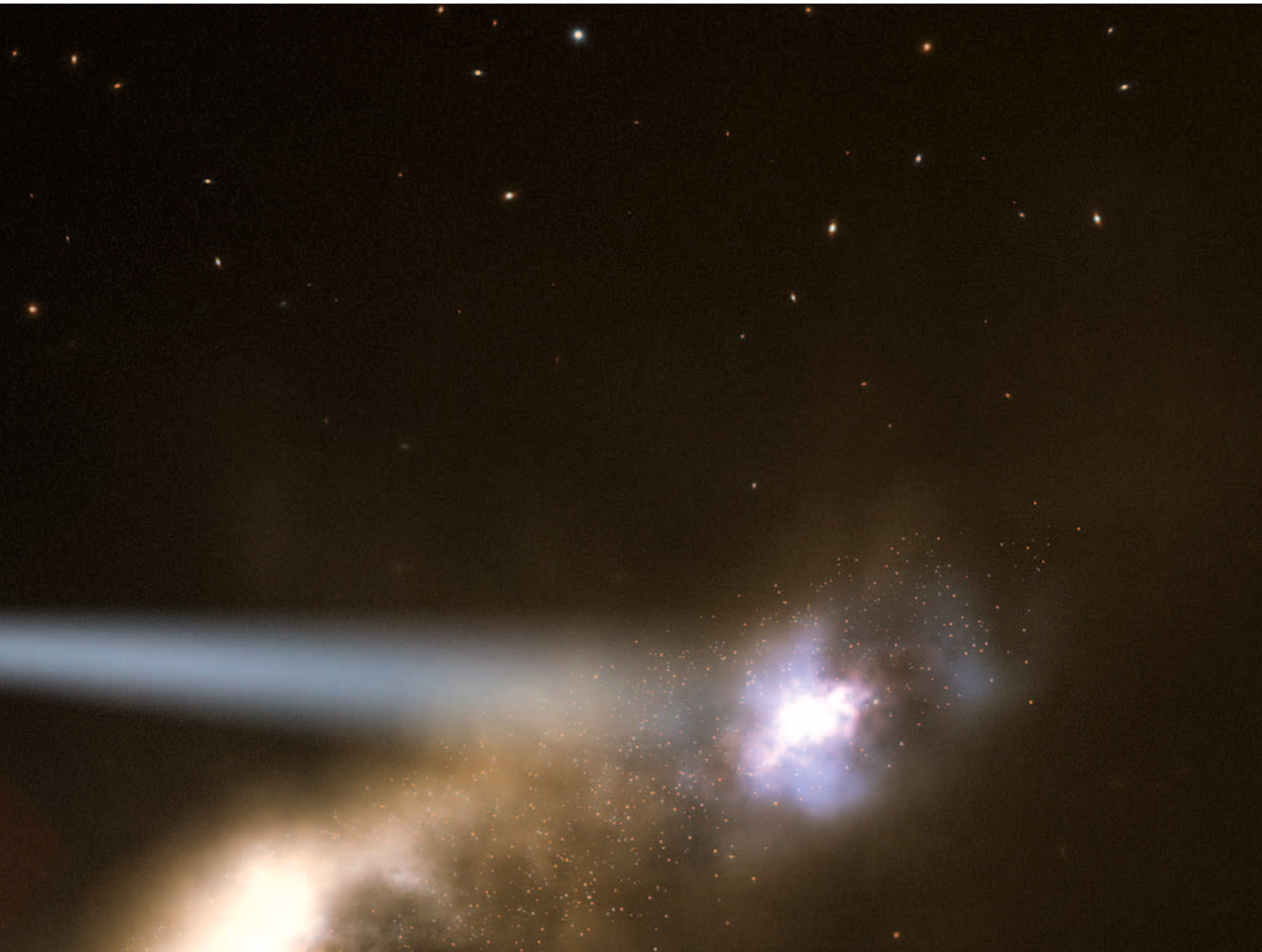
Short GRBs seem to arise from a new mechanism of black-hole birth: namely the dazzling merger of two compact objects. Black holes and neutron stars are called compact objects, simply because they are made up of enormous amounts of matter compressed into a relatively tiny space. The prevailing model for short GRBs links them to the fusion of two neutron stars or a neutron star and a black hole that were orbiting close to each other. The result of this collision would be a black hole and a brief but intense burst of gamma-ray emission. The analysis of the optical afterglow singled out this theory from many others (eso0533).

The puzzle of supermassive black holes

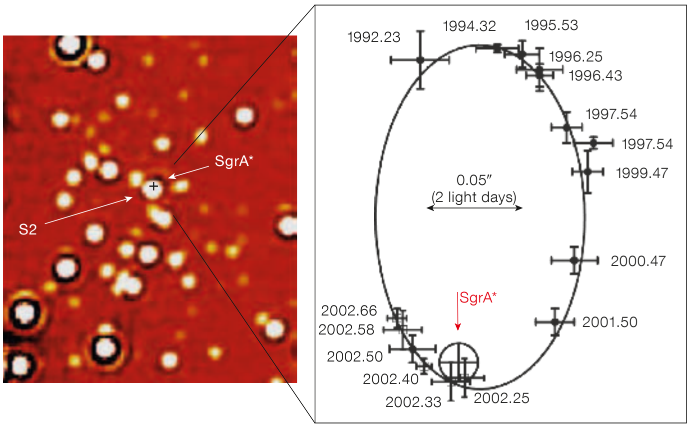
While the formation of stellar-mass black holes is fairly well understood, it is not clear how black holes as massive as a million to a billion times the mass of the Sun could have formed and have already been in place at a time when the Universe was less than 1 billion years old (current age 13.6 billion years). Supermassive black holes cannot form through the collapse of a single star. The formation and growth of supermassive black holes is the subject of intense discussion. Observations and computer simulations indicate that when the Universe was 200–400 million years old it was inhabited by stars brighter, hotter and more massive than the next generation. This first generation of stars, usually called Population III, may have been 100–1000 times more massive than the Sun and would have collapsed to black holes with masses of a few hundred up to thousands of solar masses.

One possible scenario for the formation of supermassive black holes is that these seed black holes of intermediate mass merged to form more massive black holes, which grew to build up into the supermassive black holes observed today. The growth is regulated mainly by accretion. An important aspect in the life of supermassive black holes is their interaction and co-evolution with the host galaxy: the formation of stars in the galaxy and the accretion process onto the central supermassive black hole influence each other strongly and any theory that tries to understand one of the two processes has to consider both. A fascinating challenge for astrophysicists!

Artist's impression of energy jets from a black hole creating a galaxy | ESO



The centre of the Milky Way | ESO



The Milky Way's central supermassive black hole has been weighed by measuring the proper motions of stars in its vicinity | ESO

Weighing Black Holes

Astronomers can measure the masses of black holes by studying the material that orbits around them. So far, two types of black hole have been identified: stellar-mass (just a few times heavier than our Sun) or supermassive (about as heavy as a small galaxy). But black holes might exist in other mass ranges as well. These are the most common techniques for measuring the masses of black holes.

Stellar-mass black holes

The mass of a stellar-mass black hole can be derived by measuring the speed of a companion star orbiting the black hole. The speed is encoded into the time variability of the light emitted by the accretion process onto the black hole, where material from the companion star is transferred to the black hole (eso1004).

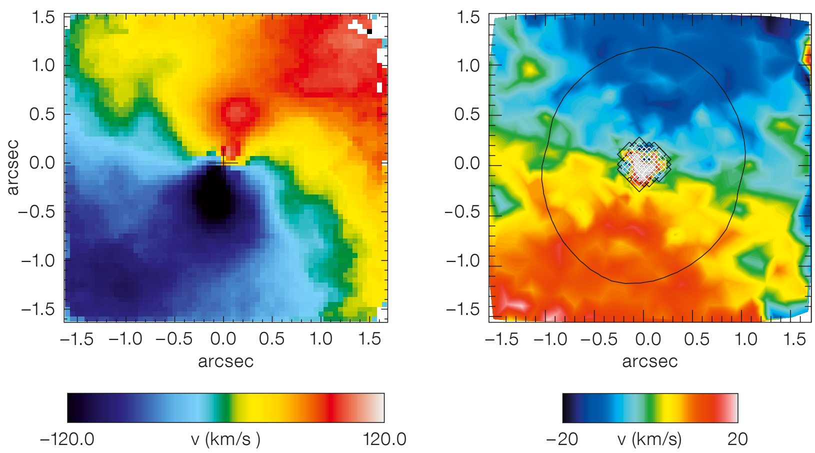
Supermassive black holes

Motion of stars

The best evidence for the existence of a supermassive black hole is provided by the centre of our own galaxy. Astronomers have monitored the movements of the individual stars at the Galactic Centre very carefully for almost twenty years. Modelling the orbits of these stars requires the presence of an unseen mass of four million times the mass of the Sun (eso0846).

For more distant galaxies it is not possible to resolve individual stars, but a close group of stars can be used to trace the kinematics. Building a dynamical model for the galactic nuclei then allows astronomers to find the best match for the observations by varying the mass of the black hole.

Composite image of the jets shooting from the central black hole of the Centaurus A galaxy | ESO/WFI (Optical); MPIfR/ESO/APEX/A. Weiss et al. (Submillimetre); NASA/CXC/CfA/R. Kraft et al. (X-ray)



Velocity map of the molecular hydrogen line emission and the stellar motion around the nucleus of Centaurus A | ESO/N. Neumayer et al./M. Cappelari et al.

Motion of gas

Gas orbiting the black hole can also be used as a kinematic tracer for the gravitational field. This method can be easily applied to active and non-active galaxies. In some cases, the orbiting gas radiates maser emission that serves as an alternative dynamical indicator for the central masses. This is a very reliable mass tracer as maser emission originates from very close to the central supermassive black holes and enables astronomers to measure the enclosed mass very accurately. Maser emission is however not so common in galactic nuclei and this method is only applicable to some sources.

Reverberation mapping

Some active galactic nuclei show very broad gas emission lines that originate from regions very close to the black hole. The lines appear broad because they come from gas that is orbiting the black hole at very high speeds from a small region that cannot be spatially resolved. Astronomers detect the direct radiation from the central source and with some time lag, indirect radiation reflected from the clouds in the broad-line region. The time lag reveals the distance of the clouds in the broad-line region to the black hole. Combining the distance of the gas clouds with their measured width, the dark central mass can be extracted by reverberation mapping.

Secondary methods

There are now a couple of well-established relations between the mass of the supermassive black hole and some more global properties of the surrounding galaxy, like mass, luminosity, stellar velocity dispersion or light concentration. These scaling laws are often used to estimate masses of supermassive black holes in galactic nuclei, as it is often easier to measure the global properties of the host galaxy.

Black Hole Research at ESO

ESO's current black-hole instruments

GROND (Gamma-Ray burst Optical/ Near-Infrared Detector) on the MPG/ESO 2.2-metre telescope takes images simultaneously in seven colours. It is mostly used to determine the distances of gamma-ray bursts.

FORS on the Very Large Telescope (VLT) at Paranal is an imager and spectrograph that allows very sensitive follow-up observations of gamma-ray burst afterglows to be made as well as mass measurements for stellar-mass black holes.

NACO (VLT) is a near-infrared imager and spectrograph equipped with a powerful adaptive optics system, which allows very sharp observations of even dust-enshrouded black holes.

SINFONI (VLT) is an integral field unit spectrograph equipped with an adaptive optics system that allows unprecedented studies of the stars and gas that are orbiting black holes.

ISAAC (VLT) is an imager and spectrograph in the near-infrared and can peer through the dust in active galactic nuclei.

FLAMES (Fibre Large Array Multi Element Spectrograph, VLT) is used for multi-fibre high spectral resolution spectroscopy.

VIMOS (VIsible Multi-Object Spectrograph, VLT) has a large field of view and can take many spectra simultaneously.

VISIR (VLT Imager and Spectrometer in the InfraRed) studies the dust emission around black holes.

MIDI (Mid-InfrareD Interferometric Instrument, VLT) combines the light of two telescopes for very high spatial resolution studies of galactic nuclei.

AMBER (Astronomical Multiple BEam Recombiner, VLT) combines the light of three VLT telescopes and works in the near-infrared for even better spatial resolution.

Future plans

The next major advance will be to combine the light from the four 8.2-metre VLT Unit Telescopes — a technique known as interferometry — with an instrument called GRAVITY. This will improve the accuracy of the observations by a factor 10 to 100 over what is currently possible. This combination has the potential to directly test Einstein's theory of general relativity in the presently unexplored region close to a black hole.

The millimetre interferometer Atacama Large Millimeter/submillimeter Array (ALMA) will have enough sensitivity and angular resolution to shed light on the growth of supermassive black holes. ALMA will be able to trace the motion of molecules in the close vicinity of black holes out to cosmological distances, when galaxies and black holes were in the process of formation.

The E-ELT will probe scales of less than a few parsecs (~10 light-years) in the very central regions of galaxies out to cosmological distances of hundreds of millions of light-years, allowing us to trace the build-up of supermassive central objects in galaxies when the Universe was as young as a quarter of its present age.

Artist's rendering of the future ALMA array of antennas in the Chilean Andes | ESO/NAOJ/NRAO

ESO Achievements — List of Black Hole Related ESO Press Releases

2010: A stellar mass black hole much further away than any previously known was detected with ESO's Very Large Telescope. (eso1004)

2009: A new scenario for the co-evolution of black holes and galaxies has emerged from observations at ESO's VLT: black hole outflows might trigger the formation of stars. (eso0946)

2009: ESO's ISAAC instrument at the VLT has identified the gamma-ray burst GRB 090423 as the most distant known object in the Universe. (eso0917)

2008: Astronomers have scrutinised the inner parts of the disc around a supermassive black hole 10 billion light-years away, and have confirmed current models of accretion discs. (eso0847)

2008: In a 16-year-long study, using several of ESO's telescopes, a team of astronomers has produced the most detailed view ever of the surroundings of the supermassive black hole at our galaxy's centre. (eso0846)

2008: Astronomers have used APEX and the VLT simultaneously to study the violent flares from the supermassive black hole in the centre of the Milky Way. (eso0841)

2008: Unique observations of the flickering light from the surroundings of two black holes have shown that magnetic fields must play a crucial role in the way black holes swallow matter. (eso0836)

2008: Combining data from ground- and space-based telescopes reveals that the jets of the gamma-ray burst called GRB 080319B were aimed almost directly at the Earth. (eso0828)

2008: Discovery of a supernova that has collapsed into a black hole and produced a jet, which is typical of much more violent events, the so-called gamma-ray bursts. This represents an important connection between the most violent phenomena observed in the Universe. (eso0823)

2008: Using ESO's VLT astronomers could uncover the true colour of the accretion discs in quasars. (eso0821)

2008: Astronomers observed four gamma-ray bursts on the same day (19 March 2008), with one of them being the most luminous object ever observed in the Universe. (eso0808)

2007: At ESO's La Silla Observatory, astronomers have measured the velocity of the explosions known as gamma-ray bursts. The material is travelling at the speed of more than 99.999% of the velocity of light, the maximum speed limit in the Universe. (eso0726)

2007: Triggered by the Swift satellite, ESO's VLT has observed two gamma-ray bursts merely minutes after the explosion. The data show that these powerful explosions are linked to the death of massive stars. (eso0717)

2007: Discovery of the first known triplet of quasars. This close trio of supermassive black holes lies about 10.5 billion light-years away towards the Virgo (The Virgin) constellation. (eso0702)

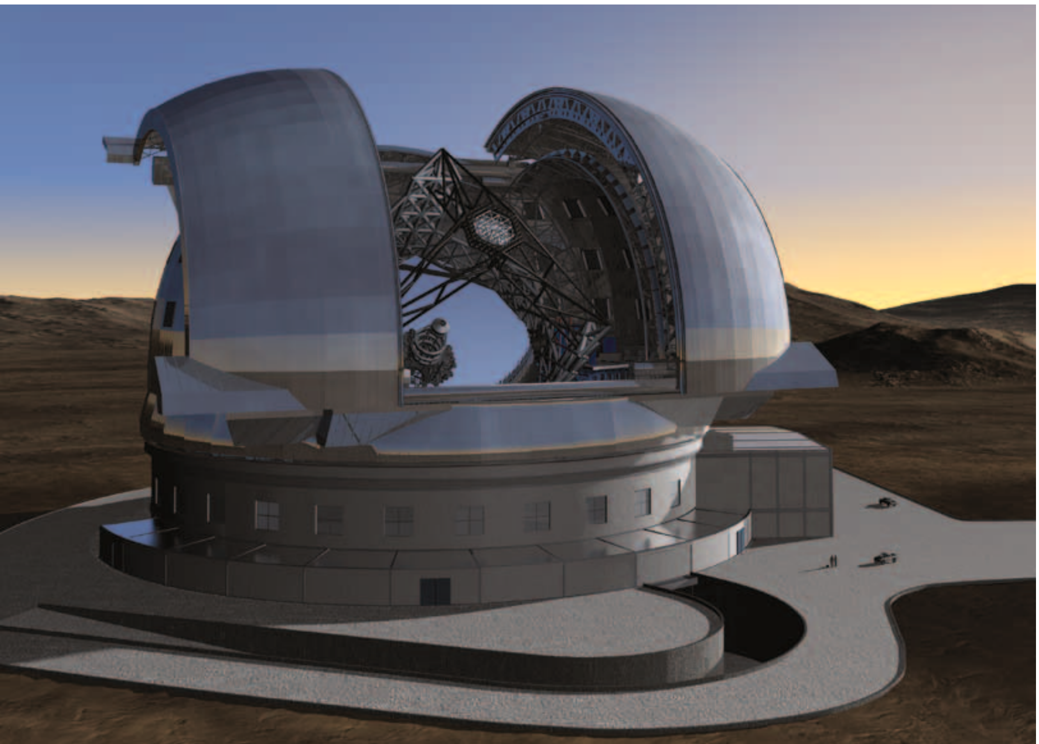
2006: Discovery of a new kind of cosmic explosion related to gamma-ray bursts that seems to arise when a newly born black hole swallows most of the matter from its doomed parent star. (eso0649)

2005: Confirmation that the formation mechanisms for short and long gamma-ray bursts are different. Short gamma-ray bursts are the result of the merger of two compact objects, while long ones mark the death of a massive star. (eso0541)

2005: Observations with NACO at ESO's VLT give new insight how black holes are fed by their surrounding material. (eso0534)

2005: First observations of the visible light from a short gamma-ray burst showing that these short, intense bursts of gamma-ray emission originate from the collision of two merging neutron stars. (eso0533)

2005: Using ESO's VLT and the Hubble Space Telescope (HST) astronomers discovered a quasar without a host galaxy. (eso0529)



Design of the E-ELT | ESO

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