Guide to the European Extremely Large Telescope (E-ELT)

The E-ELT is going to be the world's largest telescope operating from the visible- to infrared range and is being built by the European Southern Observatory (ESO, www.eso.org). Following are some brief notes on the E-ELT, including the UK involvement with the instrument programme. These notes are by no means complete, for more information please refer to www.eso.org/E-ELT.

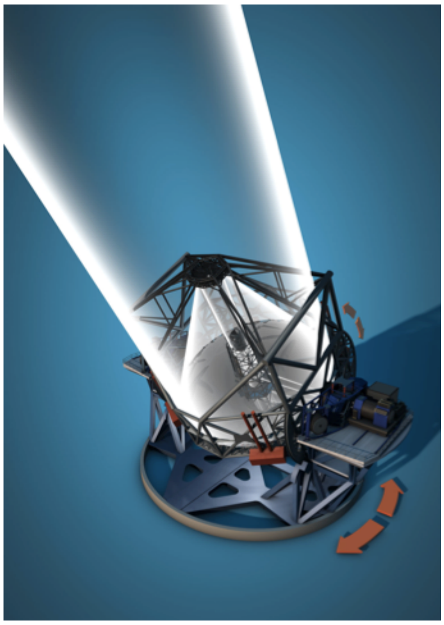


Figure 1: The E-ELT (Image credit: ESO http://www.eso.org/public/images/elt-illustration-5k-potw/)

Primary Mirror

The E-ELT is a reflector telescope with a large primary mirror (39.3m diameter) that will be capable of collecting more light than all large (4m and bigger) telescopes that are currently in operation put together. The **primary mirror** has a collecting area of 978 square metres, 1 tenth of a hectare, or about 1 seventh of a rugby field.

This mammoth mirror is built up using 798 hexagonal mirrors that are each 1.4m across and 5cm thick. A collaboration between UK Industry and Universities is making prototype mirror segments using the world's largest mirror polishing machine.

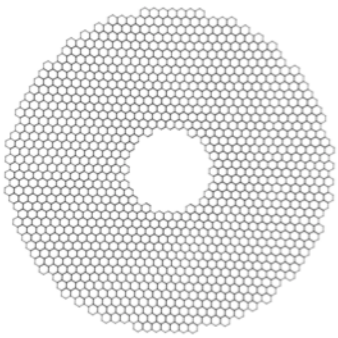


Figure 2: The E-ELT Primary Mirror (Image credit: ESO http://www.eso.org/public/images/segmented-mirror/)

To the left you see a representation of how the mirrors will be tessellated to form the continuous mirror surface. An impression of the telescope (without its protective dome) is on the left showing the continuous mirror surface made up of the segments sitting in the overall structure of the telescope.

Behind each 1.4m hexagonal mirror is a set of motors that can slightly distort the surface of each mirror. The purpose of this is to maintain the shape of the overall primary mirror whichever part of the sky the telescope is pointing to. The three blue tubes you see behind the hexagonal segment are the "pistons" or actuators that deform each segment into shape. The overall shape of the primary mirror is curved (parabolic). A 3D rendering of the E-ELT without its dome is shown below with a zoomed in view of the structure that will support it.

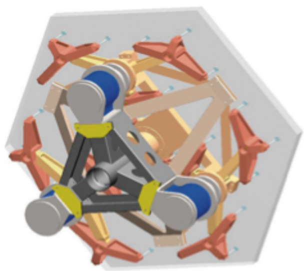


Figure 3: E-ELT Mirror Segment Assemblies (Image credit: ESO http://www.eso.org/public/images/e-elt_m1subcell/)

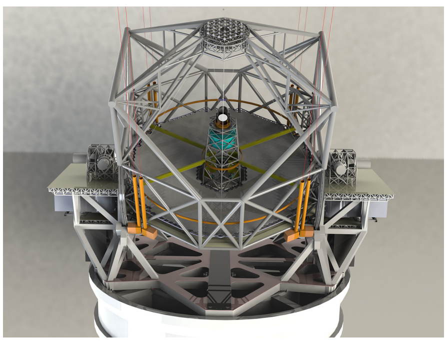


Figure 4: E-ELT 3D rendering showing the telescope without its enclosure. The parabolic segmented primary mirror can be seen. Image credit: ESO http://www.eso.org/public/images/rendering_e-elt_02/

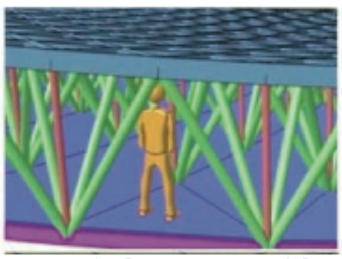


Figure 5: Close up view of the support structure of the primary mirror. Image credit: ESO Construction Proposal

The E-ELT in a multiwavelength context

The telescope and its instruments (see next section) will be able to record data in the visible, near- and mid-infrared range of the electromagnetic spectrum. In particular, the coating of the primary mirror will likely be a silver compound that has best reflectivity performance over this entire wide wavelength range. The E-ELT, together with forthcoming facilities such as the Atacama Large Millimetre Array (millimetre) and the Square Kilometer Array (radio) work in wavelength ranges where the transmission through the atmosphere is good (see below). Together this combination of instruments, with other space-borne facilities such as the James Webb Space Telescope (infrared 2-30μm), can give us a complete multiwavelength view of celestial objects. We can learn more about how much light they emit over all wavelengths, and determine their nature.

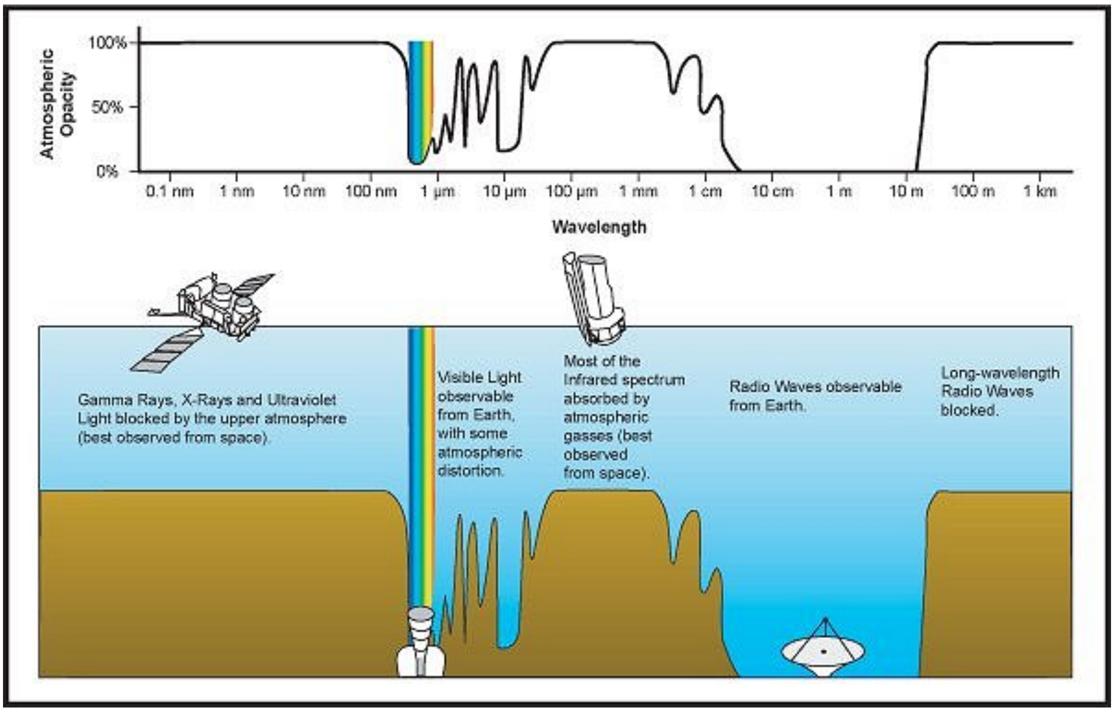


Figure 6: Electromagnetic Spectrum (from School's Wikipedia http://schools-wikipedia.org/wp/t/Telescope.htm)

Where will the E-ELT be sited?

After a long-term monitoring project of 7 international sites, Cerro Armazones, a 3000m peak in the Atacama Desert in Chile, was selected to be the site of the E-ELT. Cerro Armazones is a *high and dry* site providing excellent observing conditions. This site in the arid desert has very stable weather, it is cloudless for 320 nights a year and has very low water vapour (large amounts of water vapour can absorb some of the light from astronomical objects particularly in the mid-infrared). Cerro Armazones is located within 20km of ESOs exisiting Paranal Observatory where the Very Large Telescopes (8.2m) and the UK-built VISTA telescopes are sited. This allows infrastructure to be shared between the two sites thereby reducing cost.

In October 2011, ESO and Chile signed an agreement that outlines the support from the Chilean Government for the E-ELT and includes the donation of 189 square km of land, as well as a long-term (50 year) concession to establish a protected area around the site. Chilean astronomers will receive a 10% share in the E-ELT observing time in return for the Chilean Government's commitment to support infrastructure.The full announcement is available at http://www.eso.org/public/news/eso1139/

Figure 1: Aerial view of Cerro Paranal (foreground, see white telescopes in foreground right) and Cerro Armazones peak (back left), Chile. Image credit: ESO/M. Tarenghi (http://www.eso.org/public/images/eso1018d/)

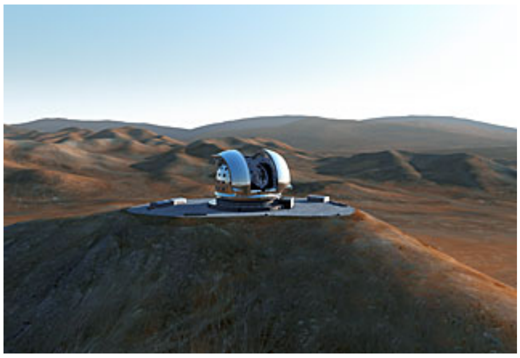


Figure 2: Artist's Impression of the E-ELT on Cerro Armazones (Image credit: ESO http://www.eso.org/public/images/eso1139e/)

The effect of the Earth's Atmosphere and Adaptive Optics

Turbulence in the atmosphere causes the images of stars and planets to be distorted i.e. Stars "twinkle" or flicker and move around. You can see the same effect when one looks to a distant object on a hot day or looking at a pattern on the bottom of a swimming pool through the water, the objects/patterns appear to "wobble". Atmospheric turbulence causes the images we record at telescopes to be blurred. This blurring means we cannot recover as much spatial detail as the telescope can technically deliver. In the absence of atmospheric turbulence, the scale of the detail that can be seen is inversely related to the size of the primary mirror, so in principle the bigger the mirror the finer the detail we can resolve. Thus, with the world's largest primary mirror, the E-ELT has the potential to deliver images of the highest spatial resolution than any other visible/IR telescope if we can overcome the blurring due to atmosperic turbulence

Adaptive optics is the technique used to mitigate the effects of atmospheric turbulence on astronomical images. It is already being successfully used on some of the world's largest telescopes. The E-ELT has a revolutionary design has specialist adaptive optics hardware as an integral part of the telescope design from the outset. This, together with real-time software processing, means the E-ELT has the capability to deliver images as detailed as the size of the primary mirror will allow, in the stable weather conditions.

The integration of adaptive optics hardware components in the telescope design is a unique feature of the E-ELT. One of these components is called an adaptive mirror that has a high density of motors behind it that deform the suface of the mirror at very fast speed. The adaptive mirror can mimic a mirror image of the turbulence on its surface thereby effectively cancelling out the effect of the atmosphere on the images received. This is done by monitoring images of real stars and artificial stars (produced by a laser) that show the effect of the atmosphere in real time. ESO has recently awarded a contract for the E-ELT adaptive mirror design study (www.eso.org/public/announcements/ann12032) to the *Ad*Optica consortium from Italy.

Adaptive Optics allows us to obtain the best possible spatial detail from the telescope. The E-ELT will deliver images that are 15 times sharper than those made with the Hubble Space Telescope. This sharpening means that more light is focussed on fewer pixels on a detector and makes our observations more sensitive so that we can look at fainter stars, galaxies and planets in the Universe.

UK & Adaptive Optics for the E-ELT

The UK is a major partner in the R&D study for a new type of adaptive optics that is currently being tested with a prototype on the William Herschel Telescope in La Palma, Canary Islands. The CANARY system is lead in the UK by Richard Myers at the University of Durham (http://www.dur.ac.uk/cfai/projects/canary/).

Current adaptive optics systems in operation can correct for the blurring caused by the atmosphere over relatively small areas or fields of view. CANARY is designed to correct a **wide field of view** using a combination of stars and laser guide stars spread across and around the field of view. This type of adaptive optics system (multi-object adaptive optics, or MOAO) has never been implemented in any astronomical telescope. Therefore the CANARY system is an important test-bed for MOAO and the team are already delivering very promising results
http://www.obspm.fr/actual/nouvelle/dec10/canary.en.shtml
http://www.ing.iac.es/PR/press/canary.html

For more information on wide field adaptive optics systems, please see
http://www.dur.ac.uk/cfai/projects/canary/wfao/

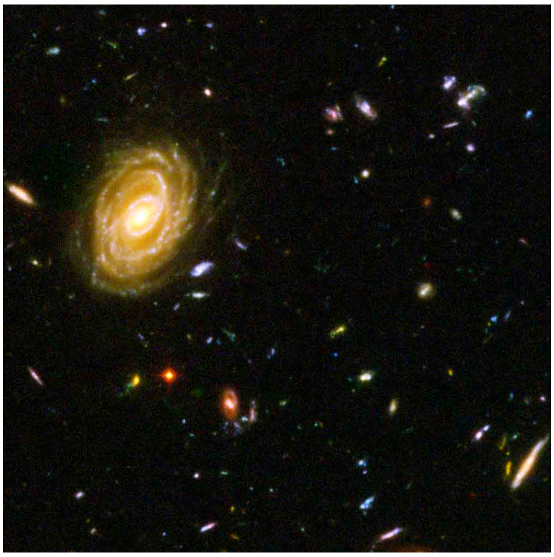
Instruments: The "Eyes" of the telescope

The large primary mirror of the E-ELT collects 15 times more light than the largest telescope currently in operation, allowing us to probe deeper into the Universe. We will be able to detect the faintest stars in the Milky Way, all the way through the Universe to the first stars and galaxies that formed soon after the Big Bang. *But how do astronomers record this light?* The earliest astronomical observations with the naked eye or through the eyepiece of a telescope were captured in sketches and notes, followed by photography in the 19th and early 20th century. Through tremendous technological advances in the last 40 years, we are now able to capture & preserve images digitally on a detector, similar to what a digital camera does. Modern telescopes therefore have a set of instruments that record the light collected from the night sky. These "instruments" are effectively the eyes of the telescope.

What types of instruments are there?

There are three main types of data that we can obtain from astronomical observations – imaging just as your camera takes digital photographs, and spectroscopy where "white" light is split by wavelength and polarimetry where the direction of the light is measured. The E-ELT will have capability in all three modes. The UK's involvement with instrumentation for the E-ELT is focussed primarily on spectroscopy, therefore the subsequent text focuses on that.

Spectrographs take incoming light (of mixed wavelengths) and split the light into different colours; this is what water droplets in the atmosphere do to light from the sun to produce a rainbow. In the same way, the light incoming to a telescope from distant stars and galaxies is sent to a spectrograph that splits this light into different wavelengths to produce a spectrum. The finer the wavelength slices or bins the higher the spectral resolution. A great deal of information can be gleaned from spectra such as, distinguishing different types of stars and galaxies, finding what chemicals and elements are present in these objects, and determining how far away objects are from us.



Just as your eyes, TV and cameras have colour channels, "white light" can be split into colours using filters. We do the same with astronomical cameras using a wide range of filters – this can be thought of as a type of very low-resolution spectroscopy – it allows us to determine the colours of celestial objects. For example, whether a star is blue (typically young) or red (typically old and/or contains cosmic dust). This multi-colour imaging allows information to be obtained for every object in a patch of sky or field, and one finds many different kinds of objects. Here you see a picture of a part of the sky observed with the Hubble Space Telescope (part of the Hubble Ultra Deep Field). There are lots of different objects with different shapes and colours. These are mostly galaxies in the distant universe. Things that are typically red are older galaxies; bluer galaxies are younger with stars being recently born. Such images allow us to obtain information on a large amount of objects simultaneously but do not reveal as much information about the sources as we would obtain from spectroscopy. It would take prohibitively long to obtain spectra of all sources seen in a given astronomical image; therefore we select individual sources, or samples of sources of which we want to obtain spectra.

There are many things we can learn from spectra. For example, with spectra of extra-solar planets we can determine the chemical composition of the planetary atmospheres, we can look for atmospheres such as our own, as well as find signatures of Carbon-based life and vegetation. Similarly when we take spectra of stars in the Milky Way, we can determine their chemical make-up and try to understand what evolutionary stage they are in and understand how they formed. Spectra of galaxies tell how old and far they are, how stars in these galaxies move and provide information on their history and formation. With the E-ELT we will be able to take spectra of galaxies in the very young Universe, soon after the Big Bang (only 500 million years later), and establish the nature of the first stars that formed when light in the Universe was effectively "switched on".

The Instrumentation Roadmap for the E-ELT

Over 2008-2010 various teams across Europe put together 8 instrument concepts to meet a range of capabilities for the E-ELT. The UK has been heavily involved with these studies with leading or key roles in 7 out of the 8 instrument concepts studied. In addition, the CANARY adaptive optics demonstration system described above is a key parallel UK instrumentation activity. UK astronomers have a long heritage in designing and building innovative astronomical instruments. In particular they are specialists in spectroscopy. Specialists from the UK Astronomy Technology Centre, the University of Oxford, University of Durham and the University of Cambridge are using their expertise to design instruments for the E-ELT.

Based on the phase A studies and the requirements for the instrument suite defined by the scientific goals of the E-ELT project, ESO has recently released a ten-year plan for the instruments that ESO will commission to be built by consortia spread over the ESO Member States. The plan is available at http://www.eso.org/sci/facilities/eelt/instrumentation/. These are technologically advanced, complex systems incorporating highly sensitive cameras and spectrographs.

ESO has named two instruments that will be available from the first-day the telescope will be used (commonly referred to as "first-light"). A third instrument will start being built one year after the first two. Overall, the roadmap comprises a suite of 7 instruments, I will briefly summarise these below. This suite of instruments is designed to have a range of capabilities that allow us to address the most exciting open questions in astrophysics and cosmology. But, because of the enormous leap in sensitivity coupled to the capabilities the instruments will provide, the most exciting prospect for the E-ELT is in fact the unexpected: the new discoveries and new questions its findings will open.

From first-light, the E-ELT will have an imaging camera, and an imaging spectrograph called ELT-CAM and ELT-IFU, respectively. In the design study phase the instrument consortia called their instruments concepts MICADO and HARMONI, respectively. Both instruments will operate in the visible to near infrared wavelengths.

ELT-CAM or MICADO lead by Professor Reinhard Genzel (Max-Planck Institute of Extraterrestrial Physics, Germany) is the E-ELT's high performance camera (http://www.mpe.mpg.de/ir/instruments/micado/micado.php?lang=de). Using the telescope's adaptive optics system, it will deliver the sharpest images the E-ELT can provide revealing the detailed structure of many different kinds of astronomical objects. By using filters, we can measure the colours of any astronomical object allowing us to discern the nature of different emitting regions within them.

ELT-IFU or HARMONI lead by Professor Niranjan Thatte (University of Oxford) is an imaging spectrograph or integral field spectrograph that will observe all kinds of astronomical objects including planetary systems, individual and groups of stars and galaxies (http://astroweb1.physics.ox.ac.uk/instr/HARMONI/). **Integral field spectroscopy** is a special kind of spectroscopy that combines imaging and spectroscopy, to produce a spectrum for every pixel in an image simultaneously. This is a key technique that is used in the E-ELT instrumentation suite, and one where British scientists and engineers have world-leading expertise. Such spectroscopy can provide a lot more information on the nature of the objects it observes over the entire extent of the object in a more efficient means than traditional spectroscopy. Like MICADO, HARMONI will be able to produce very finely detailed data at the maximum spatial resolution the E-ELT can offer.

ELT-MIR or METIS lead by Dr Bernhard Brandl (University of Leiden, Netherlands) is a multi-functional instrument that works in the mid-infrared (http://metis.strw.leidenuniv.nl/). These wavelengths are ideal for observing the cool disks around stars from which planets are thought to form. These disks are made of mostly carbonaceous compounds along with metals in a material we call dust. This dust absorbs high-energy ultraviolet and optical photons produced by stars and are seen in almost all celestial objects. The UK-Astronomy Technology Centre is a partner of the METIS concept study and leads the integral field spectrograph for METIS building on the expertise developed for the MIRI instrument for JWST. The UK involvement is lead by Dr Alistair Glasse (UK-ATC).

Following these first three instruments, there is some flexibility in the instrument roadmap primarily due to the technological readiness of the instruments that need to be built to meet the science goals of the E-ELT. The next two instruments will be a multi-object spectrograph (**ELT-MOS**) and a high-resolution spectrograph (**ELT-HIRES**). The former makes it possible to obtain spectra of multiple objects simultaneously, while the latter instrument splits up the light from astronomical sources into very fine wavelength slices. The University of Durham, UK-ATC and the University of Oxford are co-leads for instrument concepts for multi-object spectrographs. Professor Simon Morris of the University of Durham is the co-Principal Investigator of the EAGLE instrument study – a multiple integral field spectrograph for the E-ELT (http://eagle.oamp.fr/spip/). Professor Gavin Dalton is co-PI for the multi-object spectrograph OPTIMOS-EVE (http://www.optimos-eve.eu/) that is a highly flexible instrument that can use optical fibres to take the spectra of astronomical objects either on individual objects or arranged to cover a contiguous field. Professor Martin Haehnelt and Professor Roberto Maiolino from the University of Cambridge are scientific leads for concept studies of the high-resolution spectrographs SIMPLE and CODEX.

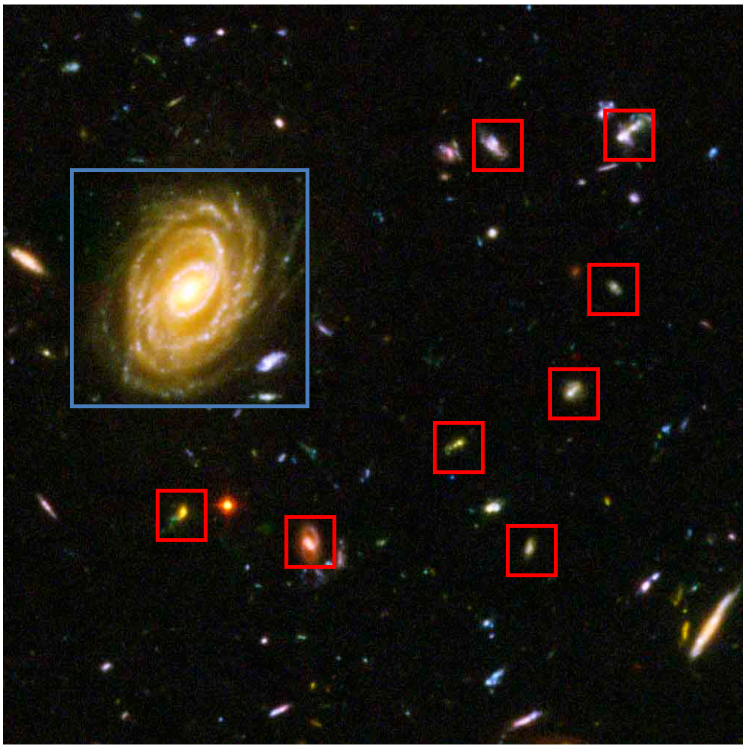
The ELT-Planetary Camera & Spectrograph (**ELT-PCS**) that requires very high-order adaptive optics system to produce data of sufficient quality to study exoplanets. Dr Matthias Tecza (University of Oxford) is leading the effort to study concepts for one of the designs for the integral field spectrograph for the EPICS instrument study. The EPICS study is lead by Dr Markus Kasper (ESO).

The sixth instrument is left open to allow teams to propose new and innovative capabilities and allows the roadmap to be flexible to the ever-changing scientific field and new science priorities. The order of these four instruments would be subject to a review. In particular the ELT-PCS is due to start as soon as the technological readiness of various instrument components have been verified.

The UK programme & expertise in spectroscopic instrumentation

The UK E-ELT programme has been funded by STFC over the next few years for continued technological and instrument development, and the construction of the UK-led first light instrument ELT-IFU/HARMONI (see http://www.stfc.ac.uk/News+and+Events/37619.aspx). This programme will ensure that UK astronomers have access to early observations with the E-ELT and it's "eyes" or instruments that will address some of the most important reasons for building the telescope: to investigate planets outside of our Solar System (including rocky planets in "habitable zones" around nearby stars); to dissect nearby galaxies by looking at their individual stars; and to improve our understanding of the first objects in the Universe; and help to elucidate the nature of dark energy that is accelerating the expansion of our Universe.

The programme currently support R&D of the following concept studies: HARMONI, EAGLE, OPTIMOS-EVE, METIS, EPICS and CANARY. SIMPLE and CODEX have contributions from the University of Cambridge that is currently supported by their own funds.



How the instruments work together

The following figure is designed to give an example of how the different instruments are complementary rather than overlapping in their capabilities. We can use integral field spectrographs such as those in HARMONI, METIS and EAGLE to observe the entireties of galaxies. For example, the integral field spectrographs of HARMONI and METIS could observe the yellow galaxy in the top left of the Hubble image (denoted by the blue box) obtaining exquisitely detailed information on the central bulges and the star-formation regions seen as bright clusters in the spiral arms. We could also determine how the stars, clusters of stars of different types and the gas are moving in this galaxy.

While HARMONI & METIS have only one field of view, EAGLE and OPTIMOS will have the capability to obtain spectra of many objects at the **same** time! EAGLE comprises of multiple integral field spectrographs it will therefore be able to acquire data on many sources simultaneously (red boxes). Similarly, OPTIMOS-EVE will have the same flexibility to place its fibres on any objects defined by the astronomers to obtain spectra of many multiple sources simultaneously.

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Further Links

For more information on the E-ELT please see
http://www.eso.org/public/teles-instr/e-elt.html

ESO Image Archive for the E-ELT
http://www.eso.org/public/images/archive/category/e-elt/

ESO Video Archive for the E-ELT
http://www.eso.org/public/videos/archive/category/e-elt/

For information on the UK programme
http://www.eelt.org.uk/