An Expanded View of the Universe

Science with the European Extremely Large Telescope

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Four Centuries of the Telescope — Four Centuries of Discovery

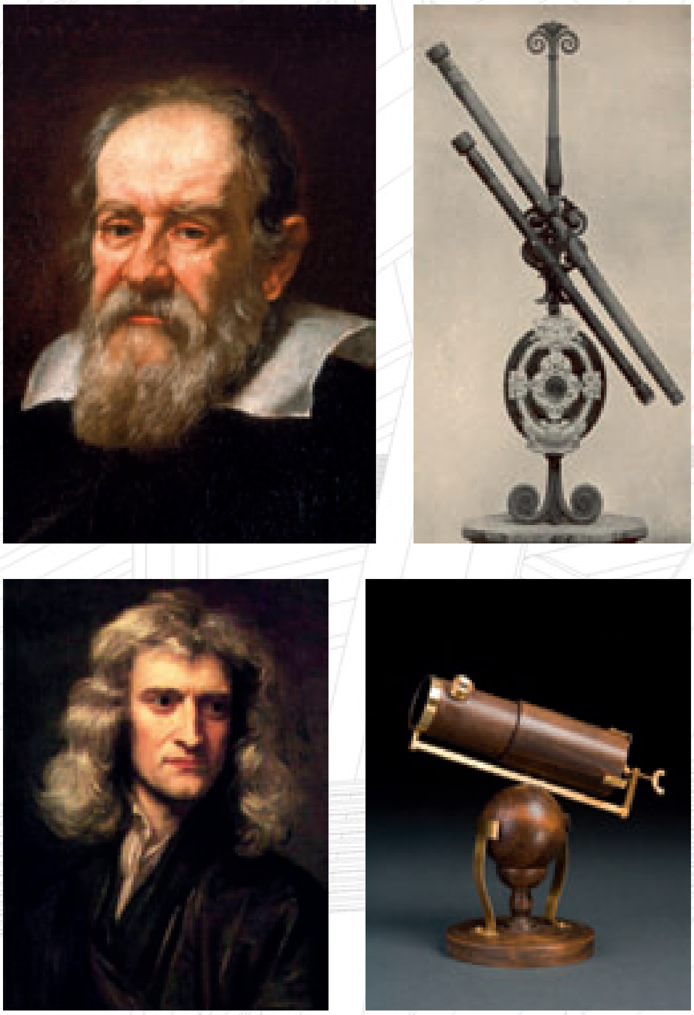
The year 2009 was celebrated by the International Astronomical Union and UNESCO as the International Year of Astronomy. It marked the passing of 400 years since Galileo Galilei first used a telescope for astronomical research, making the ground-breaking observations that would finally refute the geocentric Ptolemaic worldview and establish the heliocentric Copernican one. In the same year, Johannes Kepler published his *Astronomia Nova*, in which he introduced his laws of planetary motion for the Solar System. The year 1609 signalled a true revolution in astronomy.

Since then, astronomical observations with telescopes have increasingly become the norm, until today, when institutes around the world host giant telescopes that work every available second to collect immense quantities of data. Each technological advance has brought new, and often totally unexpected, discoveries about our Universe, enriching our cultural heritage.

Ever larger telescopes

In 1669, a few decades after the invention of the refracting telescope, a design based on lenses, Isaac Newton introduced the first practical reflecting telescope, using mirrors. Over the following 300 years, these two telescope design concepts competed and evolved into ever more powerful research facilities. For about two centuries, refracting telescopes were in the lead, overcoming image quality problems with smart choices of optical designs and glass combinations. Refractor technology peaked towards the end of the 19th century with the big Lick and Yerkes Refractors, which used lenses of 90 centimetres and one metre in diameter, respectively. However, these lenses and their supports proved to be the largest that could practically be constructed, and thus reflecting telescopes finally won the day.

Reflecting telescopes in the 19th century suffered from the poor reflectivity and thermal properties of their mirrors. Despite this limitation, William Herschel and William Parsons, the third Earl of Rosse, were able to build reflectors with diameters ranging from 1.25 to 1.80 metres around the turn of the 18th century, with which they discovered more planets and moons in the Solar System, expanding the boundaries of the then known Universe further.



The refracting (top) and reflecting (bottom) telescopes built by Galileo Galilei and Isaac Newton, respectively.

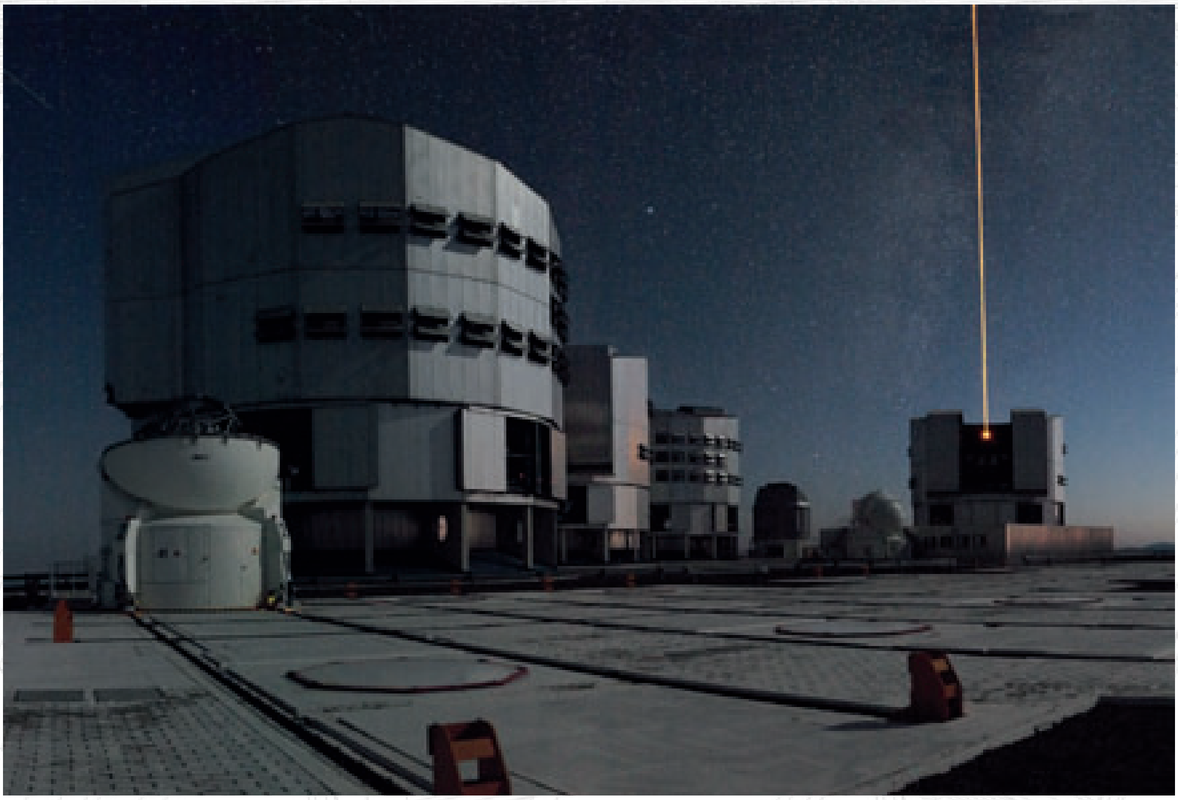
The mirror efficiency problem was only solved in the mid-19th century, when the coating of glass with silver became feasible. This paved the way for the first modern telescopes, such as the Hooker 2.5-metre telescope (1917) and the Hale 5-metre telescope (1948).

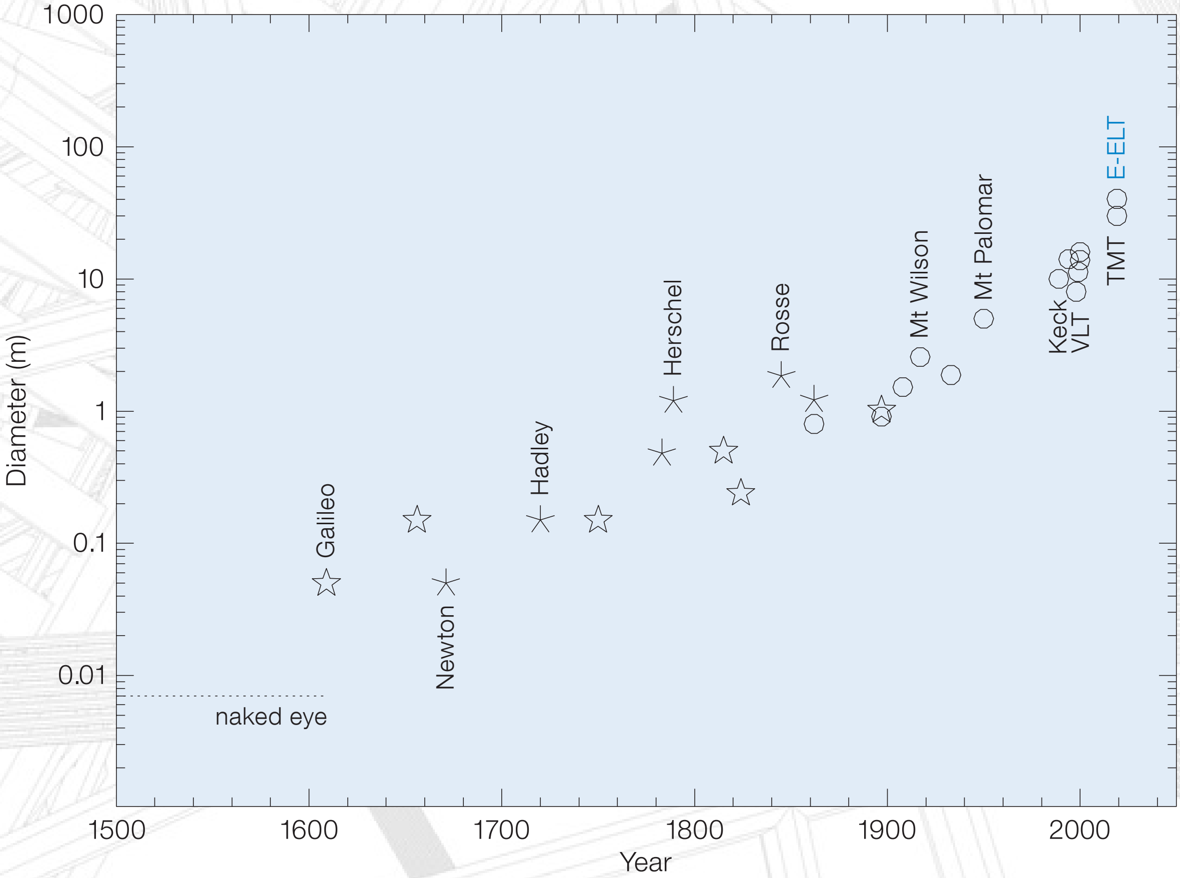
With the new giant telescopes also came the next revolution in knowledge: the Sun, the most prominent object in the sky, was downgraded to a mere dwarf star; the Milky Way was demonstrated to be only one galaxy among millions, and the Universe, assumed to be static and eternal, was found to be expanding and to have a finite age! By the middle of the 20th century, our worldview had little in common with the one preceding the invention of the telescope.

Progress has since continued. Telescopes also expand the observable wavelength domain. Over the last sixty years, astronomers have developed telescopes that are able to observe right across the electromagnetic spectrum. Antennas for low frequency — radio, millimetre and submillimetre — observations were constructed, allowing many scientific breakthroughs, such as the discoveries of quasars, pulsars, the cosmic microwave background, and much more.

Further, space observatories have allowed observations to be pushed to shorter wavelengths, into the ultraviolet, X-ray and gamma-ray regimes. This opening up of the high energy frontier generated a further flood of discoveries such as X-ray stars, gamma-ray bursts, black

The array of 8.2-metre telescopes that makes up the ESO Very Large Telescope.





Brief history of the telescope. The star symbols mark refracting telescopes, asterisks stand for speculum reflectors, circles for glass reflectors.

hole accretion discs, and other exotic phenomena. Previously unknown physical processes were taking place in the Universe around us. These discoveries led to a number of Nobel Prizes in Physics (in 1974, 1978, 1993, 2002 and 2006) and to giant leaps in our understanding of the cosmos.

While astronomy has expanded out into these new wavelength bands, many discoveries are still being made in the visible and near-infrared regimes, where stars predominantly emit their light. Technological advances in the 1980s and 1990s allowed scientists to build ever larger telescopes and ever more sensitive cameras. These instruments have opened up whole new areas of study. For example, the first exoplanets (planets orbiting other stars) were detected, and the current generation of 8–10-metre class telescopes even allowed us to take the first pictures of a few of these objects. Our knowledge in astronomy continues to progress at an incredible pace, answering many questions, but also raising exciting new ones.

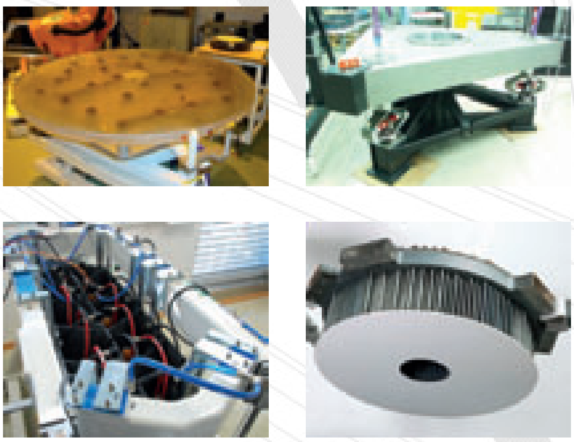
The European Extremely Large Telescope (E-ELT) will address these new questions, and in the following sections we seek to give a flavour of the kind of fundamental questions that it will finally answer. However, just as Galileo was astounded to find mountains on the Moon and moons orbiting Jupiter, the most exciting discoveries are probably those that we have not yet even imagined.

The European Extremely Large Telescope

Europe is at the forefront of all areas of contemporary astronomy, thanks, in particular, to the flagship ground-based facilities operated by ESO, the pre-eminent intergovernmental science and technology organisation in astronomy. The challenge is to consolidate and strengthen this position for the future. This will be achieved with a revolutionary new ground-based telescope concept, the European Extremely Large Telescope (E-ELT). With a majestic primary mirror almost ~40 metres in diameter, it will be the world's biggest eye on the sky.

The telescope has an innovative five-mirror design that includes advanced adaptive optics to correct for the turbulent atmosphere, giving exceptional image quality. The main mirror will consist of almost 1000 hexagonal segments, each 1.4 metres across. The gain is substantial: the E-ELT will gather 15 times more light than the largest optical telescopes operating today.

The basic reference design (phase A) for the European Extremely Large Telescope was completed in 2006. The detailed design phase (phase B), during which critical components have been prototyped, will be completed by the end of 2011. During this phase, the project placed contracts with industry and institutes in Europe amounting to about 60 million euros. In addition to these design activities, more than 30 European scientific institutes and high-tech companies studied the technological aspects of large telescopes within the EU Framework Programmes 6 and 7, partially funded by the European Commission. Ten studies for instruments and adaptive optics systems have also been completed during this phase, allowing the project to build a most competitive instrumentation plan for the first decade.

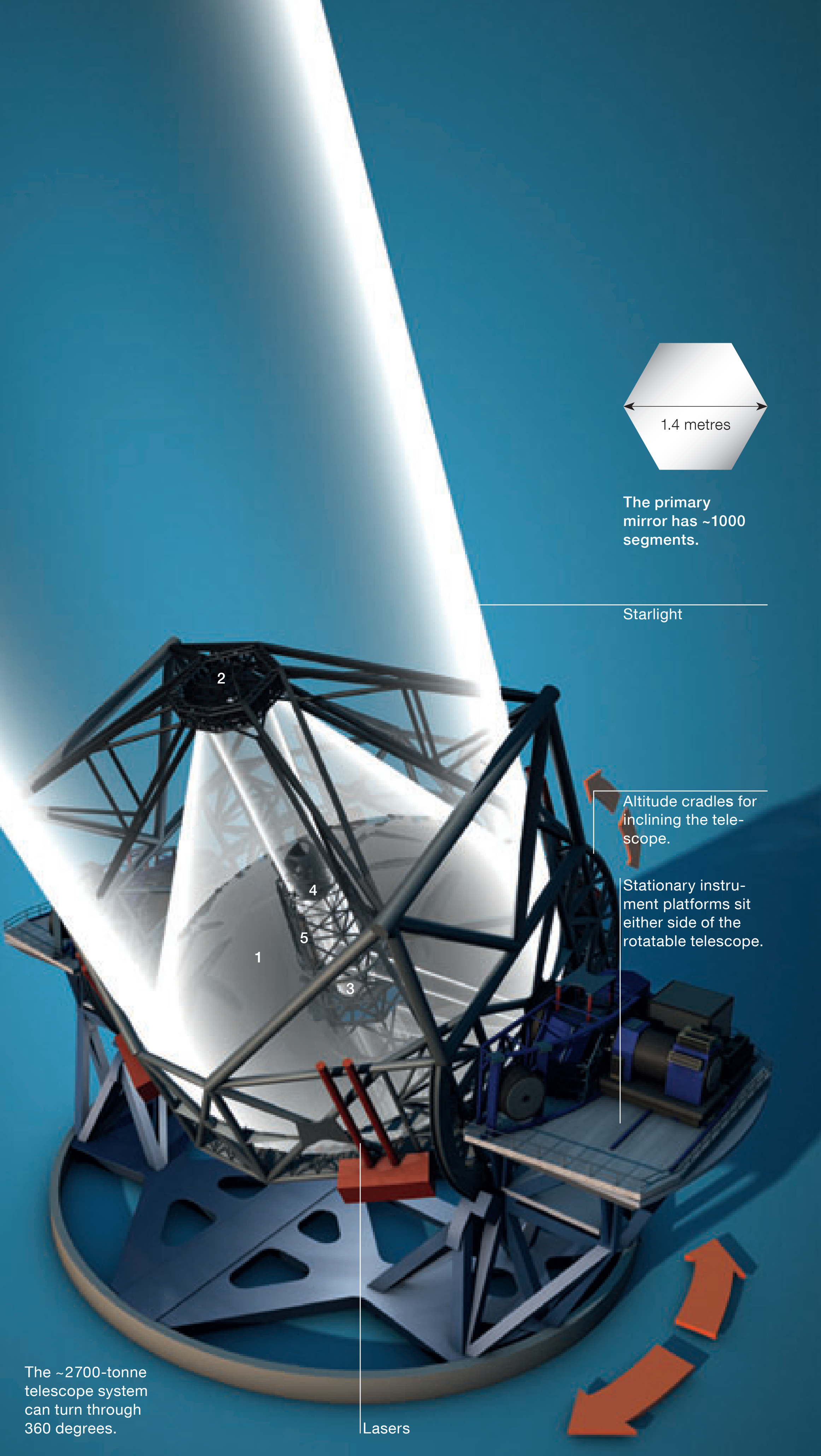


Prototypes for key components, developed during the detailed design study.

The construction phase (phases C and D) is expected to start in 2012. The construction cost is estimated to be close to a billion euros. The E-ELT is a high technology, highly prestigious science-driven project that incorporates many innovative developments, offering numerous possibilities for technology spin-off and transfer, together with challenging technology contract opportunities, and providing a dramatic showcase for European industry.

The E-ELT has already gained wide support in the European scientific community. It is the only visible-light astronomy project selected in the roadmap of the European Strategy Forum on Research Infrastructures. It also features as the top priority in ground-based astronomy in the ASTRONET *European Science Vision and Infrastructure Roadmap for Astronomy*.

With the start of operations planned early in the next decade, the E-ELT will address many of the most pressing unsolved questions in astronomy. It may, eventually, revolutionise our perception of the Universe, much as Galileo's telescope did, 400 years ago.



Five-mirror design

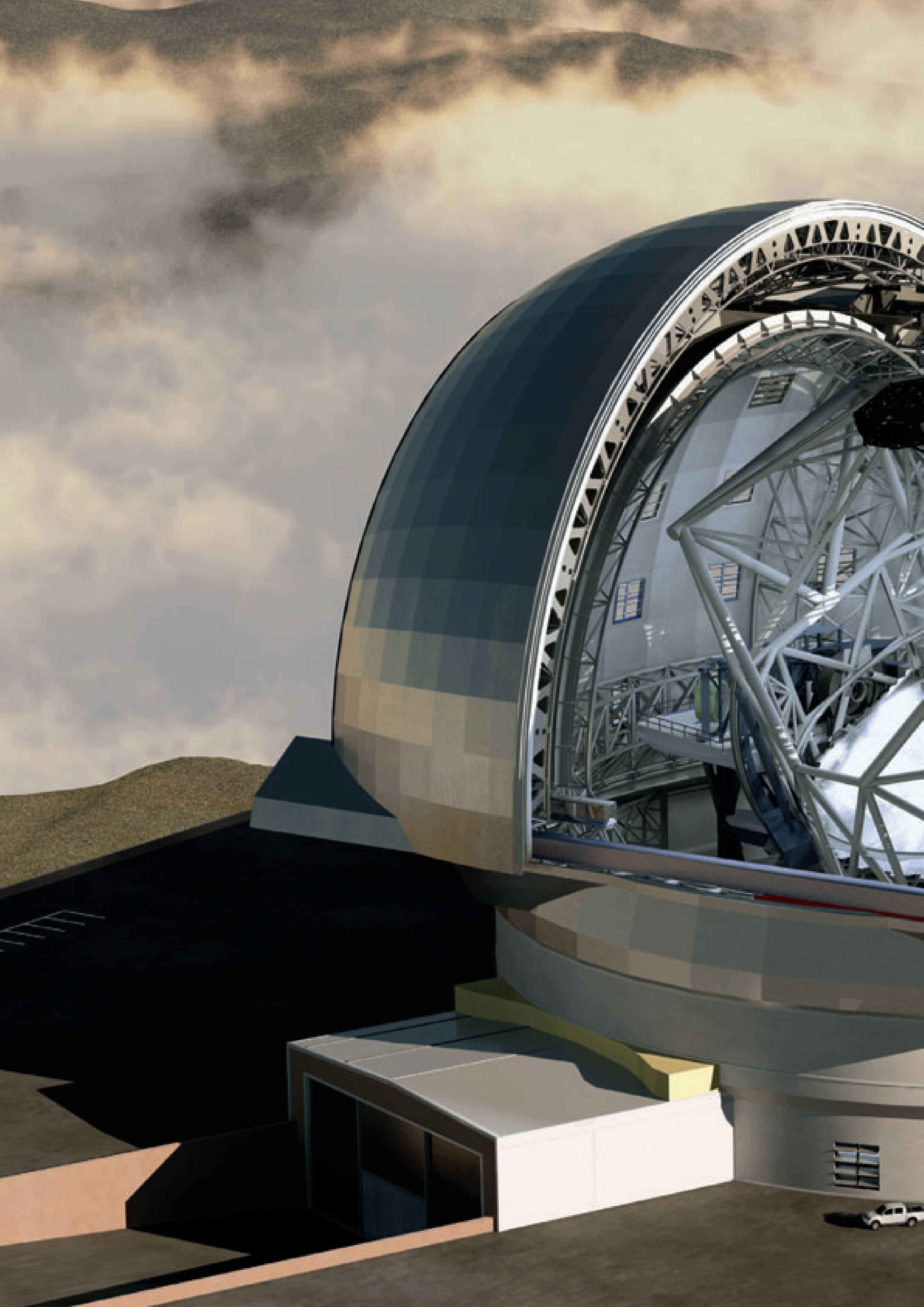
1 The ~40-metre primary mirror collects light from the night sky and reflects it to a smaller mirror located above it.

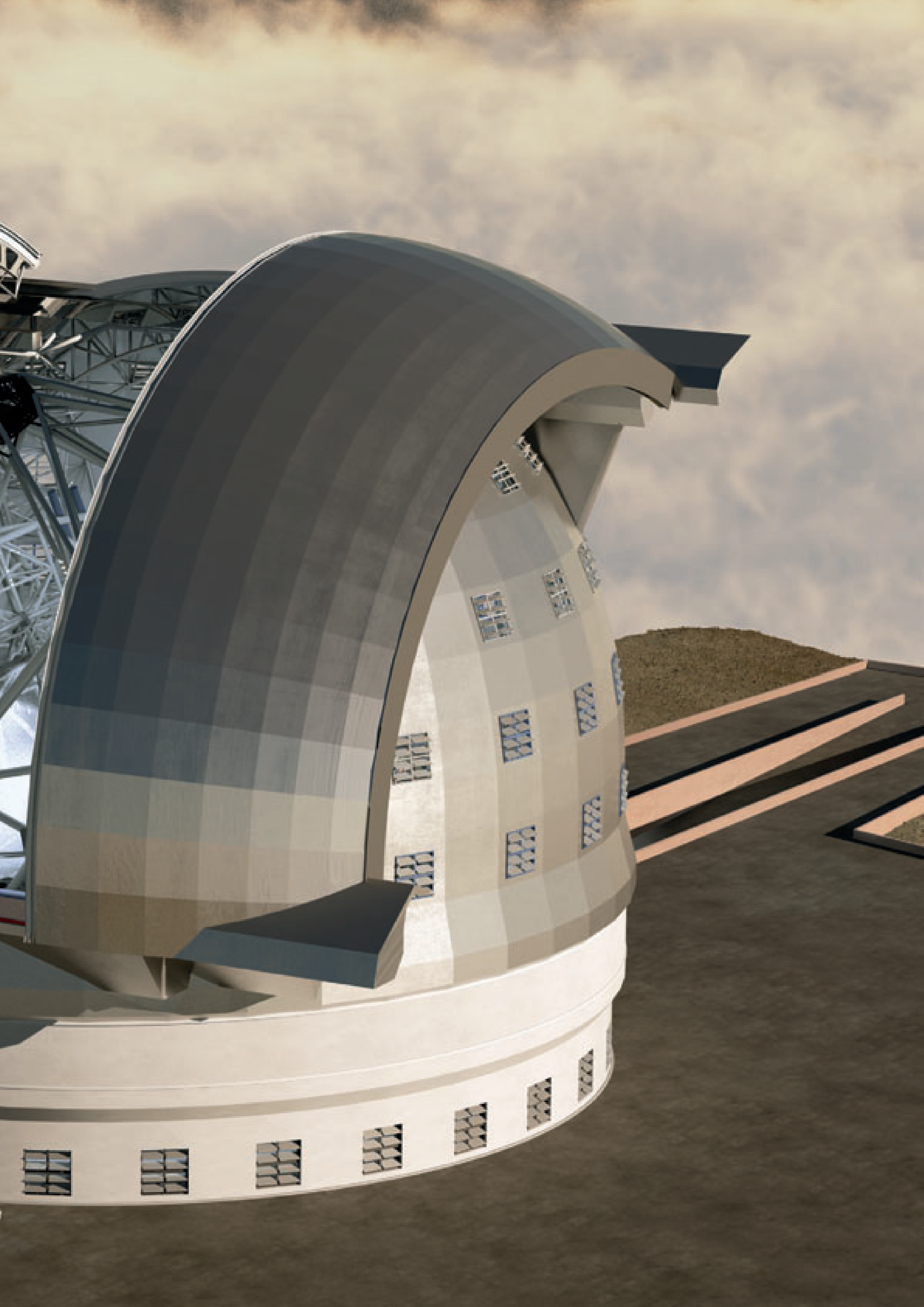
2 The secondary mirror reflects light back down to a still smaller mirror nestled in the primary mirror.

3 The third mirror relays light to an adaptive flat mirror directly above.

4 The adaptive mirror adjusts its shape a thousand times a second to correct for distortions caused by atmospheric turbulence.

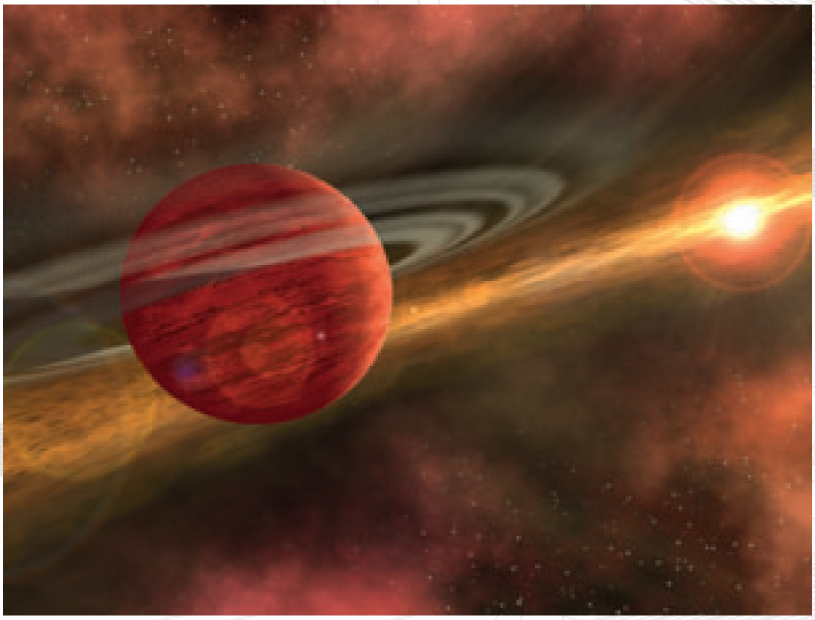
5 A fifth mirror, mounted on a fast-moving stage, stabilises the image and sends the light to cameras and other instruments on the stationary platform.





Open Questions for the E-ELT

Since the invention of the telescope, generations of astronomers have expanded the boundaries of the known Universe ever further. We now think of the Universe as of a finite age and thus of finite observable dimension. However, it is extremely large, and existing telescopes simply lack the sensitivity and angular resolution to explore its plentiful secrets. The European Extremely Large Telescope (E-ELT) will be able to address these problems and answer some of the most prominent open questions.



In this artist's view, a newfound planet orbits through a cleared region in a nearby star's dusty, planet-forming disc.

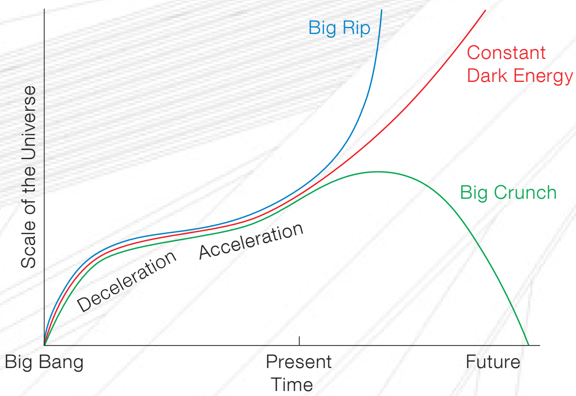
Exoplanets: are we alone?

For over a decade, we have known that exoplanets exist, but we have not yet been able to detect the faint signatures of Earth-like planets directly. The E-ELT will have the resolution to obtain the first direct images of such objects, and even to analyse their atmospheres for the biomarker molecules that might indicate the presence of life.

Are planetary systems like the Solar System common? How frequently do rocky planets settle in "habitable zones", where water is liquid? Do the atmospheres of exoplanets resemble the ones in the Solar System? How is pre-biotic material distributed in protoplanetary discs? Are there signs of life on any exoplanet?

Fundamental physics: are the laws of nature universal?

As far back in time and as far out in distance as we can observe, all the phenomena investigated so far seem to indicate that the laws of physics are universal and unchanging. Yet, uncomfortable gaps exist in our understanding: gravity and general relativity remain to be tested under extreme conditions, the amazingly rapid expansion (inflation) of the Universe after the Big Bang is not understood, dark matter seems to dominate the formation of the large scale structure but its nature remains unknown, and the recently discovered acceleration of the expansion of the Universe requires a mysterious dark energy that is even less comprehensible.



The evolution of the Universe is strongly dependent on dark energy.

Were the physical constants indeed constant over the history of the Universe? How did the expansion history of the Universe really proceed? Can we infer the nature of dark energy?

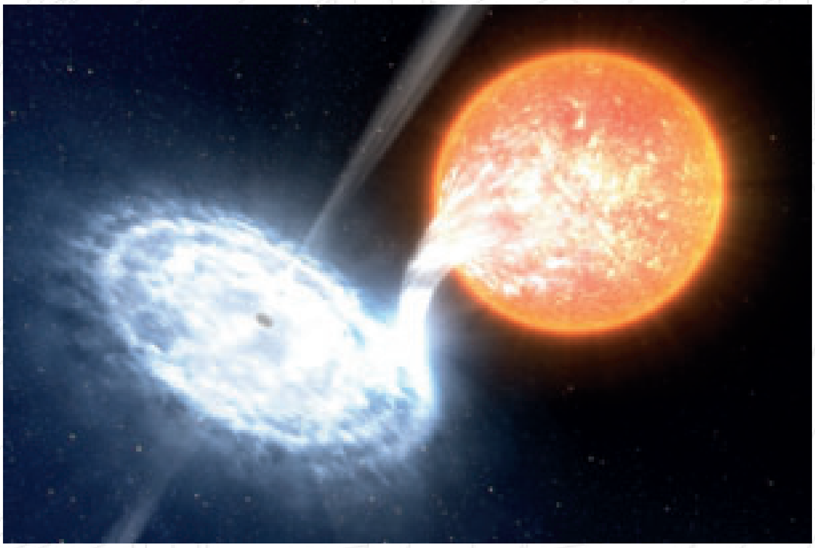
Black holes: what was their role in shaping the Universe?

Black holes have puzzled physicists and astronomers since they were first postulated in relativistic form a century ago by Karl Schwarzschild. Observations have demonstrated that these bizarre objects really exist. And on a grand scale, too: not only have black holes been found with masses comparable to stars, but also supermassive black holes, a million or even a billion times heavier than the Sun, have been found at the centres of many galaxies. These black holes also seem to "know" about the galaxies they live in, as their properties are closely correlated with the surrounding galaxy, with more massive black holes found in more massive galaxies.

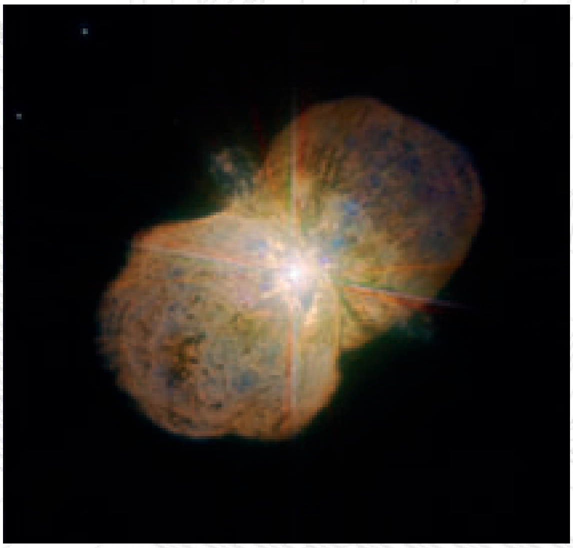
Will the supermassive black hole at the centre of the Milky Way reveal the nature of these objects? Do theories of gravitation and general relativity as we know them hold near a black hole's horizon? How do supermassive black holes grow? And what is their role in the formation of galaxies?

Stars: don't we know all there is to know?

Stars are the nuclear furnaces of the Universe in which chemical elements, including the building blocks of life, are synthesised and recycled: without stars there would be no life. Accordingly, stellar astrophysics has long been a core activity for astronomers. But much remains to be understood. With higher angular resolution and greater sensitivity astronomers will be able to observe the faintest, least massive stars, allowing us to close the current huge gap in our knowledge concerning star and planet formation. Nucleocosmochronometry — the radiocarbon-14 method as applied to stars — will become possible for stars right across the Milky Way, allowing us to study galactic prehistory by dating the very first stars. And some of the brightest stellar phenomena, including the violent deaths of stars in supernovae and gamma-ray bursts, will be traced out to very



An artist's impression of a black hole accreting material from a nearby star.



The luminous blue variable star Eta Carinae is expected to explode as a supernova in the astronomically near future.

large distances, offering a direct map of the star formation history of the entire Universe.

What are the details of star formation, and how does this process connect with the formation of planets? When did the first stars form? What triggers the most energetic events that we know of in the Universe, the deaths of stars in gamma-ray bursts?

Galaxies: how do "island universes" form?

The term "island universes" was introduced in 1755 by Immanuel Kant, and used at the beginning of the 20th century to define spiral nebulae as independent galaxies outside the Milky Way. Trying to understand galaxy formation and evolution has become one of the most active fields of astronomical research over the last few decades, as large telescopes have reached out beyond the Milky Way. Yet, even nearby giant galaxies have remained diffuse nebulae that cannot be resolved into individual stars. The unique angular resolution of the E-ELT will revolutionise this field by allowing us to observe individual stars in galaxies out to distances of tens of millions of light-years. Even at greater distances, we will be able to make the kind of observations of the structure of galaxies and the motions of their constituent stars that previously have only been possible in the nearby Universe: by taking advantage of the finite speed of light, we can peer back in time to see how and when galaxies were assembled.

The galaxy NGC 300.

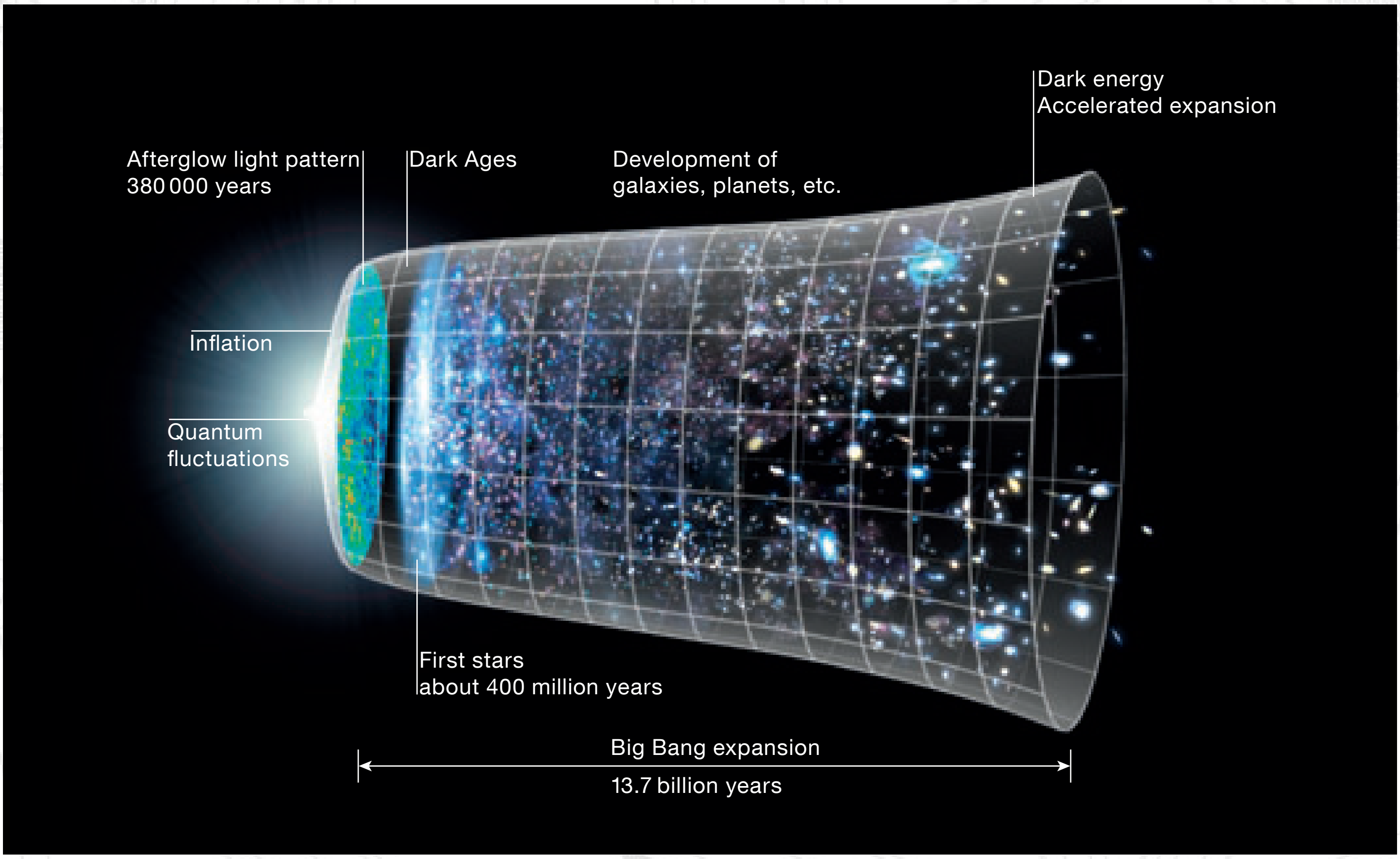
What stars are galaxies made of? How many generations of stars do galaxies host and when did they form? What is the star formation history of the Universe? When and how did galaxies as we see them today form? How did galaxies evolve through time?

The Dark Ages: can we observe the earliest epoch of the Universe?

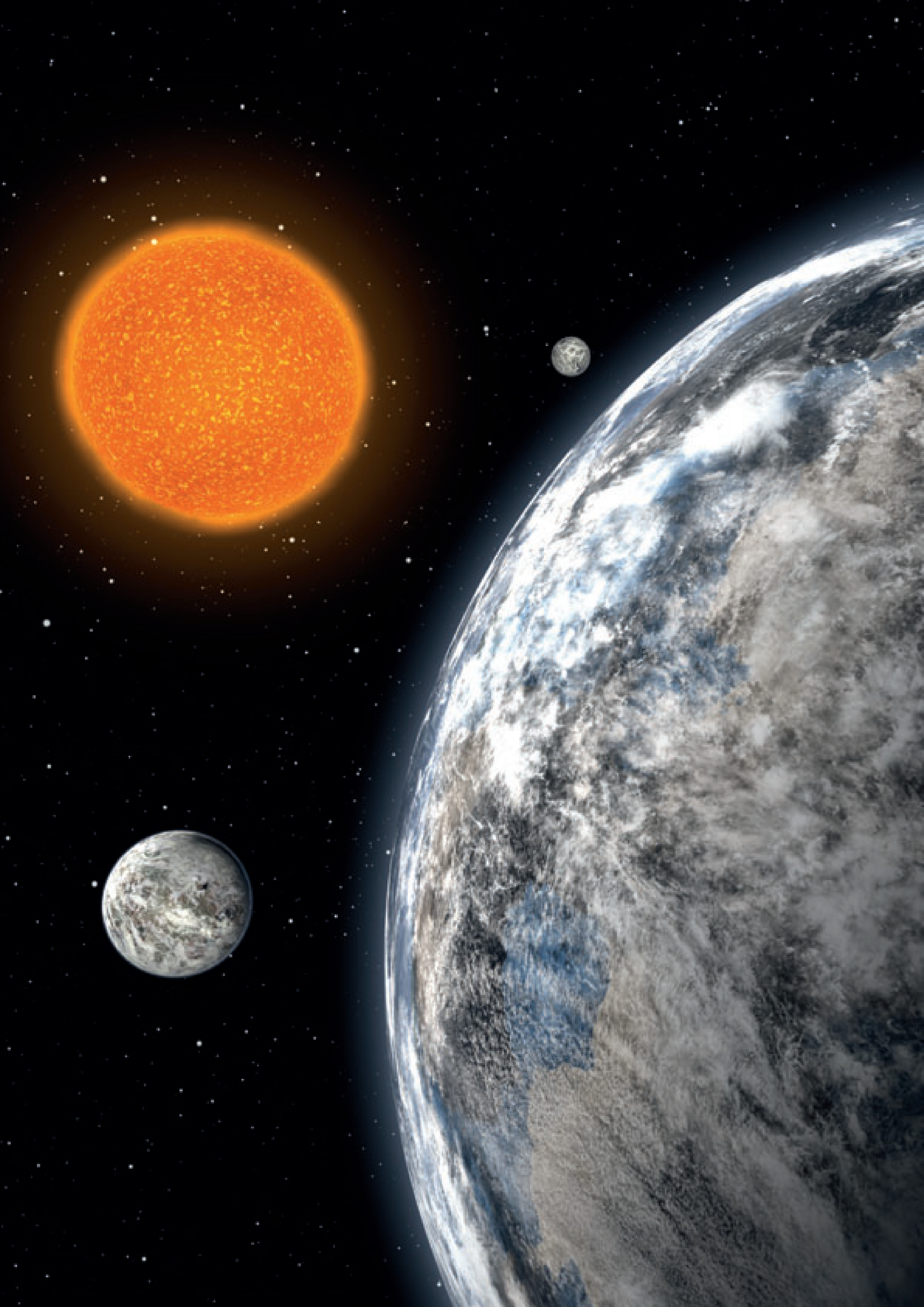
For the first 380 000 years after the Big Bang, the Universe was so dense and hot that light and matter were closely coupled. Only once the Universe had expanded and cooled sufficiently, could electrons and protons "recombine" to form the simplest element, neutral hydrogen, and photons could decouple from matter. Only then could the first stars form and start to become organised into larger structures. The E-ELT will allow scientists to look all the way back to these earliest times (dubbed the "Dark Ages") to see how this first phase of astrophysical evolution began.

What was the nature of the first stars? When did the first galaxies assemble and what were their properties? When did galaxies assemble into larger scale structures, shaping the distribution of matter as we see it today?

The above illustrations only scratch the surface of the science that the E-ELT will carry out, but they give a flavour of the range of problems, from the origins of the laws of physics to the prevalence of life in the Universe, that it will enable us to tackle. It will allow scientists to address some of the most fundamental current questions, as well as opening up whole new frontiers of human understanding.



Timeline of the Universe: A representation of the evolution of the Universe over 13.7 billion years. The far left depicts the earliest moment we can now probe, when a period of "inflation" produced a burst of exponential growth in the Universe. (Size is depicted by the vertical extent of the grid in this graphic.) For the next several billion years, the expansion of the Universe gradually slowed down as the gravitational pull of the matter in the Universe on itself dominated. More recently, the expansion has begun to speed up again as the repulsive effects of dark energy have come to dominate the expansion of the Universe. The afterglow light seen by WMAP was emitted about 380 000 years after inflation and has traversed the Universe largely unimpeded since then. The conditions of earlier times are imprinted on this light; it also forms a backlight for later developments of the Universe.



Exoplanets — Towards other Earths

Are we alone in the Universe? For millennia, this question was not posed or was purely philosophical. Recently, astronomers have started to provide an answer. With the E-ELT, for the first time in history, technology allows us to observe and to characterise exoplanets in habitable zones.

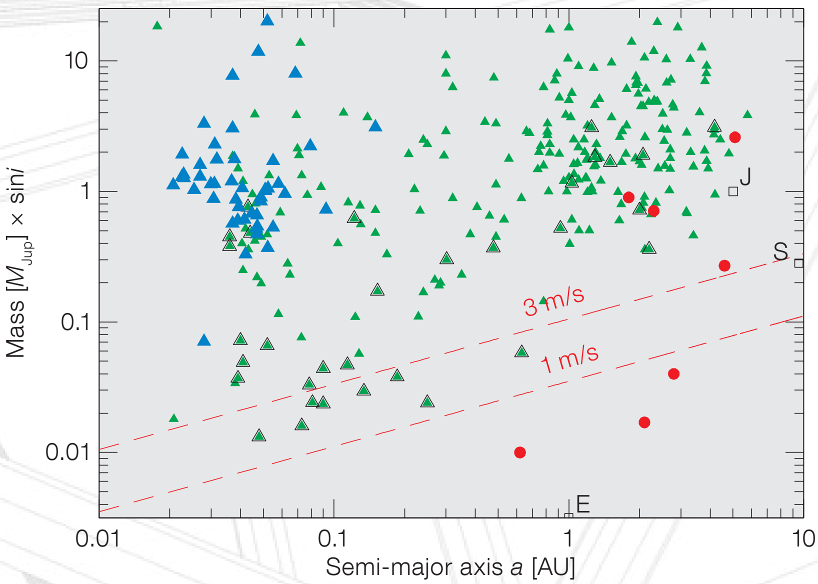
The first exoplanet orbiting a solar-type star (51 Pegasi) was discovered in 1995 by a European team. Since then, over 400 planetary companions with masses ranging from a few Earth to several Jupiter masses have been found. Most exoplanets are detected indirectly by the radial velocity technique, a method that detects planets by the "wobble" they produce on their parent star as they orbit it. However, such indirect detections only allow us to infer very limited information about the planet itself, and very few direct observations of planets have been made. With the E-ELT, we will be able to obtain direct images of some of these systems, including planets in the "habitable zones", where a rocky planet might hold liquid water on its surface.

The radial velocity technique — reaching 1 cm/s accuracy

The radial velocity technique, which measures the induced Doppler shift of features in the spectrum of the parent star, can only find certain kinds of planets. With the current generation of telescopes, this technique is limited both by the precision and the stability of the velocity measurements: current measurements have pushed the limit down to an already impressive ~1 m/s precision retained over several years. Unfortunately, though, a planet like the Earth, orbiting a star like the Sun, will only induce a radial velocity of about a tenth this size, which lies at the limit of what can be achieved with even the next generation of instruments on current telescopes. In contrast, ultra-stable spectrographs profiting from the large collecting power of the E-ELT will achieve measurement precisions of ~1 cm/s over periods ranging from minutes to years. For the detection of rocky planets in habitable zones, this precision is needed in order to overcome measurement contamination by oscillations, seismology, granulation and magnetic activity of the parent star.

Thus, the E-ELT is essential for finding Earth twins in habitable zones, for determining how common they are and for understanding the properties of their parent stars. This will allow a complete census of rocky Earth- to Neptune-mass planets around nearby stars for the first

Left: Artist's impression of the trio of super-Earths discovered by a European team using the HARPS spectrograph on ESO's 3.6-metre telescope at La Silla, Chile.



More than 400 exoplanets have been found so far. With the E-ELT, the sensitivity of the radial velocity method will be improved by a factor of one hundred.

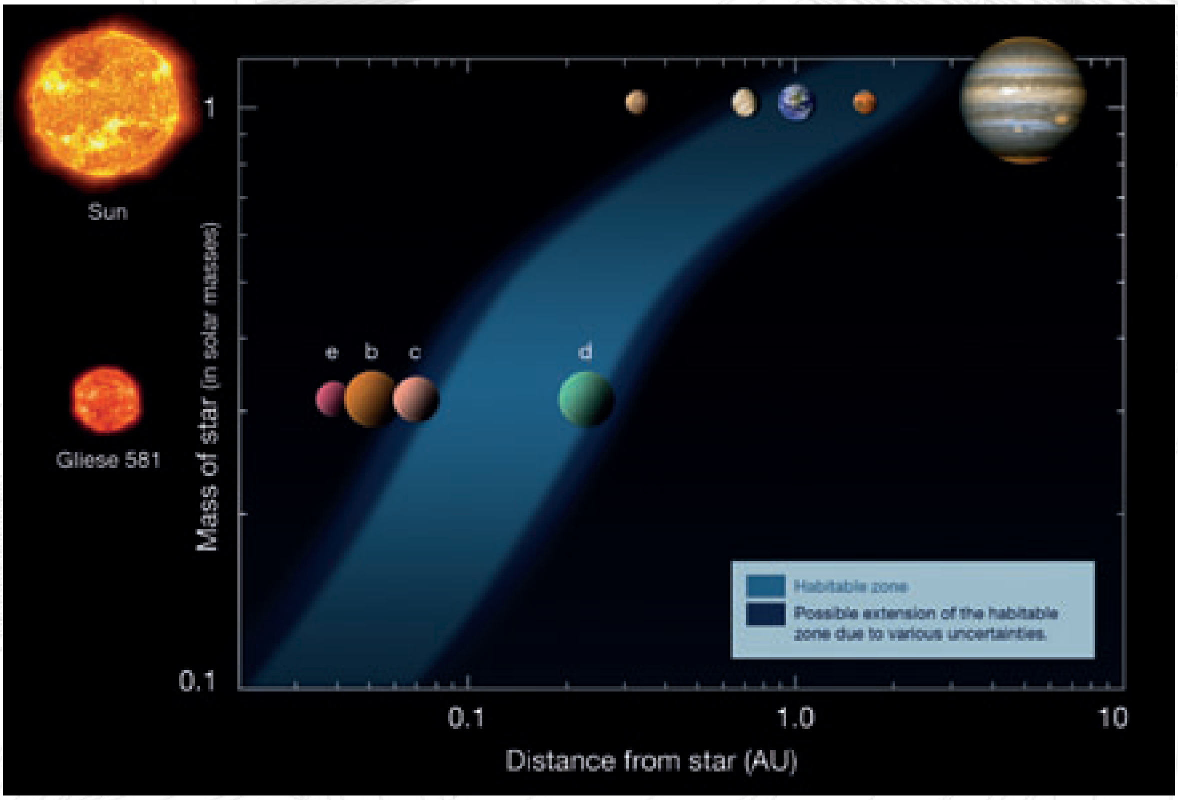
time and will provide an understanding of the architecture of planetary systems with low-mass planets. These studies will lead to an understanding of the formation of Solar System twins and will provide an answer to an important part of the fundamental question: just how unique are we?

Direct imaging — approaching 10^{-9} contrast

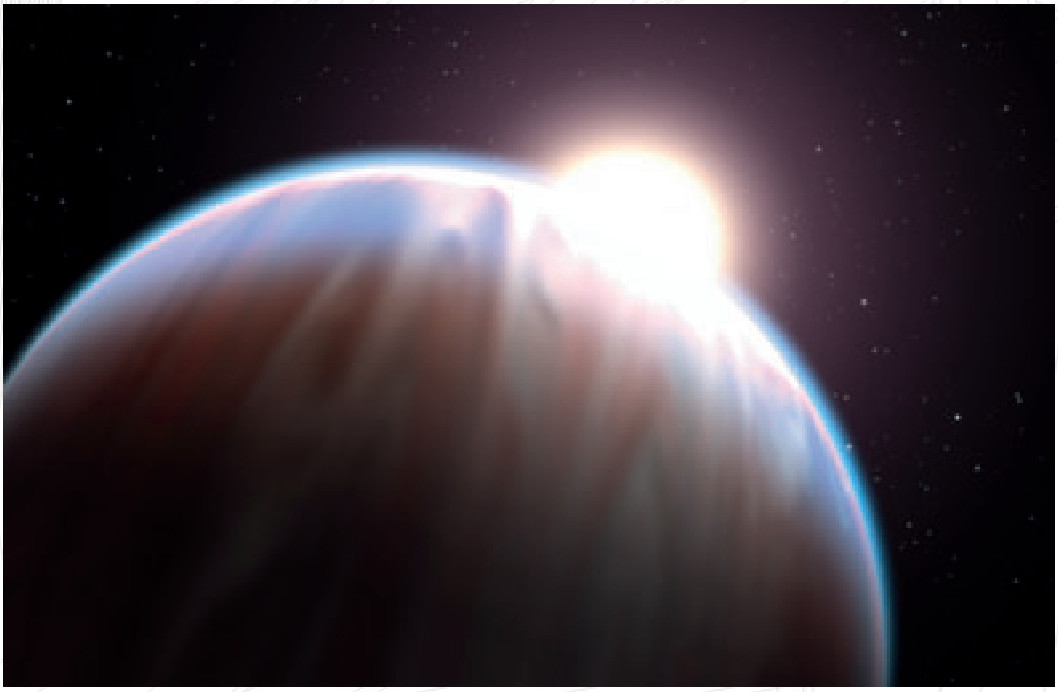
By 2020, ground- and space-based facilities will have discovered thousands of massive (Neptune- and Jupiter-mass) exoplanets. The E-ELT will start detecting Earth-twin targets in habitable zones using the radial velocity technique described above. By then, the statistical understanding of the properties of the parent stars and the distributions of the masses and orbits of exoplanets will have matured. The next step in exoplanet research will be the physical characterisation of the then known planets.

In order to achieve this, direct light from the planet must be detected and separated from the glare of its parent star. Overcoming this difference in brightness (usually referred to as the contrast) is the main challenge for this type of observation, and requires extremely sharp imaging. This capability will be a huge strength of ground-based telescopes. Planet-finder instruments on 8-metre-class telescopes will achieve similar contrasts to the James Webb Space Telescope: around 10^{-5} to 10^{-6} at sub-arcsecond distances from the parent stars.

The detection of an Earth-twin requires a contrast of 10^{-9} or better within less than 0.1 arcseconds from the star. The unprecedented light-gathering power of a 40-metre-class tele-



Direct imaging of Earth-twin planets in habitable zones is one of the main challenges for the E-ELT.



Using the Hubble Space Telescope astronomers have found water vapour and methane in the atmosphere of the Jupiter-sized planet HD 189733b.

scope, and the implementation of extreme adaptive optics in the E-ELT are absolutely crucial to reaching this limit. A planet-finder instrument on the E-ELT will allow scientists not only to study young (self-luminous) and mature giant planets in the solar neighbourhood and out to the closest star-forming regions, but also to understand the composition and structure of their atmospheres. Around the nearest hundred stars, the E-ELT will enable the first characterisation of Neptune-like planets and rocky planets located in habitable zones, establishing a new frontier in astrobiology and in our understanding of the evolution of life.

Characterising atmospheres

With the E-ELT, the detailed study of the atmospheres of young, massive exoplanets becomes feasible. Indeed, with its unprecedented sensitivity and spatial resolution at mid-infrared wavelengths, the E-ELT will be able to detect young, self-luminous exoplanets of Jupiter-mass. The contrast ratio between star and planet at these wavelengths becomes so advantageous that, for the nearest stars, hydrogen, helium, methane, water ammonia and other molecules can all be detected in low resolution spectra of the atmospheres of Neptune-like planets in habitable zones.

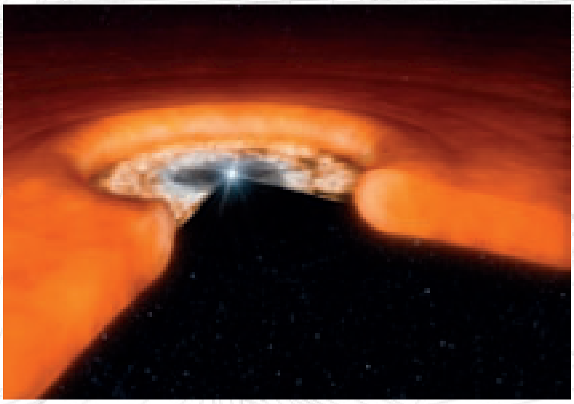
Alternatively, exoplanet atmospheres can be observed during transits. Ground- and space-based facilities (such as the CoRoT and Kepler missions) are accumulating target stars for which an exoplanet, as seen from Earth, transits in front of its parent star. During these events (lasting a few hours every few months or years), spectral features of the exoplanet's atmosphere, back-lit by their parent star, can be seen in the spectrum of the system. Such measurements are challenging, but lie within reach of the E-ELT. In the case of rocky planets in the habitable zone, the spectra can be examined for the biomarker molecules that are indicative of biological processes, offering perhaps the best opportunity to make the first detection of extraterrestrial life.

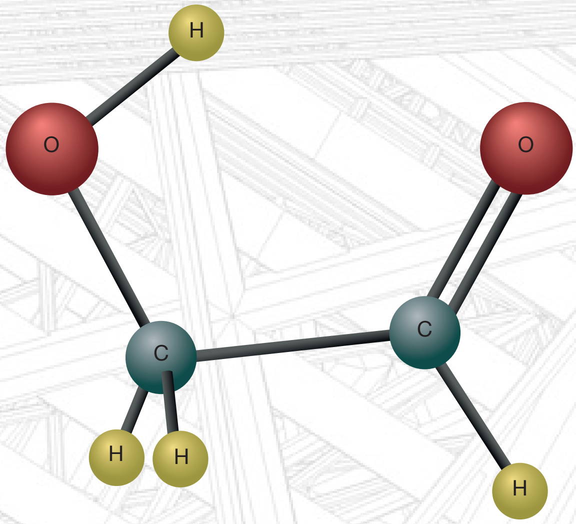
Protoplanetary discs and pre-biotic molecules

The observed diversity in the properties of exoplanets must be related to the structure and evolution of the discs of preplanetary material from which they form. A crucial step for our understanding of the origin of life is thus the study of the formation of such protoplanetary discs. The transition from the gas-rich to the gas-poor phase of discs is of particular interest: it is the time when gaseous planets form and rocky planets gradually accrete "planetesimals" — essentially boulders — onto their cores.

The E-ELT's spatial resolution of a few to tens of milliarcseconds allows it to probe the inner few astronomical units of these discs, out to the nearest star-forming regions (at about 500 light-years from us), allowing us to explore the regions where Earth-like planets will form for the first time. These data will beautifully complement observations with the new international ALMA submillimetre array that will look at the colder material further out in these systems, to provide a full understanding of protoplanetary disc evolution. Furthermore, the inner discs probed by the E-ELT are those where the key molecules for organic chemistry, such as methane, acetylene, and hydrogen cyanide, occur, and more complex, pre-biotic molecules are expected to form. Their study will provide a further vital piece in the astrobiology puzzle.

An artist's concept of the environment of a young star, revealing the geometry of the dust disc.





Glycolaldehyde

Pre-biotic molecules, like glycolaldehyde, are building blocks of life and found in dense interstellar clouds even before planet formation starts there.

Right: An artist's view of the exoplanet CoRoT-7b, the closest known to its host star. The role of the E-ELT is to characterise similar rocky planets, but in habitable zones.

Fundamental Physics

What is the Universe made of? In the standard cosmological model, only 4 % of the energy density of the Universe is composed of normal matter (gas and stars), while a further 22 % is made up of some mysterious dark matter. For the remaining 74 %, the even more enigmatic dark energy has been invoked. The E-ELT will explore the nature of this dark energy and our theory of gravity by probing two of its manifestations with unprecedented accuracy: the accelerated expansion of the Universe and the variability of fundamental physical constants.

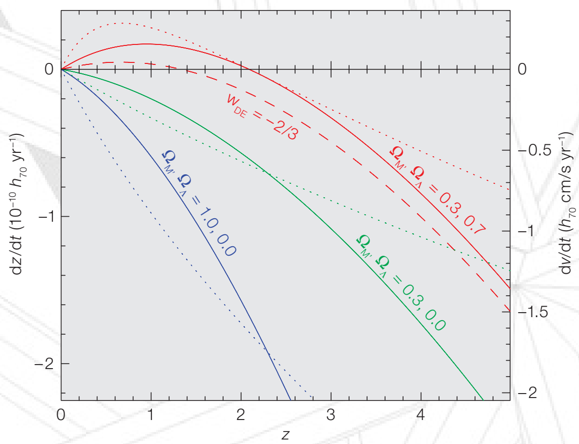
How does the expansion of the Universe evolve?

The revolutionary observations made by Edwin Hubble in the late 1920s were the first direct evidence that the Universe was not static. The systematically increasing spectroscopic redshift observed in increasingly distant galaxies was a clear sign that the Universe expands. For a long time this expansion was believed to be slowing down due to the combined gravitational pull exerted by all of the matter in the Universe. However, at the end of the 1990s the measured dimming of Type Ia supernovae (used as standard candles) with increasing redshift revealed that this is not the case. Instead, there is now broad consensus that the expansion must have recently begun to accelerate! This result came as a surprise to most, but also as a big challenge. It has profoundly changed cosmology and implies a need for new physics.

Dark energy

Some form of dark energy, acting against gravity, is invoked by many cosmologists as an explanation for the accelerated expansion of the Universe. Ironically the simplest form of such a dark energy is the cosmological constant originally introduced by Einstein in order to explain a now-discredited static Universe, and with this addition general relativity can explain this late acceleration very well. Alternatively, it has been proposed that general relativity should be replaced with a modified theory of gravity, which reproduces the new observational facts, but preserves the success of the original theory in explaining the formation of structures in the early Universe.

The most direct way to probe the nature of the acceleration in order to distinguish between these possibilities is to determine the expansion history of the Universe. Observables that depend



The redshift drift as a function of redshift for various combinations of cosmological parameters.

Left: The Hubble Ultra Deep Field images reveal some of the most distant known galaxies, when the Universe was just 800 million years old. The E-ELT is expected to look even further.

on the expansion history include cosmic distances and the linear growth of density perturbations. Surveys of Type Ia supernovae, weak gravitational lensing and the signature that perturbations in the primordial baryon–photon fluid imprinted shortly after the Big Bang on today's distribution of galaxies are considered to be good probes of the acceleration. However, extracting information about the expansion from these quantities relies on assumptions about the curvature of space, depends on the adopted cosmological model, and can only estimate the averaged expansion history over large periods of time.

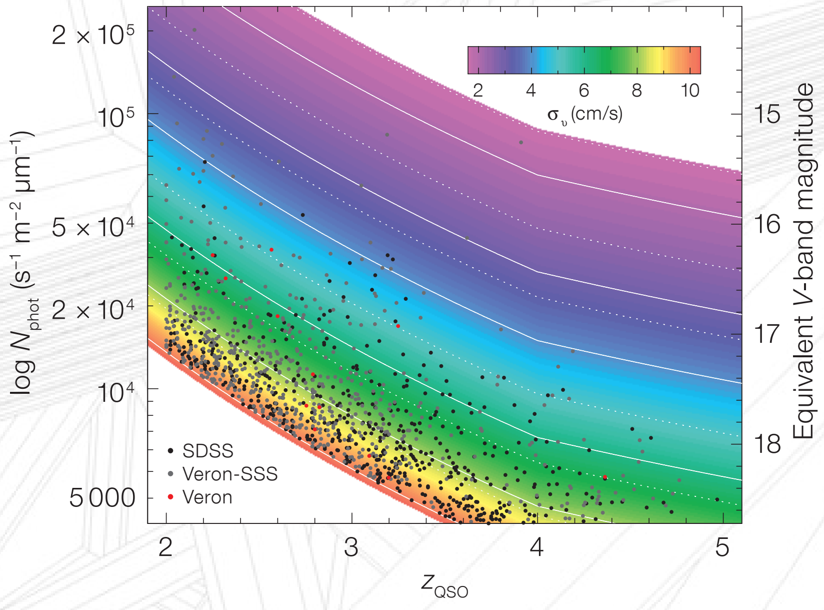
A new approach — the redshift drift

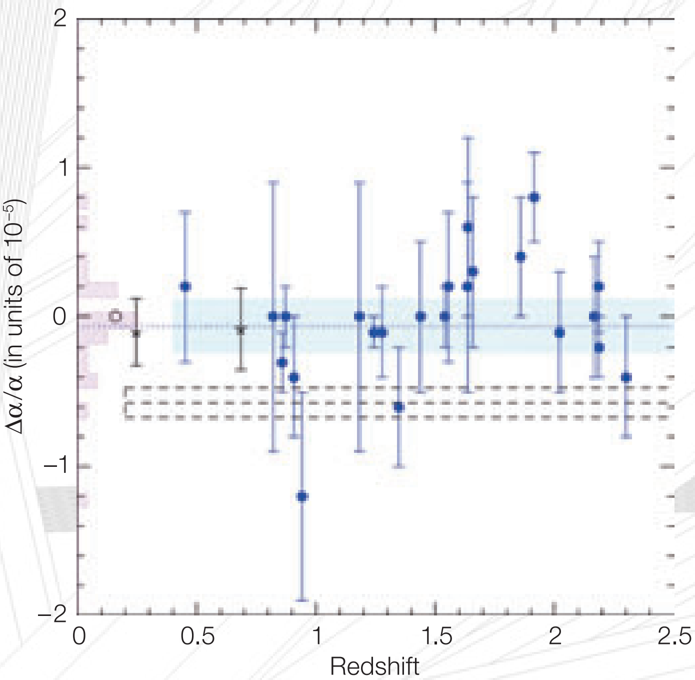
A model-independent approach that measures the expansion rate directly was proposed as early as the 1960s, but limitations in technology did not allow astronomers to consider making such a measurement in practice. As the redshift of the spectra of distant objects is an indication of the expansion of the Universe, so is the change in this redshift with time a measure of the change of the rate of expansion. However, the estimated size of this redshift drift over a decade is only about 10 cm/s. Such a signal is about 10–20 times smaller than measurements made with today's large telescopes on such distant galaxies. However, the huge light-collecting area of the E-ELT, coupled with new developments in quantum optics to record ultra-stable spectra, means that this amazing measurement now lies within reach: the E-ELT will be able to determine the accelerating expansion of the Universe directly, allowing us to quantify the nature of the dark energy responsible for the acceleration.

Are the fundamental constants of physics really constant?

The values of fundamental constants in physics generally have no theoretical explanation: they just are what they are, and the only way we

A simulation of the accuracy of the redshift drift experiment, which will be achieved by the E-ELT. The results strongly depend on the number of known bright quasars at a given redshift.





The variability of the fine structure constant is not yet proved and awaits the extreme sensitivity of the E-ELT.

know their values is by measuring them in the laboratory. These fundamental quantities include the fine structure constant, α, and the strong interaction coupling constant, μ. The former is central to our understanding of electromagnetism, and is made up from three other constants: the charge on the electron, *e*, Planck's constant, *h*, and the speed of light, *c*. The latter, μ, is the ratio of the mass of the proton to the mass of the electron.

In the traditional understanding of physics, the laws of nature have always and everywhere been the same, but this is really just an assumption. If this assumption does not hold, then the fundamental constants may vary with the epoch and location of the measurement. Such variations can have a profound impact on the physical properties of the Universe. An upper limit is given by the fact that if the value of α were larger by just 4 % in the early Universe, then the processes of nuclear fusion would be altered in such a way that the amount of carbon produced in the cores of stars would be drastically reduced, making carbon-based life impossible.

Strings, scalar fields, dark energy…

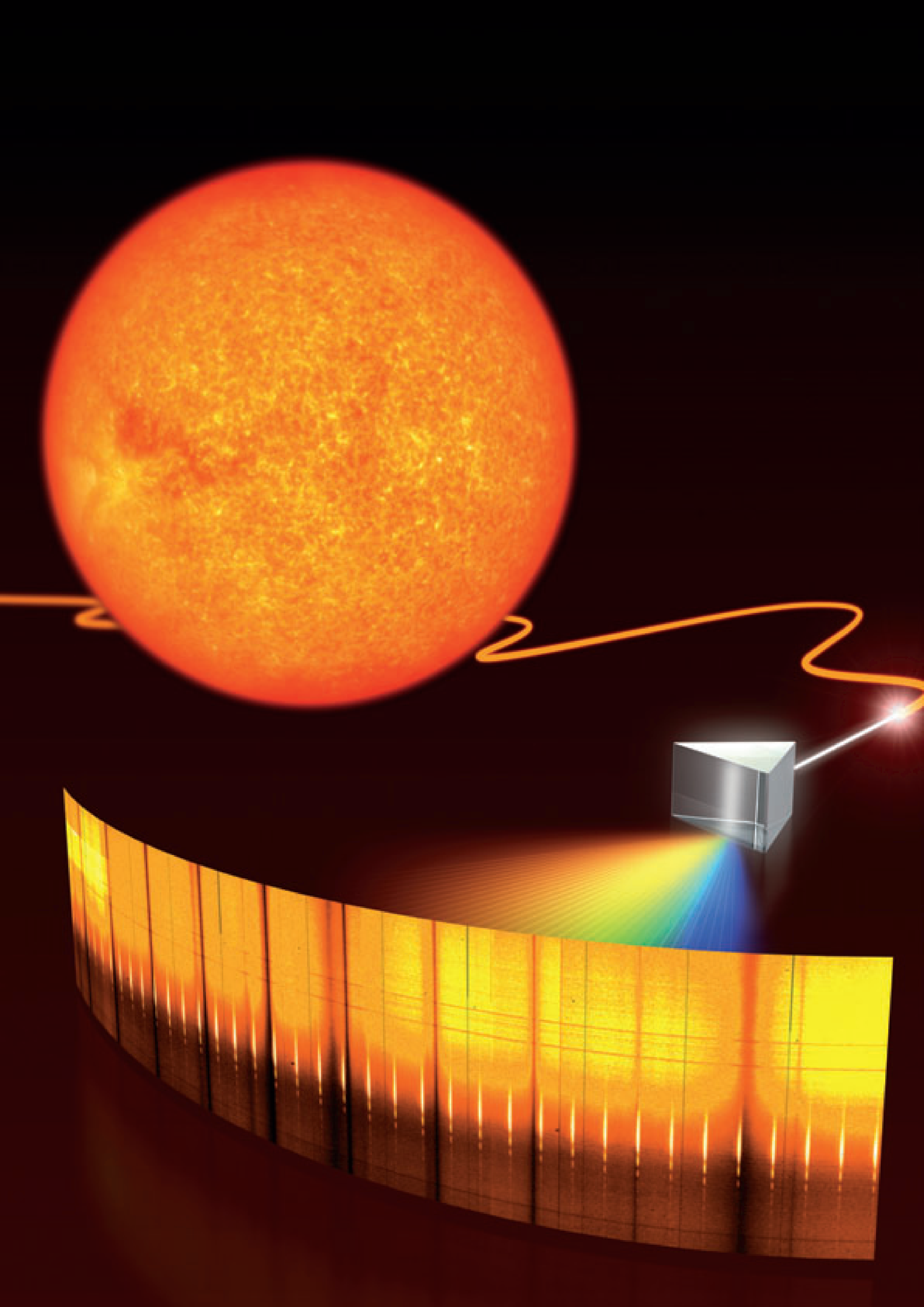
Theoretical models have been proposed where the variability of fundamental constants is due to a scalar field that is coupled to the electromagnetic field. We do not know whether such scalar fields exist, but they are predicted by a whole number of theories and the Large Hadron Collider experiment at CERN could detect the first such scalar field very soon. String theory also suggests that fundamental constants may vary by a tiny amount, of the order of one part in 10 000 or 100 000. In this case the variability is due to the changing size scale of hidden space-time dimensions. Other proposed explanations for a possible variability of fundamental constants are related to the contribution of dark energy to the energy density of the Universe.

Astronomical observations probe much longer timescales and are therefore much more sensitive to possible variations of the fundamental constants than laboratory experiments. By exploring the spectra of distant quasars, the variability can be probed over a large fraction of the history of the Universe. A team led by Australian researchers has used a method called the "many-multiplets" method, where the relative shifts between iron and magnesium absorption lines are measured, leading to claims of a detected variation in the value of α. The team measured a very small relative variation of $\Delta\alpha/\alpha \sim -6 \times 10^{-6}$. However, a European research team obtained later new measurements consistent with no variability. It has also been suggested that the strong interaction coupling constant varies. Studies of the vibrational and rotational states of the hydrogen molecule in damped Lyman-α systems have been claimed to vary at a level of $\Delta\mu/\mu \sim 2 \times 10^{-5}$, although these measurements have also been disputed.

The reason for these conflicting results is that the measurements involved are very challenging. Testing the variability of fundamental constants with quasar absorption line spectra is essentially a measurement of the relative wavelength shifts of pairs of absorption lines whose wavelengths have different sensitivity to the fundamental constants. The strength of the constraint on the variability is therefore critically dependent on the accuracy of the wavelength calibration. The ultra-stable high resolution spectrograph proposed for the E-ELT will essentially remove the systematic uncertainties due to the wavelength calibration which plague current measurements. It will improve the constraints on the stability of fundamental constants by two orders of magnitude. The E-ELT will thus confirm or disprove the current claims that fundamental constants vary and that we are living in a fine-tuned location of space time where the fundamental constants are conveniently suitable for life.

Quasars are some of the most distant objects that could be observed.

Right: The laser comb method allows ultra-stable measurements of the redshift drift and fundamental constants variations, when applied to the light collected by the E-ELT.



Black Holes

Black holes are some of the most bizarre objects in the Universe, challenging the imaginations of even the most creative scientists. They are places where gravity trumps all other forces in the Universe, pushing our understanding of physics to the limit. Even more strangely, supermassive black holes seem to play a key role in the formation of galaxies and structures in the Universe.

Galactic Centre

Over the last 15 years or so, an enormous amount of work has gone into improving our understanding of the closest supermassive black hole — Sagittarius A* at the centre of the Milky Way.

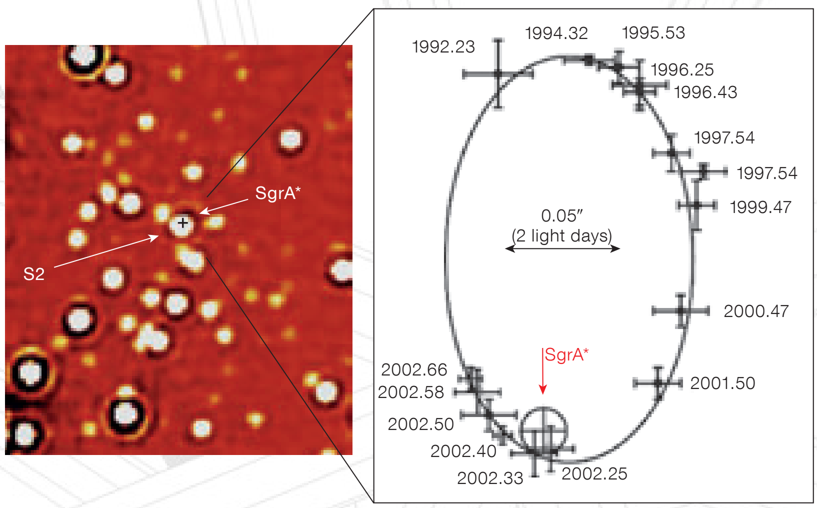
Technological progress, in particular in the areas of adaptive optics and high angular resolution with ground-based 8-metre-class telescopes, has allowed impressive progress in understanding supermassive black holes and their surroundings. Key progress was made in proving the very existence of a supermassive black hole at the centre of the Milky Way, in refining our knowledge of how matter falls into black holes, and in identifying gas discs and young stars in the immediate vicinity of the black hole. The Galactic Centre was thus established as the most important laboratory for the study of supermassive black holes and their surroundings.

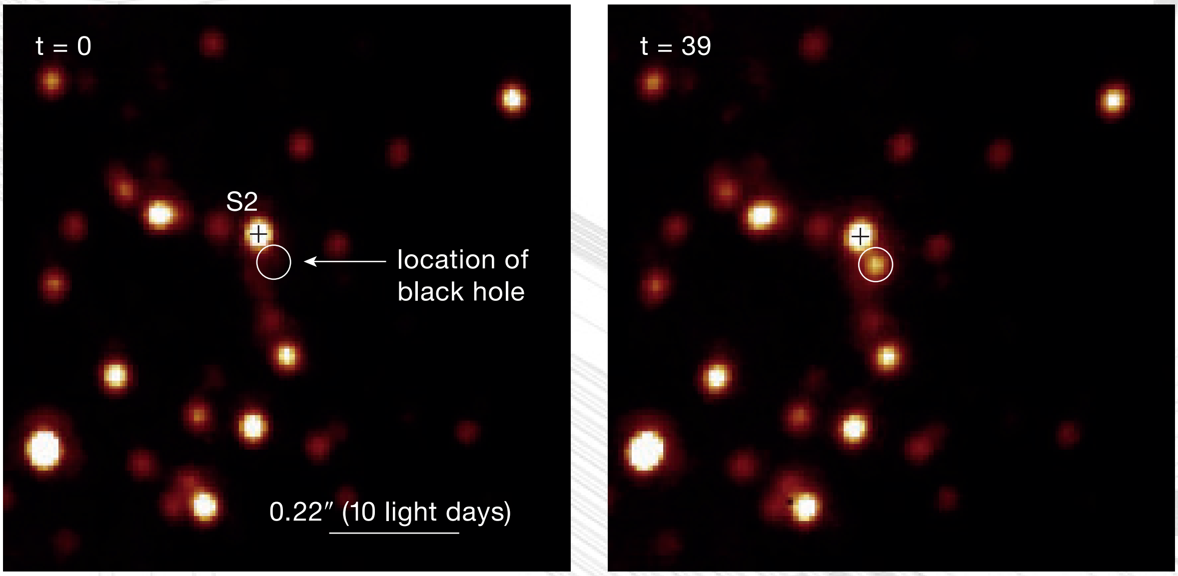
But its potential for progress in fundamental physics and astrophysics is far from being fully exploited. The Galactic Centre remains the best place to test general relativity directly in a strong gravitational field. The E-ELT will enable extremely accurate measurements of the positions of stars (at the 50–100 microarcsecond level over fields of tens of arcseconds), as well as radial velocity measurements with about 1 km/s precision, pushing our observations ever closer to the black hole event horizon. Stars can then be discovered at 100 Schwarzschild radii, where orbital velocities approach a tenth of the speed of light. This is more than ten times closer than can be achieved with the current generation of telescopes. Such stellar probes will allow us to test the predicted relativistic signals of black hole spin and the gravitational redshift caused by the black hole, and even to detect gravitational wave effects. Further out, the dark matter distribution around the black hole, predicted by cold dark matter cosmologies (ΛCDM), can be explored. The distance to the Galactic Centre can be measured to 0.1%, constraining in turn the size and shape of the galactic halo and the Galaxy's local rotation speed to unprecedented levels. Crucial progress in our understanding of the interaction of the black hole with its surroundings will be made. The puzzling stellar cusp around the Galactic Centre, as well as the observed star formation in the vicinity of the black hole will be studied in detail for the first time.

Left: Very Large Telescope (VLT) observations have revealed that the supermassive black hole closest to us is located in the centre of the Milky Way.

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

S2 Orbit around SgrA*





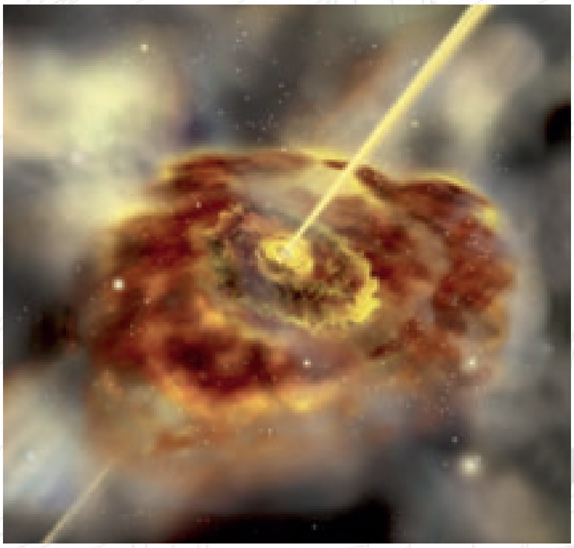
A powerful flare from the centre of the Milky Way, where a supermassive black hole resides.

Looking at the Galactic Centre with the collecting power and spatial resolution of the E-ELT will truly allow us to reach new dimensions in our understanding of black hole physics, their surroundings and the extent of the validity of general relativity.

Messier 15 is one of the very few globular clusters thought to host an intermediate-mass black hole.

Intermediate-mass black holes

Black hole research with the E-ELT will not be limited to the Galactic Centre. An open question awaiting the advent of the E-ELT is the existence and the demographics of intermediate-mass (100–10 000 solar masses) black holes. These black holes 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. They could plausibly form from the first ultra-massive stars, or via the same unknown mechanism that forms supermassive black holes. Their existence in the local Universe cannot unambiguously be proven with current observational facilities. To date, only a few detections at the centres of dwarf galaxies and massive star clusters have been reported. Their existence has been inferred either from X-ray and radio emission that is believed to originate from matter falling onto a black hole, or from the disturbance in the motions of stars and gas at the centre of these objects. The E-ELT will be able to measure accurately the three-dimensional velocities of stars in these star clusters and dwarf galaxies. This will allow to determine the masses of the intermediate-mass black holes that are speculated to lie at their cores.



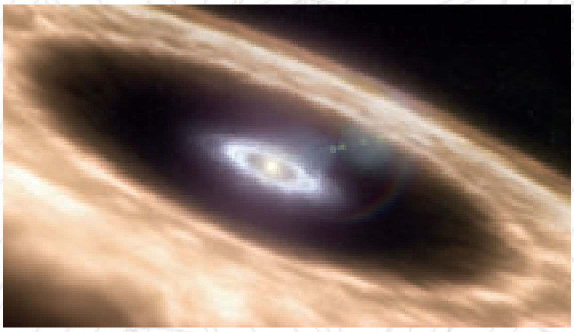
An artist's impression of an active galactic nucleus, powered by a supermassive black hole surrounded by an accretion disc. The E-ELT will provide us with such detailed views of the centres of galaxies out to 300 million light-years.

Supermassive black holes and active galactic nuclei

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 magnitudes in scale, from galaxy environments to the "sphere of influence" of the black hole. 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 study nuclear clusters and active galactic nuclei in galaxies with unprecedented detail. The combination of high spatial resolution with spectroscopic capabilities available with the E-ELT will enable us to map the gas motions in the regions immediately around the active nucleus of galaxies and to understand the inflow of material accreted by the central black hole. Furthermore, supermassive black holes will be characterised out to large distances with the E-ELT, 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.

The Birth, Life and Death of Stars

Stars emit nearly all of the visible light that we see in the Universe. The details of their formation process, coupled to the formation of protoplanetary discs, but also their evolution and their (sometimes most energetic) death still present some of the most interesting puzzles in astrophysics. The E-ELT is the key facility to answering many of these open fundamental questions.



With the E-ELT, astronomers will be able to study planet-forming discs in unsurpassed detail at distances larger by a factor of ten than possible today.

Star formation and the conditions for the formation of planetary systems

The formation of a star follows a complicated route. The earliest phases of this process, during which protostellar discs start to emerge from molecular clouds, is often thought to be in the realm of longer wavelength (submillimetre, millimetre, radio) facilities, due to their ability to peer into heavily dust-obscured regions. While this is partly true for present day optical/near-infrared telescopes, the E-ELT, with its gain in sensitivity and, in particular, in angular resolution, will be a major player in protostellar/protoplanetary disc research, even in their early stages.

At mid-infrared wavelengths, the spatial resolution limit of the E-ELT represents, at the distance of the closest star-forming regions (located about 150 parsecs away), a few astronomical units (AU), i.e. a few times the mean Sun–Earth distance. Thus, the E-ELT will be able to probe the innermost regions of the protoplanetary discs, and study where rocky planets form. The closest high-mass star formation regions are a few thousand parsecs away.
At this distance, the E-ELT resolution can probe the very inner regions (tens of AU) of the surrounding accretion discs, allowing us to study in great detail the formation of these stars, which dominate the energy budget of the interstellar medium. The E-ELT will allow a close look at how a star forms and to make decisive progress in the study of the pre-main-sequence phases of star formation.

Stellar tribulations

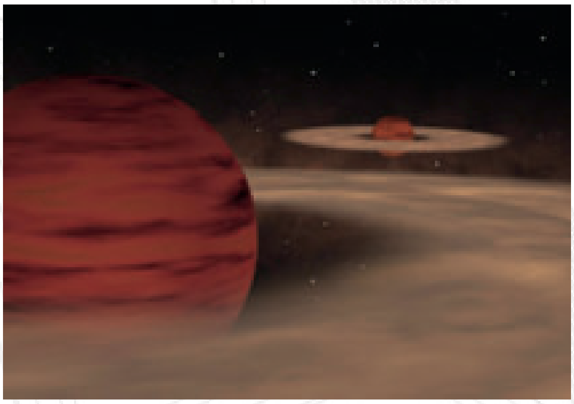
The path taken by a star through its lifecycle varies greatly with its mass. Mass determines not only a star's lifetime and evolution but also its final fate. Understanding the evolution of stars is critical to our understanding of the evolution of the Universe: the continuous recycling process of matter, the energetic processes shaping the interstellar medium, the feedback processes in the evolution of galaxies, and the overall chemical enrichment history of the Universe, all the way to the chemistry enabling life.

High resolution spectroscopy from the optical to the infrared with the E-ELT will allow unprecedented progress in this field. The E-ELT will allow us to perform nuclear dating ("nucleocosmochronometry") on individual stars with ages between 1 and 12 billion years. Current facilities are limited in their collecting power and have performed this measurement on only a handful of stars. The E-ELT will allow measurements of elements such as ^{232}Th (mean lifetime 20.3 billion years) and ^{238}U (mean lifetime 6.5 billion years) and their ratios to other elements in hundreds of stars in different regions

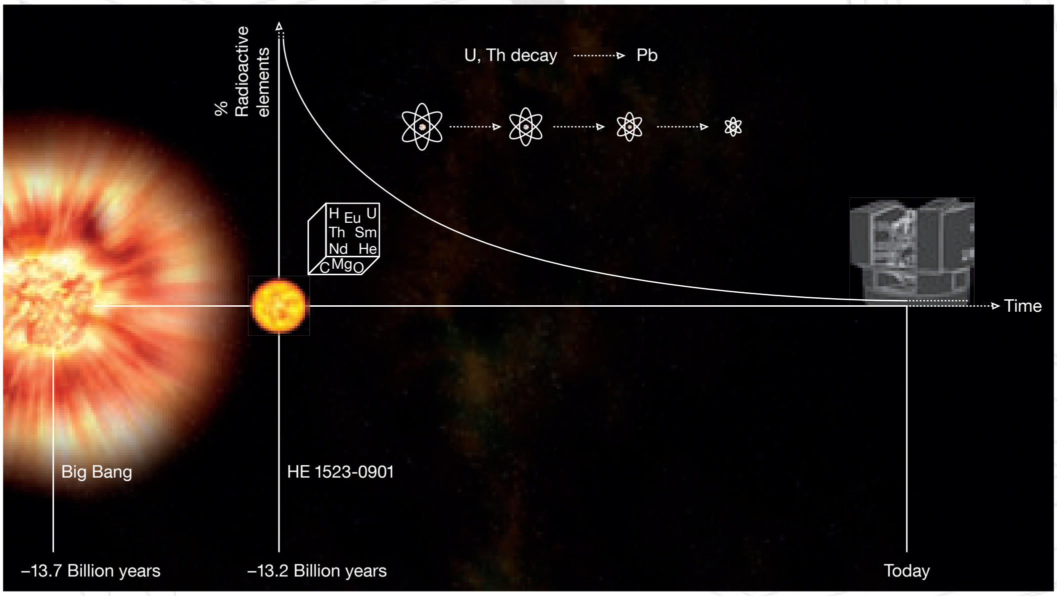
Left: In the Large Magellanic Cloud, a part of which is pictured here, astronomers can explore the complete cycle of stellar evolution.

of the Milky Way. Combined with precise element abundance measurements in stars, and with results from space missions such as Gaia, it will allow us to determine not only the precise age of the major components of our galaxy, but also to date their assembly phases and to describe their chemical evolution. A full understanding of the assembly of the Milky Way is within reach with the E-ELT.

At the low-mass end of star formation, we enter the realm of brown dwarfs, which are not massive enough to have started the central nuclear fusion process that powers stars. These objects are particularly interesting as they are expected to have masses and atmospheric properties intermediate between stars and giant planets. Only the E-ELT has the collecting power to reach out in distance and to study the faint brown dwarfs in nearby open star clusters in detail. In addition, the E-ELT has the spatial resolution to study brown dwarfs and planetary-mass objects in so-called ultra-cool binaries (with separations of only a few hundred AU) in nearby environments ranging from young stellar associations (one million years old) to young star clusters (a few hundred million years old). The study of such binary stars allows us to determine precisely the masses of the stars at different evolutionary stages. Thus, the E-ELT will reveal the evolution of sub-stellar mass objects, supporting its work on exoplanets and



Free-floating planetary-mass objects, like the "planemo" twins Oph 1622, put forward some of the most intriguing questions about low-mass star and planet formation.



Nucleocosmochronometry allows precise measurements of stellar ages, as in the case of the Milky Way star HE 1523-0901.

bringing us closer to a full understanding of the evolution of planets and stars over the full mass spectrum.

Violent deaths and their consequences

At the high-mass end of the range of stellar properties, the most spectacular events are undoubtedly the deaths of stars of eight or more solar masses in stellar explosions. These supernova events seeded the early Universe with heavy chemical elements by ejecting, among others, carbon, oxygen and iron into the interstellar medium. These elements not only critically influenced the formation of stars and galaxies, but also were ultimately necessary for the later evolution of life. Supernova explosions are also some of the most luminous events in the Universe. As such, they can be used out to great distances as signposts of the evolution of the Universe.

Gamma-ray bursts have been one of the most enigmatic phenomena in astronomy since their discovery in the 1960s, until they were recently successfully associated with the formation of stellar-mass black holes and highly collimated supernovae at high redshift. Gamma-ray bursts are the most energetic explosions observed in the Universe and currently among the competitors for the record holders as the furthest object observed. The collecting power of the E-ELT will allow us to use them as distant lighthouses, shining through billions of years of evolution of the Universe, similar to the way that quasars have previously been used as remote beacons. Gamma-ray bursts have a few advantages: with the E-ELT, they can be detected at redshifts beyond 7 to 15, taking scientists into the largely unknown epoch of the reionisation of the Universe; and since they fade away, they allow us to study the emission components of previously detected absorption line systems. Gamma-ray bursts represent one more route for the E-ELT to study the Dark Ages of the Universe.

This supernova has been associated with a gamma-ray burst. The E-ELT will explore such events up to a redshift of 15.

The E-ELT will be able to study supernova explosions in exquisite detail. Similar to gamma-ray bursts, supernova explosions can be used as cosmic probes. Indeed, supernovae provide the most direct evidence to date for the accelerating expansion of the Universe and hence for the existence of a dark energy driving this acceleration. With the current combination of 8-metre-class ground-based telescopes and the Hubble Space Telescope, supernova searches can reach back to only around half the age of the Universe. Infrared spectroscopy with the E-ELT combined with imaging from the upcoming James Webb Space Telescope will allow us to extend the search for supernovae to redshifts beyond 4, a look-back time of nearly 90% of the age of the Universe! Supernova studies with the E-ELT will thus critically contribute to the characterisation of the nature of dark energy and the investigation of the cosmic expansion at early epochs.

The Stellar Content of Galaxies

Galaxies are the main building blocks of the visible large-scale structure of the Universe. The galaxies themselves are made up of billions of stars of all ages and chemical compositions. When astronomers study the light of a galaxy, they are observing the diffuse light emitted by all the individual stars in the galaxy. To make significant progress in our understanding of structure formation in the Universe, i.e. of galaxy formation and evolution, many of the individual stars in these distant galaxies need to be analysed. In this regard, the E-ELT is again an unprecedented facility.

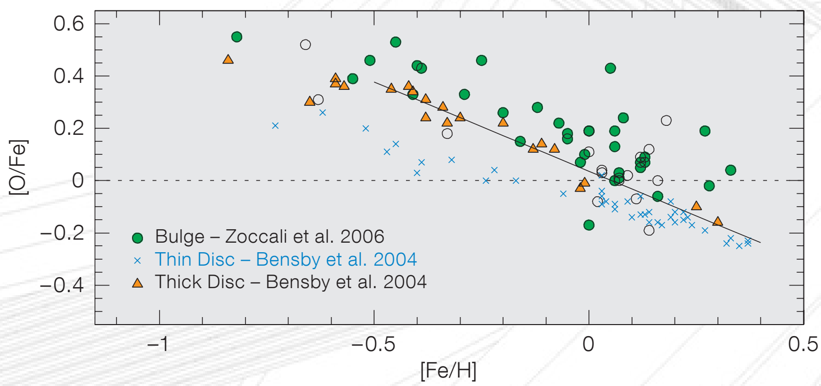
The most plausible current theory for galaxy formation is the hierarchical assembly model, in which all galaxies are built up from smaller pieces. This theory has been extensively explored by numerical simulations as a theoretical experiment, and tested against the global characteristics of galaxy populations, but not against the detailed properties of individual galaxies. The ultimate test of this model is to compare predictions of the stellar content of galaxies to what we actually see in galaxies of all types, spirals, giant ellipticals, irregular and dwarf galaxies.

Star formation throughout the Universe

The billions of individual stars that make up a galaxy carry information about the formation and subsequent evolution of their host, but only if we can study the stars individually. If we can measure the amounts of the different chemical elements in stars as a tracer of their ages and origins, and combine such information with the current motions of these stars, we can begin to unravel the complex formation history of the galaxy. For instance, the first generation of stars contains very low abundances of the heavier elements like iron and oxygen. As supernovae explode and enrich the interstellar medium out of which the next generation of star forms, subsequent generations will contain more of these elements. By measuring the content of such trace elements in the stars, we can determine how many stars formed where and when and thus extract the star formation history of the galaxy. Current telescopes can only resolve individual stars for the nearest few large galaxies, which has already yielded interesting results, but does not allow us to draw any general conclusions about galaxy formation.

By contrast, the E-ELT will allow the method to be applied to some thousands of galaxies across a more representative slice of the Universe, allowing us to compare the stellar contents of galaxies of all types for the first time and to draw the first general conclusions about their formation histories.

Left: Panorama of the Milky Way.



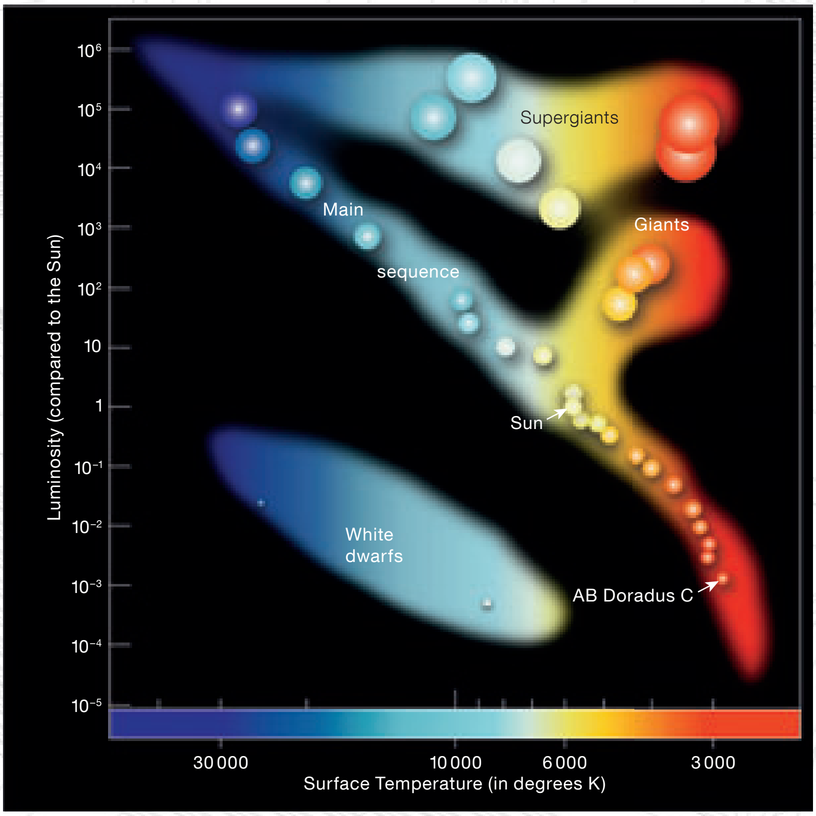
The metal content of stars reveals valuable information about the star formation history of galaxies throughout the Universe. This figure uncovers the different formation timescales of the various components of the Milky Way.

Colours and luminosities of individual stars out to nearby galaxy clusters

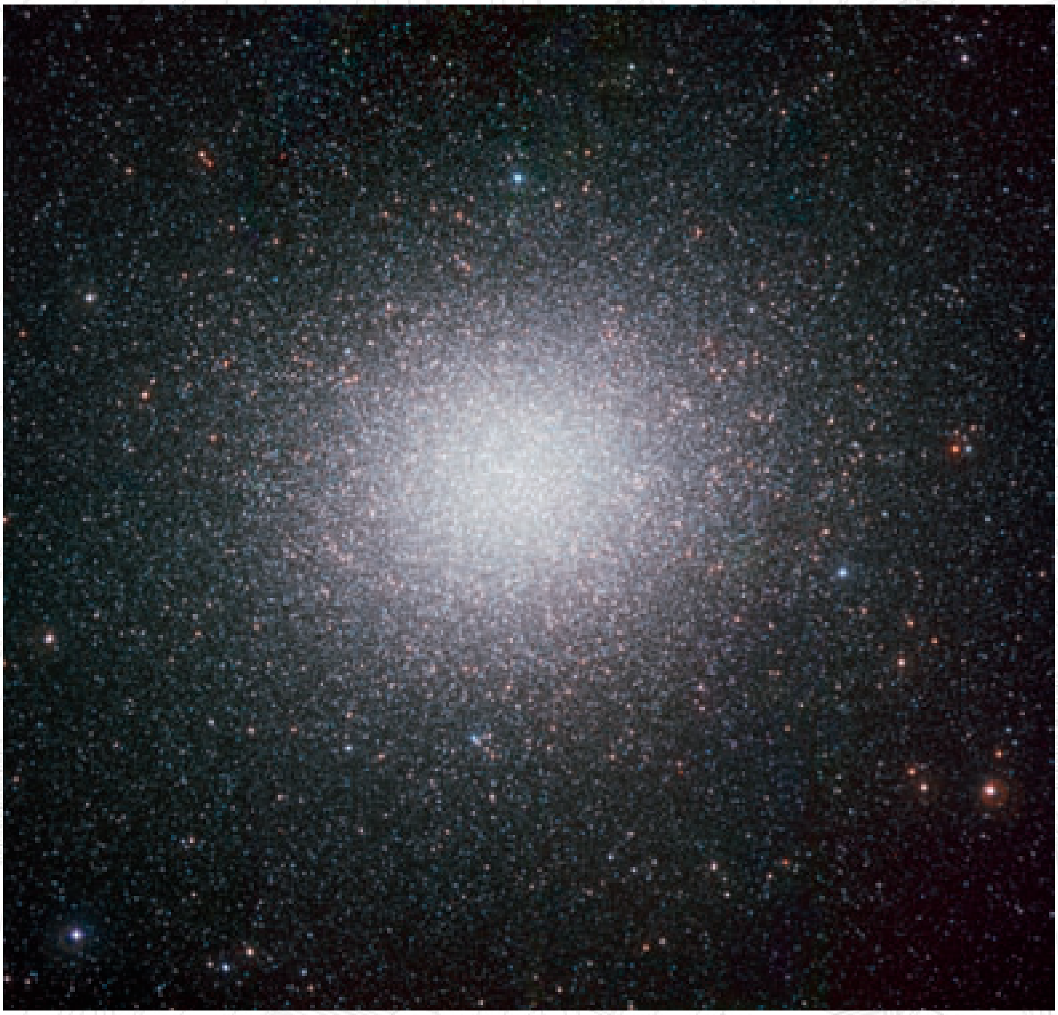
Pushing out a little further in distance, the nearest galaxy clusters, located at a distance of about 60 million light-years, are prime targets for the E-ELT. These clusters, containing thousands of galaxies packed in close proximity, are believed to have evolved very differently from the more sparsely distributed "field galaxies". Even at these distances, the E-ELT will be able to resolve the individual stars, and study their basic properties, such as colour and luminosity, to obtain a measure of their ages and heavy element content. Within individual galaxies, it will be possible to see whether the star formation history varies with position, as might be expected if star formation continues in the inner parts of the apparently quiescent galaxies that populate these clusters, and such measurements can then be compared with what we find in the sparser non-cluster environments, to see how a galaxy's surroundings affect its star formation history.

The stellar initial mass function

The study of individual stars in nearby and distant galaxies not only reveals the history of their host, but is also crucial for our understanding of fundamental star formation and stellar evolution. The predominant factor determining the evolution of a star is its initial mass. The initial mass function — how many stars there are of different masses — is a key ingredient in all



The evolutionary stage of a star can be deduced from its colour and luminosity. The E-ELT will be able to use this diagnostic method out to the nearest galaxy clusters.



The E-ELT will be able to resolve individual stars in galaxies, very much in the same way as the VLT does for the galactic globular cluster Omega Centauri, but at a much greater distance.

interpretations of stellar populations. However, the relative fraction of low-mass stars remains unknown due to the limited abilities of current telescopes to detect low-mass, very faint stars even in the closest galaxies. With its unprecedented sensitivity, the E-ELT will be able to detect these low-mass stars in star-forming regions of the Milky Way and even in other galaxies. Any variation in the initial mass function with environment is an extremely important physical parameter for a wide variety of astrophysical investigations. The E-ELT will allow us to resolve this issue by, for the first time, providing us with observations of these lowest-mass stars in a representative range of astrophysical environments.

The E-ELT will expand the portion of the Universe resolvable into stars by a factor of more than ten. It will allow scientists to obtain accurate knowledge of the present-day stellar populations in galaxies out to nearby galaxy clusters. It will return a comprehensive picture of galaxy formation and evolution through a detailed study of stellar populations in nearby galaxies and provide the most stringent tests to date for current theories of galaxy formation and evolution.

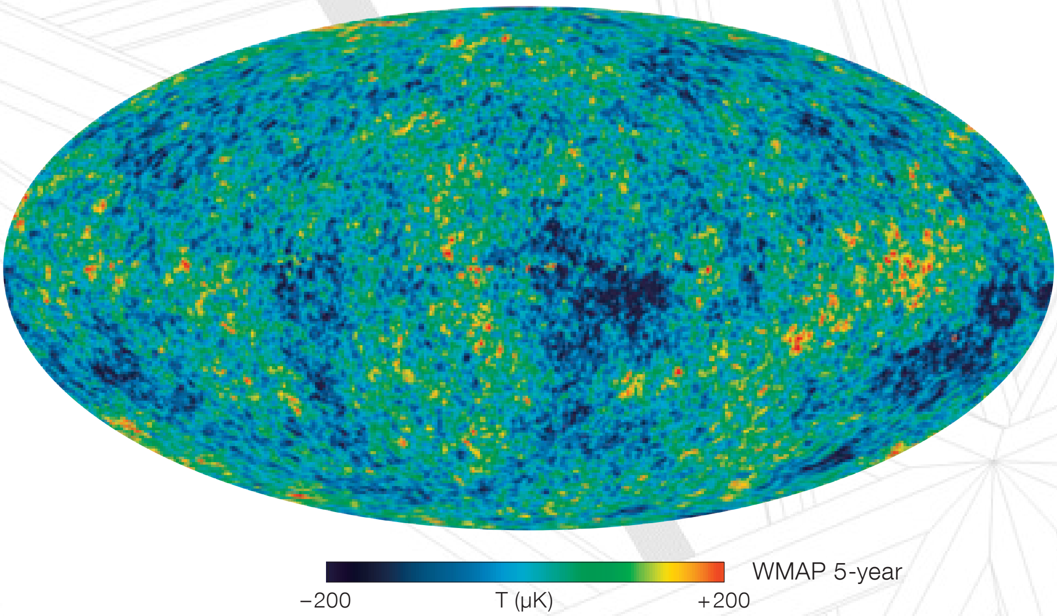
The End of the Dark Ages – First Stars and the Seeds of Galaxies

What was the nature of the first object to shine through the Universe? How did the gas, dust, heavy elements and stars build up? What caused the reionisation of the Universe? Were the first galaxies fundamentally different from present ones? The E-ELT is the key to establishing the physics of the first light-emitting objects in the Universe.

Over the last decade significant progress in determining the processes of galaxy evolution has been made using the combined power of current ground-based telescopes and the Hubble Space Telescope. The limits of the observable Universe have been pushed to a redshift of 6, which corresponds to looking back over about 90% of the age of the Universe. The global star formation activity from that epoch to the present day has been estimated, and first insights into the stellar mass assembly history out to a redshift of 3 have been acquired. However, the most uncertain issue in present day cosmology remains how and when galaxies assembled across cosmic time.

The current cosmological model gives a credible explanation of the formation of structures in the Universe through the hierarchical assembly of dark matter halos. In contrast, very little is known about the physics of formation and evolution of the baryonic component of gas and stars, because the conversion of baryons into stars is a complex and poorly understood process. As a result, all advances in understanding galaxy formation and evolution over the last decade have been essentially empirical, often based on simplified phenomenological models. Cornerstone parameters in this empirical framework are the total and stellar masses of galaxies, together with their physical properties. They include detailed knowledge about the ages and metallicities of the underlying stellar populations, dust extinction, star formation rates and morphological parameters. The study of well-established scaling relations involving a number of these physical parameters, such as those between mass and heavy element abundance, or galaxy morphology and the density of the surrounding environment, are essential for understanding the physical processes that drive galaxy evolution.

Left: Image in visible light of the Chandra Deep Field South. The synergy between X-ray and optical spectroscopy has led to the discovery of some of the most distant quasars known.



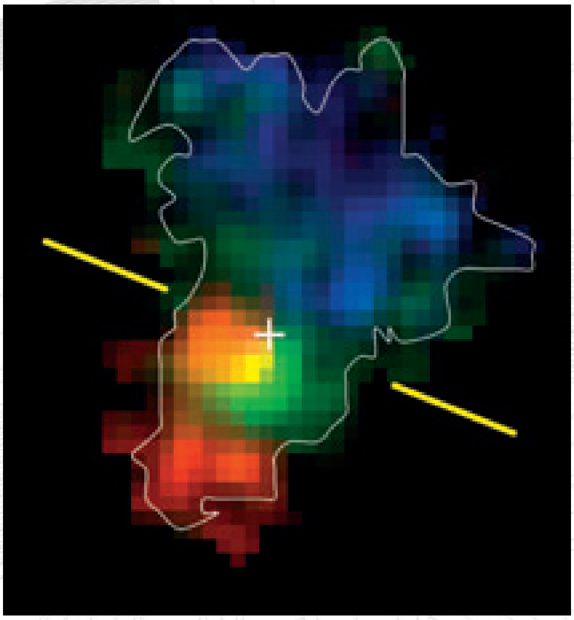
Map of the residual temperature fluctuations, imprinted on the cosmic microwave background by the earliest growth of structures in the Universe.

With the current generation of telescopes, we have been able to study these telltale correlations between the properties of galaxies over a wide range of masses in the nearby Universe. However, only the brightest or most massive galaxies have been accessible at redshifts larger than one, and a direct measurement of masses has been almost completely out of reach at redshifts larger than two. Thus, our ability to explore the evolution and origin of these scaling relations has rapidly reached the limits of current technology telescopes, and will only be advanced in the era of the E-ELT.

Observations beyond the limit

High spatial resolution, diffraction-limited imaging and spectroscopy with the E-ELT will provide invaluable information about the morphology, dynamical state and variations in physical parameters across galaxies over large cosmological timescales. With these in hand, our knowledge of galaxy evolution will make a giant leap forward. Pushing the limits of the observable Universe beyond redshift of 6 by detecting the first ultraviolet-emitting sources will allow us to probe the era a few hundred million years right at the end of the Dark Ages, when the first light-emitting objects, which ionised much of the content of the Universe, switched on.

Questions still to be answered are whether galaxies caused this reionisation, and whether they were then similar to the relatively normal galaxies that we see at somewhat lower redshifts, or whether they were fundamentally different. Direct kinematics of the stars and gas in the first generation of massive galaxies, obtainable with the unprecedented spatial resolution of the E-ELT, will be used to draw a consistent picture of the mass assembly and star formation of galaxies across the entire history of the Universe.



Snapshot of the evolution of a rotating galaxy, when the Universe was three billion years old. The E-ELT is expected to yield such velocity maps of galaxies at much earlier look-back times.

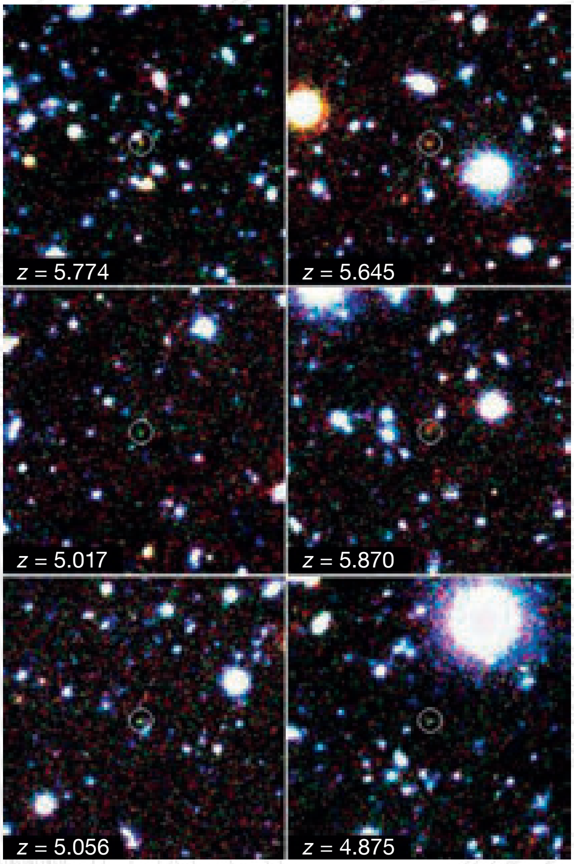
Peering through the dust

With E-ELT's enhanced sensitivity in the near-infrared, it will be possible to derive dust extinction maps from intensity ratios of hydrogen Balmer lines over a variety of redshifts. Star formation rates will be derived from the extinction-corrected emission line luminosities, using suitable diagnostic emission lines. These results will be combined with other indicators coming from multi-wavelength observations to produce a truly definitive measure of the star formation histories of galaxies of different types.

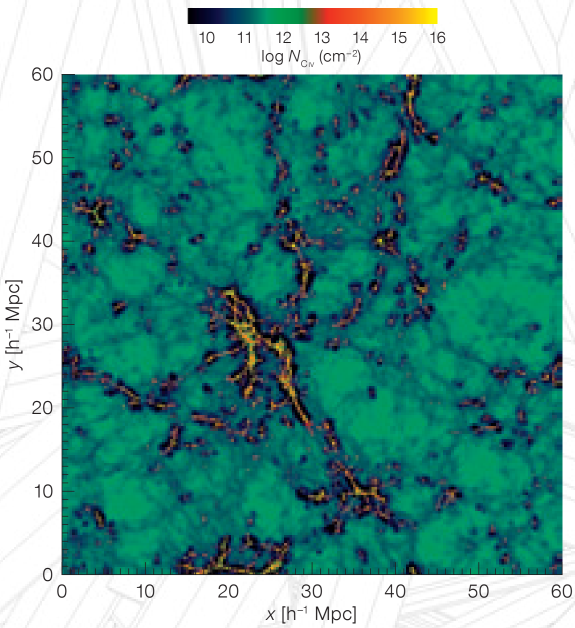
Detailed knowledge of star formation across all cosmic epochs will allow us to explore how the star formation histories of galaxies depend on the environment in which they find themselves. Thus, the migration of the peak efficiency of star formation rate from high to low masses as galaxies evolve, known as the "downsizing effect", will be studied through the epochs when the effect is believed to have occurred.

The intergalactic medium

A key to further progress is a better understanding of the complex interplay between galaxies and the surrounding intergalactic medium. The intergalactic medium provides the reservoir of gas for the ongoing infall of fresh material into galaxies. At the same time, it acts as a repository for the gas driven out of galaxies by energetic processes such as active galactic nuclei and supernovae. The combination of



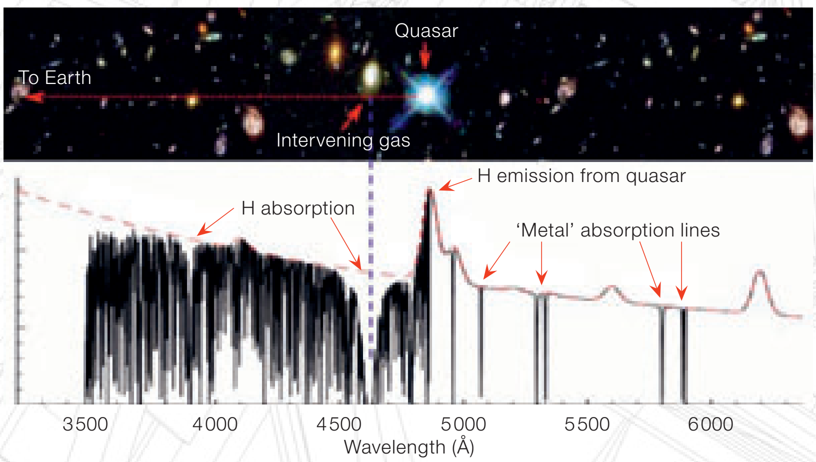
A close look at some of the most distant galaxies known.



The cosmic web of filaments and sheets at redshift 3 as simulated using the hydrodynamical code GADGET-2. Here, the predicted C IV column density is shown.

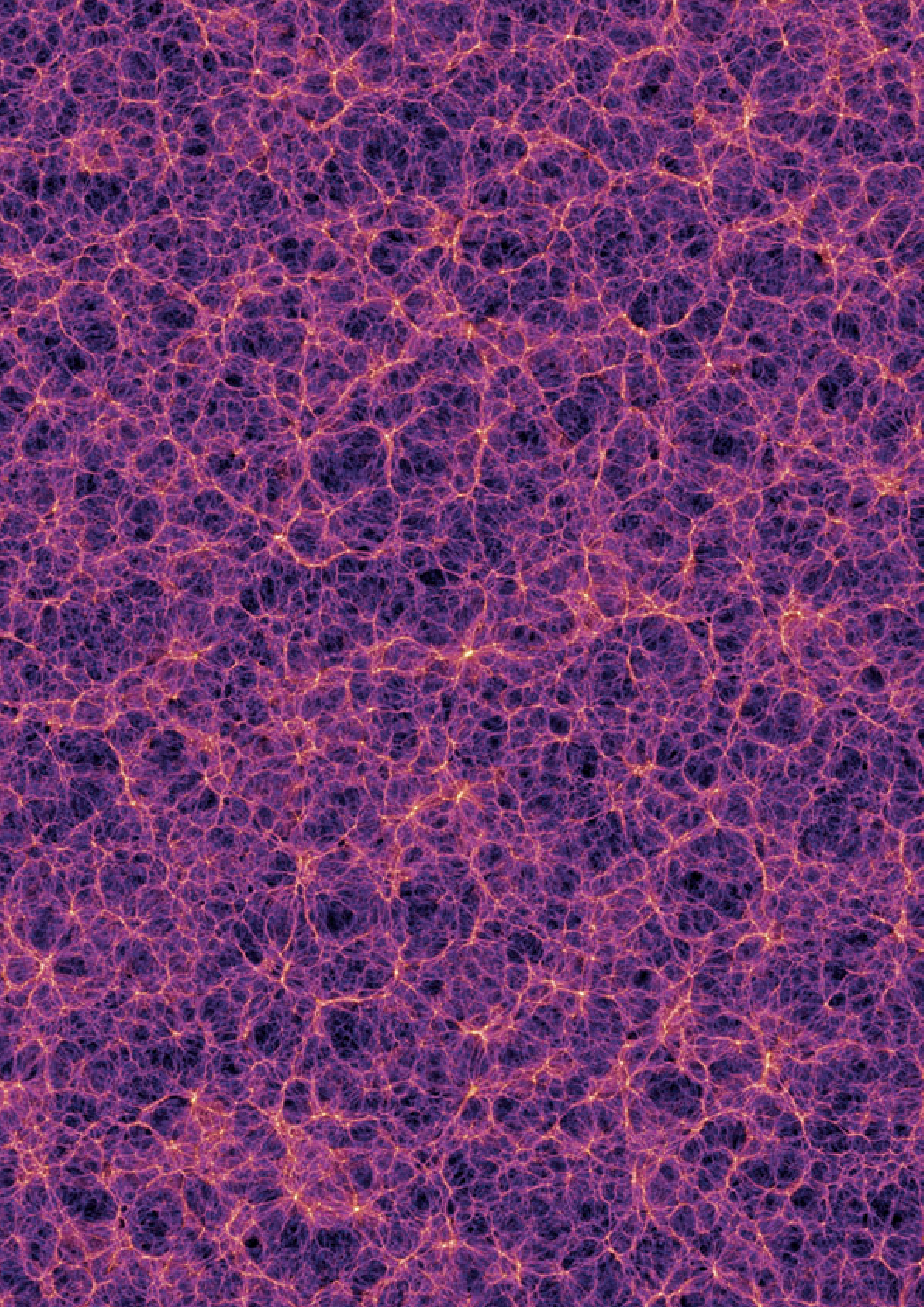
these processes is responsible for the regulation of the gas supply, which ultimately dictates star formation and black hole growth as well as the chemical and structural evolution of galaxies. Heavy elements play a very important role for most, if not all, aspects of the complex lifecycle of gas in galaxies and the intergalactic medium. Measuring the widths of the absorption lines of triply ionised carbon, C IV, is a powerful tool for studying this lifecycle. However, the intrinsically low column densities of C IV make this cardinal test very difficult with existing telescopes. With the E-ELT we will be able to use this and similar diagnostics to determine the properties of the intergalactic medium in galaxies of different types over a wide range of cosmic epochs, fully addressing the critical role that it has performed in shaping the galaxies that it was feeding.

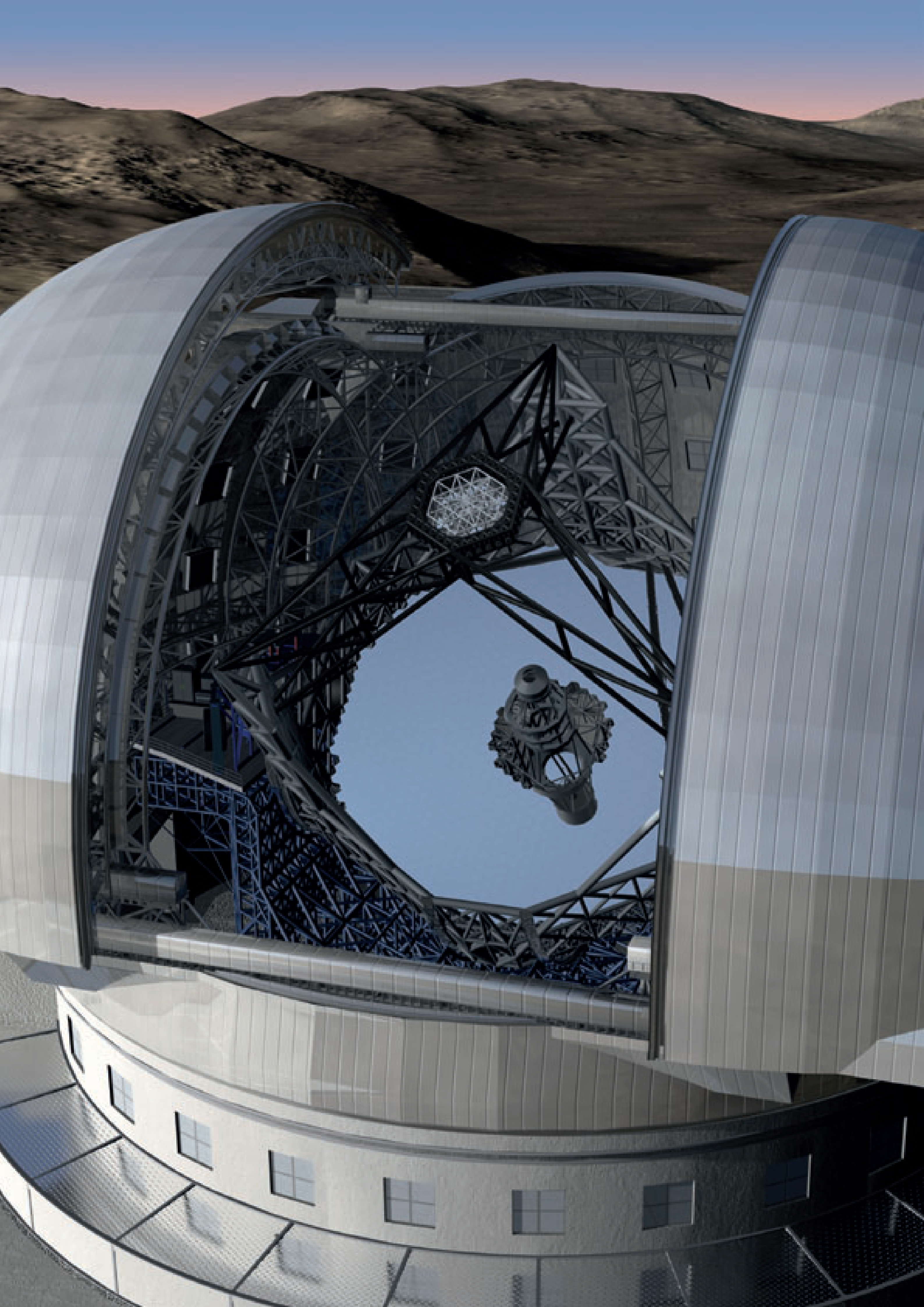
The E-ELT will directly probe the physical properties of galaxies as a function of their mass and environment for over 90% of the age of the Universe, which, for the first time, will cover the entire epoch over which these systems formed. With these additional observational inputs astronomers shall be able to directly determine many of the parameters currently assumed in models of galaxy formation.



A distant quasar is used as a beacon in the Universe. Galaxies and intergalactic material that lie between the quasar and us will reveal themselves by the features seen in the quasar spectrum.

Right: The large-scale structure of the Universe when it was one billion years old. Galaxies are formed in the densest dark matter regions.





The E-ELT: A Pillar in the Astronomical Landscape of 2020+

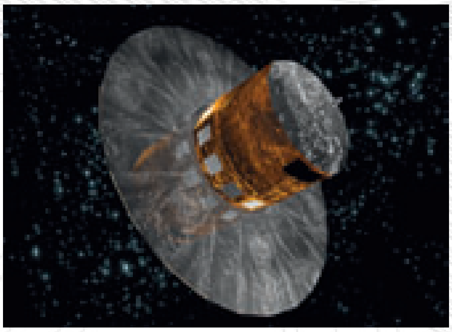
When the E-ELT starts operations a decade from now, astronomy will be in a golden era. By that time, a rich heritage will have been gathered from today's working facilities. In addition, new and ambitious facilities complementing the E-ELT will be deployed on the same timescale.

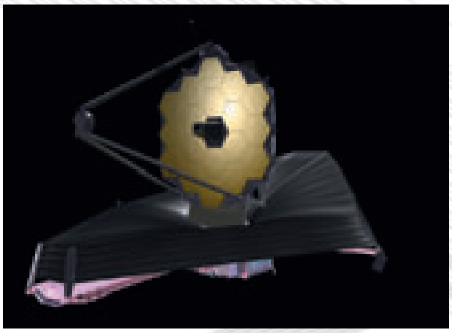
By 2020 observations with current telescopes will have led to a significant accumulation of knowledge and inevitably invited many new questions. Discoveries with ground-based telescopes such as ESO's Very Large Telescope (VLT) and its interferometer (VLTI), and other 8–10-metre class telescopes will have prepared the scene for further fascinating discoveries with the E-ELT. For example, it is expected that in the field of exoplanets, many candidates for E-ELT follow-up will have been identified, and the first galaxies emerging from the Dark Ages will have been tentatively identified and awaiting the E-ELT to be characterised and understood.

At the start of E-ELT operations, the Atacama Large Millimeter/submillimeter Array (ALMA) will have been exploring the cold Universe for a little less than a decade. A recent consultation of the ALMA and E-ELT communities revealed a wealth of synergies between these facilities: while ALMA will see the molecular gas in distant galaxies, the E-ELT will reveal the ionised gas — together ALMA and the E-ELT will revolutionise our understanding of star formation. Similarly, the two facilities will probe different regions in nearby protoplanetary discs, ideally complementing each other in exploring the early phases of planetary systems.

The VLT, located on Cerro Paranal in Chile, is the most advanced and efficient observatory in the world.

ALMA is the largest astronomical project in existence and will start observing the southern sky in 2011.





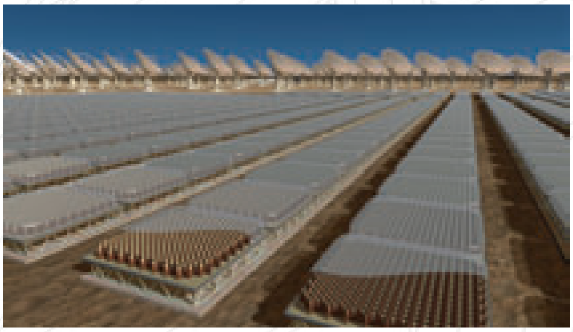
Several space observatories will work together with the E-ELT. Shown from left to right are Gaia, Kepler and Herschel. The James Webb Space Telescope (bottom) is expected to be launched in 2014.

The next decade will also see the advent of many survey telescopes. ESO's 2.6-metre VLT Survey Telescope (VST) and the 4.1-metre Visible and Infrared Survey Telescope for Astronomy (VISTA) will have been surveying the sky for a decade, supplemented by many similar facilities worldwide. These telescopes will be complemented by even more powerful survey facilities, such as the Pan-STARRS network and the 8-metre Large Synoptic Survey Telescope (LSST), which will ramp up towards the end of this decade. While much exciting science will come out of these surveys directly, a wealth of understanding will follow from more detailed follow-up observations of targets identified by such projects, and it will only be with the larger, more sophisticated E-ELT that such an understanding can be obtained.

Existing or soon-to-be-launched space telescopes such as Hubble, Spitzer, Chandra, XMM-Newton, Herschel, Planck, CoRoT, Kepler and Gaia will have been working for a number of years as the E-ELT starts operations. These missions will have produced a major legacy for the E-ELT to exploit. For example CoRoT and Kepler will reveal nearby exoplanets transiting making them perfect candidates for exoplanet atmosphere studies with the E-ELT. Gaia will have studied a billion stars in the Milky Way in detail, revealing rare jewels such as the first stars that can be followed up with nucleocosmochronometry with the E-ELT. Herschel, together with ALMA, will collect a sample of galaxies in the early Universe, awaiting the E-ELT to be resolved and analysed. The list goes on; it is only by using the amazing power of the E-ELT to understand the detailed physics of the objects discovered by these missions that the benefits from the huge investment in space technology will be fully realised.

An exciting scientific interplay can be foreseen between the E-ELT and Hubble's successor, the James Webb Space Telescope (JWST), the ambitious optical/infrared space observatory scheduled for launch in 2018. Indeed, just as the combination of 8–10-metre class telescopes and the Hubble offered two decades of discoveries, the E-ELT and JWST complement each other perfectly. The 6.5-metre JWST, unhindered by the atmosphere, will be able to obtain deeper images, in particular in the infrared, while the 40-metre-class E-ELT will have over six times higher spatial resolution and will be able to collect fifty times more photons for high resolution spectroscopy and studies of rapid time variability.

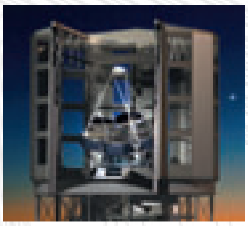
Finally, the plans for the Square Kilometre Array (SKA) could have it starting operations soon after the E-ELT. Despite the very different wavelength regimes, the cosmology science drivers of the E-ELT and SKA are remarkably complementary. Survey observations with the SKA are likely to follow-up on the studies of the fundamental constants and dark energy made with the E-ELT. In many other fields the SKA will probe the cold Universe, where the E-ELT can see the luminous one.

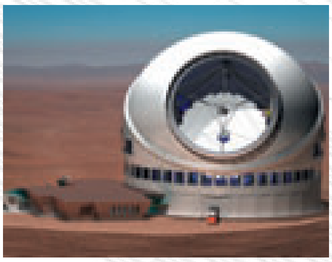


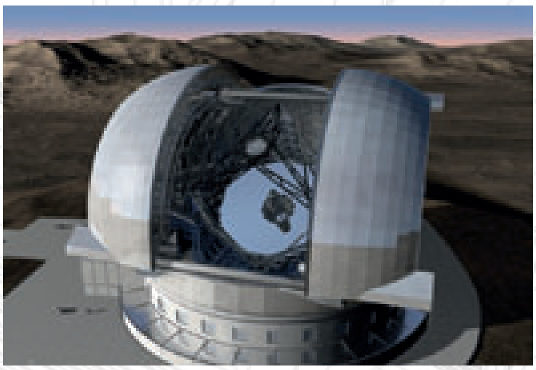
An artist's view of the planned Square Kilometre Array radio telescope.

In summary, the E-ELT will be built on the most solid foundations. In the coming decade enormous progress is expected from the many ground-based and space observatories. While the E-ELT will have a sharper eye and higher sensitivity than all of them, it will profit from their capabilities to observe at other wavelengths or wider areas of the sky. The synergy between all these facilities will enable the most fascinating discoveries with the E-ELT.

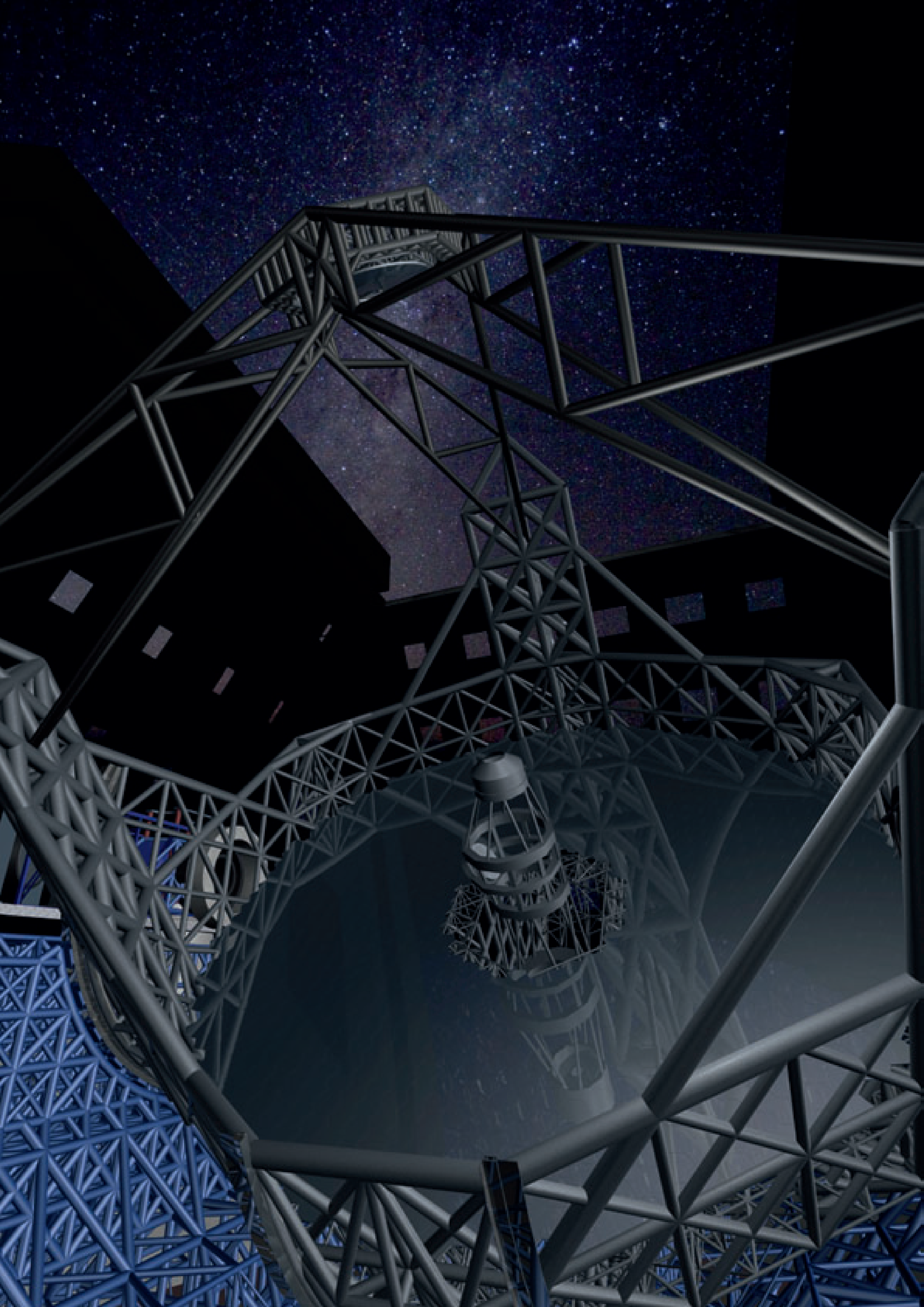
The E-ELT compared to other ELTs







GMT-project	TMT-project	E-ELT-project	
~24 m	~30 m	~40 m	Diameter
~400 m^2	~600 m^2	~1000 m^2	Collecting area
~9 mas	~7 mas	~5 mas	Diffraction limit at 1 μm

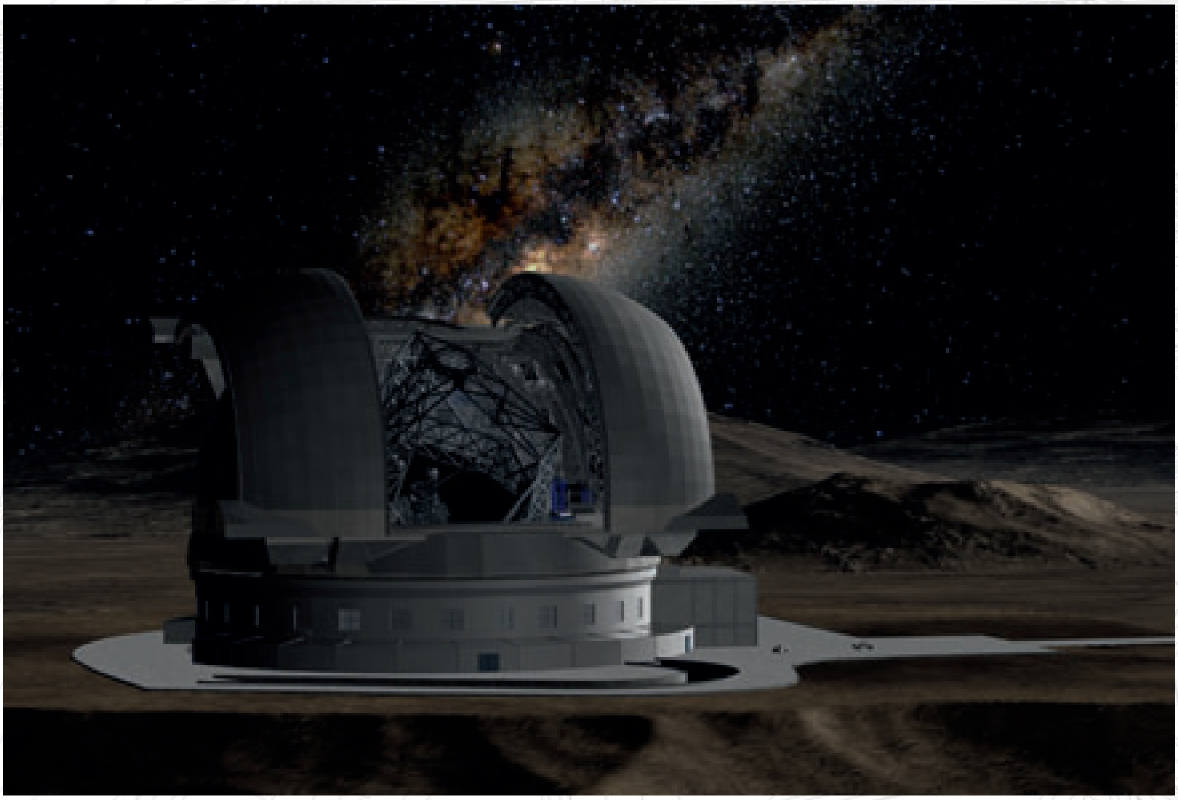


Discovery Potential — Expect the Unexpected!

The previous chapters presented the great scientific achievements to be anticipated with the E-ELT. These alone represent a giant leap in our understanding of the Universe and potentially the first step towards finding life beyond the Solar System. Yet, all previous telescopes have shown that, no matter how hard scientists have tried to predict the future, the greatest discoveries come as totally unexpected. Is this still possible in the case of the E-ELT?

The discovery potential of a telescope is, by definition, hard to quantify. However, astronomer Martin Harwit pointed out in his landmark book that one key indicator is the opening of a new parameter space: by looking somewhere where no one has been able to look before, one is very likely to make new discoveries. The E-ELT will open such new frontiers in at least three ways. First, the E-ELT will, thanks to its immense collecting power, increase the sensitivity of observations by up to a factor of 600. Furthermore, the E-ELT will increase the spatial resolution of images by an order of magnitude (even improving on the sharpness of future space telescopes). Finally, the E-ELT will open a new window on time resolution, enabling observation in the nanosecond regime. These leaps forward in what a telescope can do, coupled with other advances such as unprecedented spectral resolution, new abilities to study polarised light, and new levels of contrast allowing us to see the very faint next to the very bright, mean that we will open up an entire new universe of possibilities. It is in this great unknown that the ultimate excitement of the E-ELT lies.

Left: The E-ELT (artist's impression).



E-ELT — the most inspiring ground-based observatory project today (artist's impression).

Glossary

AGN — Active Galactic Nucleus: a compact region in the centre of a galaxy where luminosity is much higher than usual. It is believed that the radiation from an AGN is due to the accretion of mass by a supermassive black hole at the centre of the host galaxy.

ALMA — The Atacama Large Millimeter/submillimeter Array is the largest astronomical project in existence. ALMA is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. It is currently under construction at 5000 metres above sea level in northern Chile. Composed initially of 66 high precision millimetre and submillimetre antennas, it is expected to start scientific observations with a partial array as early as 2011.

Arcsecond — A unit of angular measurement, corresponding to 1/3600th of a degree.

AU — Astronomical Unit, the mean distance between the Sun and the Earth, or about 150 million kilometres.

Black hole — A region where a huge amount of matter is concentrated into a small space, and where the gravitational pull is so strong that even light cannot escape.

Damped Lyman-α system — Galaxies that host large amounts of neutral hydrogen gas and that are detected as they absorb the light from a background quasar.

E-ELT — The European Extremely Large Telescope, the world's largest optical/near-infrared telescope, with a diameter of ~40 m, to be built by ESO. First light is foreseen early in the next decade.

ESO — The European Southern Observatory, the foremost intergovernmental astronomy organisation in Europe and the world's most productive astronomical observatory. ESO provides state-of-the-art research facilities to astronomers and is supported by Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

Gaia — Space mission of the European Space Agency, whose goal is to precisely chart the positions, distances, movements of one billion stars in the Milky Way, and physically characterise them. To be launched in 2012.

GMT — The Giant Magellan Telescope is a project for the construction of an optical/near-infrared telescope, consisting of seven 8-metre mirrors, combined together to reach the resolving power of a 24.5-metre telescope. It is a collaboration between US, Australian and South Korean institutions. It is expected to start operations early in the next decade in the Chilean Andes.

HST — The Hubble Space Telescope, a joint project of NASA and the European Space Agency, is a 2.4-metre ultraviolet/optical/near-infrared telescope above the Earth's atmosphere. Launched in 1990.

JWST — The James Webb Space Telescope, a project for the next generation, is an optical/infrared-optimised space-based telescope with a 6.5-metre diameter primary mirror. It is scheduled for launch in 2018.

ΛCDM — Lambda–Cold Dark Matter model — often referred to as the concordance model — is the simplest model that currently matches best the observable facts about the evolution of the Universe. Lambda stands for the cosmological constant describing the dark energy, which is held responsible for the current accelerated expansion of the Universe.

LSST — Large Synoptic Survey Telescope, an 8.4–metre optical/near-infrared telescope to be built in the Chilean Andes through a US-based public–private partnership. First light is expected at the end of this decade. With its ability to cover the whole accessible sky twice per week, the data from the LSST will be used to create a 3D map of the Universe with unprecedented depth and detail.

mas — Milliarcsecond, 10^{-3} arcseconds.

μas — Microarcsecond, 10^{-6} arcseconds.

Parsec (pc) — A unit of distance, corresponding to about 31×10^{12} km or 3.26 light-years. It is defined as the distance from which the mean Earth–Sun distance is visible as 1 arcsecond on the sky.

Planetesimals — Solid objects formed during the accumulation of planets whose internal strength is dominated by self-gravity and whose orbital dynamics are not significantly affected by gas drag. This corresponds to objects larger than approximately 1 km in diameter in the solar nebula.

Redshift — A shift towards longer wavelengths of the spectrum of the light emitted by astronomical objects. It indicates the age of the Universe when the light was first emitted. A redshift of zero corresponds to the current epoch; a redshift of 5 to 12.5 billion years ago.

Reionisation — Occurred when the Universe was between 400 million and 1 billion years old. The neutral hydrogen then filling up space was ionised by the first light-emitting objects, making the Universe transparent to photons.

SKA — Square Kilometre Array, a proposed radio telescope project with a collecting area of one million square metres. It is expected to be completed during the next decade in the southern hemisphere.

Spitzer — An infrared, space-based 0.85-metre telescope launched by NASA in 2003. Most of the spectral window accessible to Spitzer is blocked by the Earth's atmosphere and cannot be observed from the ground.

TMT — Thirty Meter Telescope, a proposed 30-metre optical/near-infrared telescope on Mauna Kea, Hawaii (US) project, expected to see first light early in the next decade. The TMT is a collaboration of Caltech, the University of California (US), the Association of Canadian Universities for Research in Astronomy, and the National Astronomical Observatory of Japan.

VISTA — A 4.1-metre-wide field survey telescope, equipped with a near infrared camera. Built by a consortium of UK institutions for ESO, it is installed at the Paranal Observatory and started operations in 2010.

VLT — Very Large Telescope, currently the world's leading astronomical observatory. Operated by ESO and located in the Chilean Andes at Paranal, it comprises four 8.2-metre optical/infrared telescopes.

VLTI — The Very Large Telescope Interferometer is able to combine, in twos or threes and, in the future, in fours, the light from the four 8.2-metre Unit Telescopes of the VLT, or from four 1.8-metre mobile Auxiliary Telescopes.

VST — The VLT Survey Telescope is a state-of-the-art 2.6-metre telescope equipped with OmegaCAM, a monster 268 megapixel CCD camera with a field of view four times the area of the full Moon.

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