11 Outlook

The past decade has been a tremendously active and fruitful time for extragalactic astronomy and cosmology, as hopefully is well documented in the previous chapters. Here, we will try to see what progress we may expect for the near and not-so near future.

11.1 Continuous progress

Progress in (extragalactic) astronomy is achieved through information obtained from increasingly improving instruments and by refining our theoretical understanding of astrophysical processes, which in turn is driven by observational results. It is easy to foresee that the evolution of instrumental capabilities will continue rapidly in the near future, enabling us to perform better and more detailed studies of cosmic sources. Before we will mention some of the forthcoming astronomical facilities, it should be pointed out that some of the recently started projects have at best skimmed the cream, and the bulk of the results is yet to come. This concerns the scientific output from the Herschel and Planck satellite missions, as well as the recently commissioned ALMA interferometer, which has already provided exciting results. The great scientific capabilities of these facilities have been impressively documented, so it is easy to predict that far more scientific breakthroughs are waiting to be achieved with them.

Within a relatively short period of $\sim$ 15 years, the total collecting area of large optical telescopes has increased by a large factor, as is illustrated in Fig. 11.1. At the present

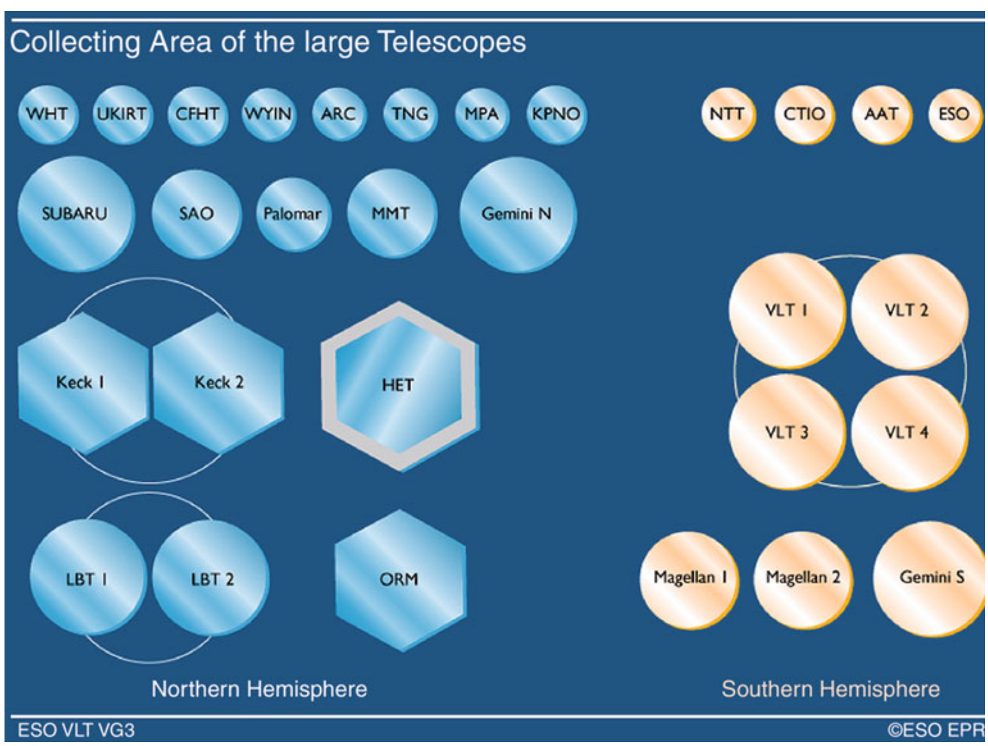

Fig. 11.1 The collecting area of large optical telescopes is displayed. Those in the Northern hemisphere are shown on the *left*, whereas southern telescopes are shown on the *right*. The joint collecting area of these telescopes has been increased by a large factor over the past two decades: only the telescopes shown in the *upper row* plus the 5-m Palomar telescope and the 6-m SAO were in operation before 1993. If, in addition, the parallel development of detectors is considered, it is easy to understand why observational astronomy is making such rapid progress. Credit: European Southern Observatory

P. Schneider, *Extragalactic Astronomy and Cosmology*, DOI 10.1007/978-3-642-54083-7_11,

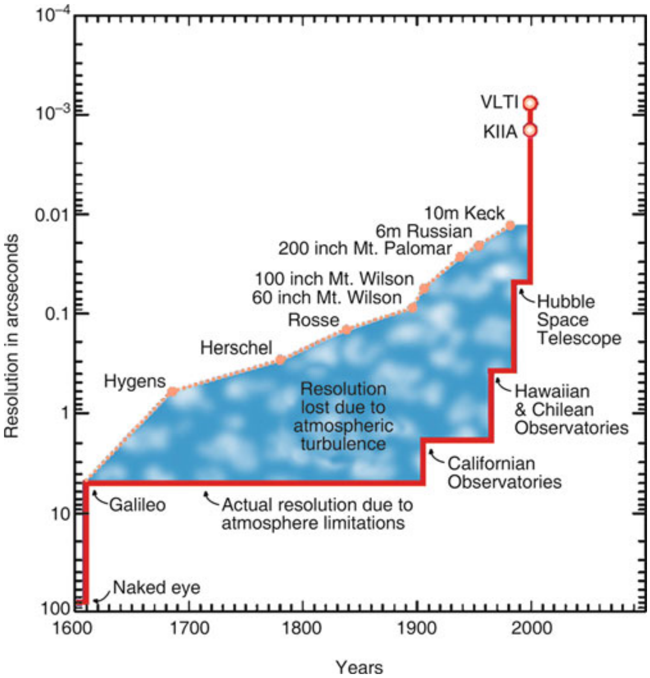

Fig. 11.2 This figure illustrates the evolution of angular resolution as a function of time. The *upper dotted curve* describes the angular resolution that would be achieved in the case of diffraction-limited imaging, which depends, at fixed wavelength, only on the aperture of the telescope. Some historically important telescopes are indicated. The *lower curve* shows the angular resolution actually achieved. This is mainly limited by atmospheric turbulence, i.e., seeing, and thus is largely independent of the size of the telescope. Instead, it mainly depends on the quality of the atmospheric conditions at the observatories. For instance, we can clearly recognize how the opening of the observatories on Mount Palomar, and later on Mauna Kea, La Silla and Paranal have lead to breakthroughs in resolution. A further large step was achieved with HST, which is unaffected by atmospheric turbulence and is therefore diffraction limited. Adaptive optics and interferometry characterize the next essential improvements. Credit: European Southern Observatory

time, 13 telescopes with apertures above 8 m (and four more with an aperture of 6.5 m) are in operation, the first of which, Keck I, was put into operation in 1993. In addition, the development of adaptive optics allows us to obtain diffraction-limited angular resolution from ground-based observations (see Fig. 11.2).

The capability of existing telescopes gets continuously improved by installing new sensitive instrumentation. The successful first generation of instruments for the 10-m class telescopes gets replaced step-by-step by more powerful instruments. As an example, the Subaru telescope will be equipped with Hyper Suprime-Cam, a 1.5 $\deg^2$ camera, by far the largest of its kind on 10-m class telescope. This instrument will allow the conduction of large-area deep imaging surveys, e.g., for cosmic shear studies.

In another step to improve angular resolution, optical and NIR interferometry will increasingly be employed. For example, the two Keck telescopes (Fig. 1.38) are mounted such that they can be used for interferometry. The four unit telescopes of the VLT can be combined, either with each other or with additional (auxiliary) smaller telescopes, to act as an interferometer (see Fig. 1.39). The auxiliary telescopes can be placed at different locations, thus yielding different baselines and thereby increasing the coverage in angular resolution. Finally, the Large Binocular Telescope (LBT, see Fig. 1.44), which consists of two 8.4-m telescopes mounted on the same platform, was developed and constructed for the specific purpose of optical and NIR interferometry.

From HST to its successor. The Hubble Space Telescope has turned out to be the most successful astronomical observatory of all time (although it certainly was also the most expensive one).[1] The importance of HST for extragalactic astronomy is not least based on the characteristics of galaxies at high redshifts. Before the launch of HST, it was not known that such objects are small and therefore have, at a given flux, a high surface brightness. This demonstrates the advantage of the high resolution that is achieved with HST. Several service missions to the observatory led to the installation of new and more powerful instruments which have continuously improved the capacity of HST. With the Space Shuttle program abandoned, no more service to Hubble is possible, and it is only a matter of time before essential parts will start to malfunction.

Fortunately, the successor of HST is already at an advanced stage of construction and is currently scheduled to be launched in 2018. This Next Generation Space Telescope (which was named James Webb Space Telescope—JWST; see Fig. 11.3) will have a mirror of 6.5-m diameter and therefore will be substantially more sensitive than HST. Furthermore, JWST will be optimized for observations in the NIR (1–5 μm) and thus be able, in particular, to observe sources at high redshifts whose stellar light is redshifted into the NIR regime of the spectrum.

We hope that JWST will be able to observe the first galaxies and the first AGNs, i.e., those sources responsible for reionizing the Universe. Besides a NIR camera, JWST will carry the first multi-object spectrograph in space, which is optimized for spectroscopic studies of high-redshift galaxy samples and whose sensitivity will exceed that of all previous instruments by a huge factor. Furthermore, JWST will carry

[1]The total price tag on the HST project will probably be on the order of 10 billion US dollars. This is comparable to the total cost of the Large Hadron Collider and its detectors. I am convinced that a particle physicist and an astrophysicist can argue for hours which of the two investments is more valuable for science—but how to compare the detection of the Higgs boson with the manifold discoveries of HST! However, both, the particle physicist and the astrophysicist, easily agree that the two price tags are a bargain, when compared to an estimated cost of 45 billion US dollar for the B2 stealth bomber program.

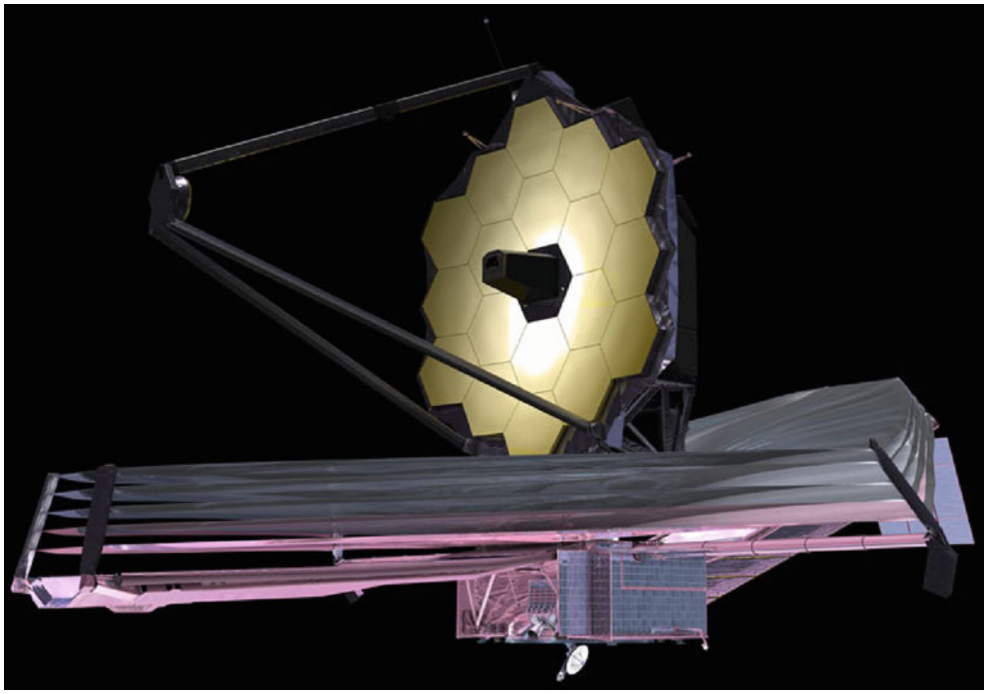

Fig. 11.3 Artist's impression of the 6.5-m James Webb Space Telescope. Like the Keck telescopes, the mirror is segmented and protected against Solar radiation by a giant heat shield, having the size of a tennis court. Keeping the mirror and the instruments permanently in the shadow will permit a passive cooling at a temperature of $\sim 35\,\mathrm{K}$. This will be ideal for conducting observations at NIR wavelengths, with unprecedented sensitivity. Credit: NASA

a MIR instrument which was developed for imaging and spectroscopy in the wavelength range $5\,\mu\mathrm{m} \le \lambda \le 28\,\mu\mathrm{m}$.

11.2 New facilities

There are research fields where a single instrument or telescope can yield a breakthrough—an example would be the determination of cosmological parameters from measurements of the CMB anisotropies. However, most of the questions in (extragalactic) astronomy can only be solved by using observations over a broad range of wavelengths; for example, our understanding of AGNs would be much poorer if we did not have the panchromatic view, from the radio regime to TeV energies. Our inventory of powerful facilities is going to be further improved, as the following examples should illustrate.

New radio telescopes. The Square Kilometer Array (SKA) will be the largest radio telescope in the world and will use a technology which is quite different from that of current telescopes. For SKA, the beams of the telescope will be digitally generated on computers. Such digital radio interferometers not only allow a much improved sensitivity and angular resolution, but they also enable us to observe many different sources in vastly different sky regions simultaneously. SKA will consist of about 3000 15-m dishes as well as two other types of radio wave receivers, known as aperture array antennas. Together, the receiving area amounts to about one square kilometer. The telescopes are spread over a region $\sim 3000\,\mathrm{km}$ is size, yielding an angular resolution of $0\farcs02$ at $\nu = 1.4\,\mathrm{GHz}$, and are linked by optical fibers (with a total length of almost $10^5\,\mathrm{km}$). The instantaneous field-of-view at frequencies $\gtrsim 1\,\mathrm{GHz}$ will be $\sim 1\,\mathrm{deg}^2$, increasing to $\sim 200\,\mathrm{deg}^2$ for lower frequencies. This huge (in terms of current radio interferometers) field-of-view is achieved by synthesizing multiple beams using software. The limits of such instruments are no longer bound by the properties of the individual antennas, but rather by the capacity of the computers which analyze the data. SKA will provide a giant boost to astronomy; for the first time ever, the achievable number density of sources on the radio sky will be comparable to or even larger than that in the optical.

SKA is not the first of this new kind of radio telescopes. The first one is the Low-Frequency Array (LOFAR), centered in the Netherlands but with several stations located in neighboring countries to increase the baseline and thus the angular resolution. LOFAR, operating at $\nu \lesssim 250\,\mathrm{MHz}$, can be considered as a pathfinder for the low-frequency part of SKA. LOFAR began its routine operation at the end of 2012. Other pathfinder observatories for SKA include the Australian Square Kilometre Array Pathfinder (ASKAP), and MeerKAT in South Africa.

To avoid terrestrial radio emission as much as possible, the SKA will we constructed in remote places in Australia and South Africa. The remoteness brings with it several great challenges—to mention just one, the power supply will most likely be decentralized, i.e., obtained through Solar panels near the telescopes to generate electricity. The data rate to be transmitted is far larger than the current global

Internet traffic! To process the huge data stream, one needs a computer capable of about 100 petaflops per second—such a computer does not yet exist (at least not with access for scientists).

The scientific outcome from SKA and its pathfinders is expected to be truly revolutionary. To mention just a few: The epoch of reionization will be studied by the redshifted 21-cm hydrogen line; a detailed time- and spatially dependent picture of the reionization process will be obtained. Normal galaxies can be studied via their 21-cm and their continuum (synchrotron) emission out to large redshifts, with an angular resolution better than that of HST. Since the HI-line yields the redshift of the galaxies, large redshift surveys can be employed for studies of the large-scale structure, including baryonic acoustic oscillations. The beam of the interferometer represents the point-spread function, and is very well known. Weak gravitational lensing studies using the radio emission from normal galaxies can thus make use of that knowledge to correct the measured image shapes.

New (Sub-)millimeter telescopes. The Large Millimeter Telescope (LMT) on the Volcán Sierra Negra, Mexico, is a 50-m radio telescope that recently went into operation (though in its first phase, the inner 32-m diameter of its primary surface will be fully installed). The LMT will observe in the range $0.85\,\mathrm{mm} \le \lambda \le 4\,\mathrm{mm}$. In addition to the much increased surface area compared to existing single-dish telescopes in this wavelength regime, the large aperture will provide an important step forward in angular resolution, and thus provide far more accurate positions of (sub-)mm sources. The Cerro Chajnantor Atacama Telescope (CCAT, Fig. 11.4) is a planned 25-m sub-millimeter telescope, to be built close to the site of ALMA, but at a higher altitude of ~ 5600 m. This ~ 600 m difference in altitude yields a further decrease of the water vapor column, and thus increases the sensitivity of the observatory. Equipped with powerful instruments, and a 20 arcmin field-of-view, CCAT will be able to map large portions of the sky quickly; it is expected that the CCAT will have a survey speed ~ 1000 times faster than the SCUBA-2 camera (see Sect. 1.3.1). CCAT will carry out large surveys for SMGs over a broad redshift range, and may be able to probe the earliest bursts of dusty star formation out to $z \sim 10$. CCAT will also be a powerful telescope for studying the Sunyaev–Zeldovich effect in galaxy clusters, and thus conduct cluster cosmology surveys. Last but not least, it will provide targets for observations with the ALMA interferometer, and in combination allows the joint reconstruction of compact and extended source components.

The next step in astrometry: Gaia. The ESA satellite mission Gaia, which was launched in Dec. 2013, will conduct astrometry of $\sim 10^9$ stars in the Milky Way, and provide very precise positions, proper motions and parallaxes of these stars. It is thus much more powerful than the previous astrometry satellite Hipparcos, and will provide us with a highly detailed three-dimensional map of our Galaxy, allowing precise dynamical studies, including the study of the total (dark +luminous) matter in the Milky Way and providing tests of General Relativity. Gaia will determine the distances to a large number of Cepheids, thus greatly improving the calibration of the period-luminosity relation which is one of the key elements for determining the Hubble constant in the local Universe. In addition, Gaia is expected to detect $\sim 5 \times 10^5$ AGNs.

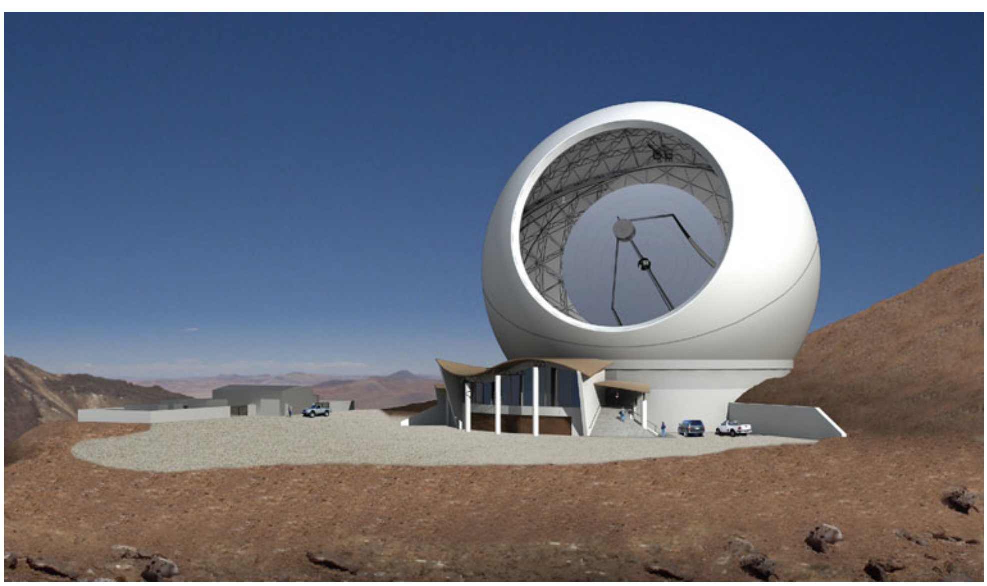

Fig. 11.4 Artist's impression of the CCAT telescope, a planned 25-m sub-millimeter telescope to be built in Chile. At an altitude of 5600 m, it will be highest altitude ground-based telescope world-wide. Credit: Cornell University & Caltech

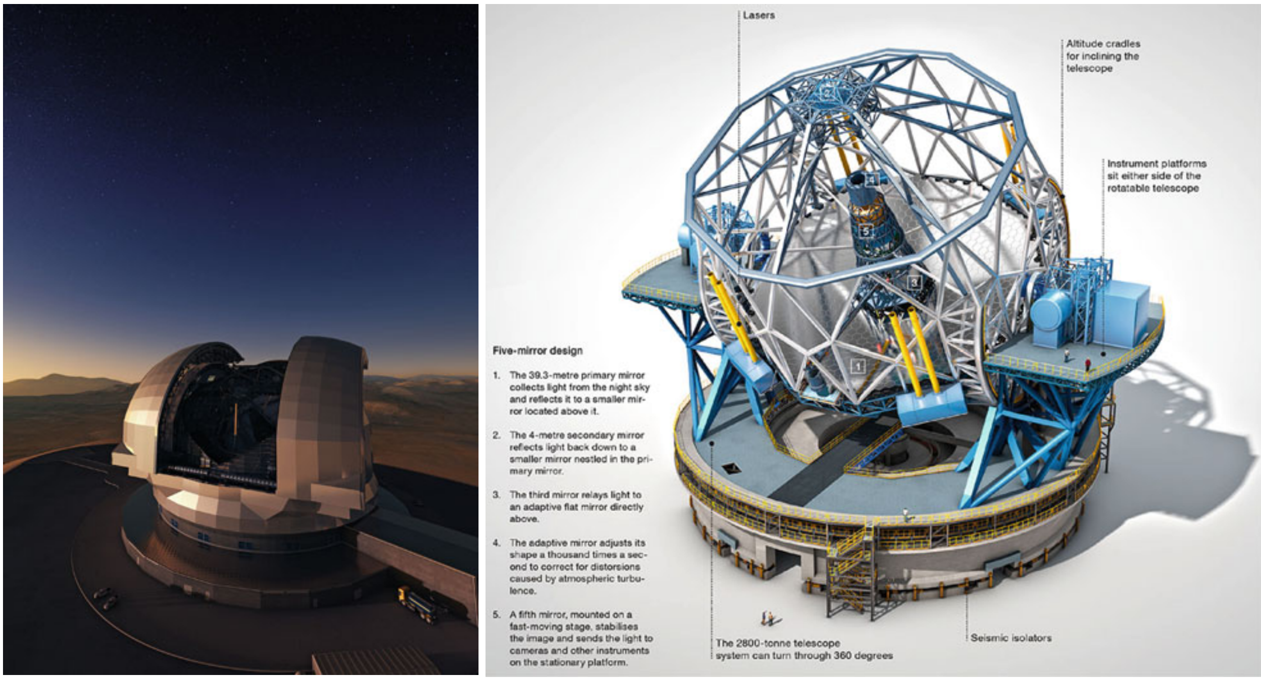

Fig. 11.5 Artist impression of the planned European Extremely Large Telescope, a 39-m telescope. Credit: European Southern Observatory

Giant near-IR/optical telescopes. A new era in observational astronomy will start with the installation of optical telescopes with an aperture of $\sim$ 30 m or larger. Three such giant telescope projects are currently in their planning stage. One of them is ESO's European Extremely Large Telescope (E-ELT, see Fig. 11.5), with a 39-m primary mirror (this mirror has about the same area as all the telescopes displayed in Fig. 11.1 together!). It will be built on Cerro Armazones, Chile, at an altitude of slightly more than 3000 m, not very far away from the Paranal, the mountain that hosts the VLT. The other two projects are the Thirty Meter Telescope (TMT), to be built on Mauna Kea in Hawaii, and the Giant Magellan Telescope (GMT) close to Gemini-South in Chile. All these telescopes will have segmented mirrors, similar to the Keck telescopes (Fig. 1.38), and sophisticated adaptive optics, to achieve the angular resolution corresponding to the diffraction limit of the telescope. For example, the E-ELT primary mirror will consist of 798 hexagonal segments, each with a size of 1.4 m. The secondary mirror will have a diameter of 4 m, which by itself would be a sizeable telescope aperture.

With their huge light-gathering power, these giant telescopes will open totally new opportunities. One expects to observe the most distant objects in the Universe, the first galaxies and AGNs which ionized the Universe. The cosmic expansion rate can be studied directly, by measuring the change of redshift of Lyα forest lines with time. High-resolution spectroscopy will enable studying the time evolution of chemical enrichment throughout cosmic history.

Optical/near-IR wide-field survey telescopes. The huge impact of the SDSS has demonstrated the versatile use of large surveys in astronomy. Several multi-band wide-field deep imaging surveys are currently ongoing, of which we mention two: The Kilo Degree Survey carried out with the VLT Survey Telescope on Paranal (see Fig. 1.39) and complemented with the near-IR VIKING survey with the VISTA telescope, covering $\sim$ 1500 deg^2 in nine bands. The Dark Energy Survey (DES) will image $\sim$ 5000 deg^2 with a newly designed camera on the Blanco Telescope, located at Cerro Tololo Inter-American Observatory (CTIO) in Chile. Both of these surveys have a wide range of science goals, including weak lensing and cosmic shear, the identification of galaxy clusters found at different wavebands (X-ray surveys, Sunyaev–Zeldovich surveys), and the large-scale distribution of galaxies and AGN, to name a few.

However, a revolution in survey astronomy will occur with the Euclid satellite (Fig. 11.6). Motivated by the empirical study of the properties of dark energy, Euclid will observe essentially the full extragalactic sky ($\sim$ 15 000 deg^2) in one broad optical band, and three near-IR bands, making use of its $\sim$ 0.5 deg^2 focal plane. The optical images will be used for a cosmic shear study and thus profit from the high resolution images obtainable from space. The fact that Euclid will be in an orbit around L2 implies that one can expect a very high stability of the telescope and instruments, which is an essential aspect for the correction of galaxy images with respect to PSF effects. The near-IR images are essential for obtaining photometric redshifts of the sources whose shapes

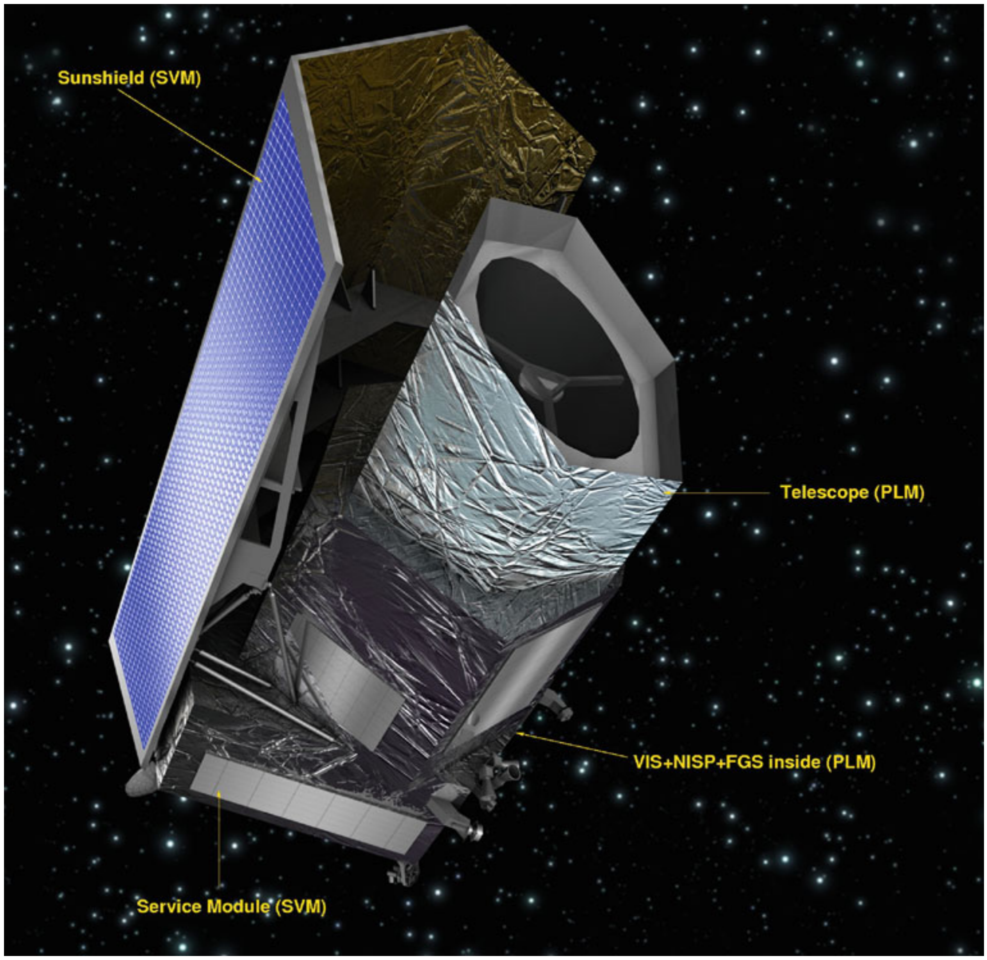

Fig. 11.6 The Euclid satellite, designed to provide a $\sim 15\,000\,\text{deg}^2$ imaging survey in the optical and near-IR, together with NIR slitless spectroscopy. Credit: European Space Agency

are used in the lensing analysis. For the same reason, the Euclid data will be supplemented with images in additional optical bands, to be obtained with ground-based telescopes. Altogether, we expect to measure the shapes of some two billion galaxies. In addition, Euclid will conduct slitless spectroscopy of some 50 million galaxies over a broad range in redshift, to yield a measurement of baryonic acoustic oscillations at $z > 1$. Euclid is scheduled for launch by the end of this decade.

Whereas the primary science goal of Euclid is dark energy, the mission will leave an enormous scientific legacy. Compared to the 2MASS all-sky infrared survey (Fig. 1.52), Euclid is about 7 magnitudes deeper, and will image almost 1000 times more galaxies in the near-IR bands. Together with the optical multi-color information, this data set will indeed provide a giant step in studies of the cosmos at large.

Sometimes nice surprises happen! We have stressed many times the incredible value of the Hubble Space Telescope for astronomy. In the summer of 2012, NASA received an offer from the US National Reconnaissance Office (NRO) intelligence agency for two telescopes which are very similar to the HST, originally planned as spy satellites, but never used. These telescopes have a shorter focal length than HST, allowing a much wider field-of-view. This offer came in handy, as it fits well into the plan to build a Wide Field Infrared Space Telescope (WFIRST), operating in the near-IR. Its planned NIR camera has a field-of-view $\sim$ 200 times larger than the WFC3 onboard HST. Its science goals are manifold, including supernova cosmology, baryonic acoustic oscillations, cosmic shear, and galaxy evolution studies.

A further ambitious project regarding optical sky surveys is the Large Synoptic Survey Telescope (LSST), an 8.4-m telescope in Chile equipped with a huge camera covering $9.6\,\text{deg}^2$. It is designed to survey half the sky in six optical bands every 4 days, taking short exposures. After 10 years, the coadded image from all the short exposures will yield a sky map at a depth of $m \sim 27.5$. A projected start of operations is 2022.

Apart from the telescopes and instrumentation, these projects are extremely demanding in terms of data storage and computing power. To wit, LSST will yield a data rate of $\sim$ 15 TB per night, and this raw data has to be reduced also within a day—to avoid any serious backlock. It is expected that most of the resources for this project will be invested into computer power and software for data storage and analysis.

A new X-ray all-sky survey. Twenty-five years after Rosat carried out its all-sky survey, the German-Russian mission Spectrum-X-Gamma will carry the eROSITA (extended ROentgen Survey with an Imaging Telescope Array) instrument, an X-ray telescope operating between 0.5 and $\sim$ 10 keV. eROSITA, expected to be launched at the end of 2015, will be located at L2 and carry out eight full sky surveys. The coadded sky survey will be $\sim$ 20 deeper than the RASS, and extend to higher photon energies. The all-sky survey is expected to detect $\sim 10^5$ clusters of galaxies, many of them at redshifts larger than unity, and $\sim 3 \times 10^6$ AGNs. For the latter, the higher energy band will be particularly useful. This will not only provide a much improved statistical basis for studying the AGN population over cosmic time, but also allow us to map the large-scale structure as traced by AGNs, including the study of baryonic acoustic oscillations. Together with cluster cosmology, eROSITA will be of great value for extragalactic astronomy and cosmology.

The scientific exploitation of the eROSITA data will depend significantly on the availability of auxiliary data for the identification and redshift estimates of the detected sources. The wide-field optical and near-IR imaging surveys described before—KiDS/VIKING, DES, PanSTARRS, and later, Euclid and LSST—will be invaluable for the eROSITA analysis. Furthermore, spectrographs with large multiplexing capabilities will allow to obtain spectra for millions of sources in the e-ROSITA catalog, including the AGNs and galaxies in the detected clusters.

New windows to the Universe will be opened. The first gravitational wave antennas are already in place, and their upgraded versions, to go into operation around 2016, will probably be able to discover the signals from relatively nearby supernova explosions or mergers of compact binaries. With the Laser Interferometer Space Antenna (LISA), mergers of supermassive black holes will become detectable throughout the visible Universe, as we mentioned before. Giant neutrino detectors will open the field of neutrino astronomy and will be able, for example, to observe processes in the innermost parts of AGNs.

Theory. Parallel to these developments in telescopes and instruments, theory is progressing steadily. The continuously increasing capacity of computers available for numerical simulations is only one aspect, albeit an important one. New approaches for modeling, triggered by new observational results, are of equal importance. The close connection between theory, modeling, and observations will become increasingly important since the complexity of data requires an advanced level of modeling and simulations for their quantitative interpretation.

Data availability; virtual observatories. The huge amount of data obtained with current and future instruments is useful not only for the observers taking the data, but also for others in the astronomical community. Realizing this fact, many observatories have set up archives from which data can be retrieved—essentially by everyone. Space observatories pioneered such data archives, and a great deal of science results from the use of archival data. Examples here are the use of the HST deep fields by a large number of researchers, or the analysis of serendipitous sources in X-ray images which led to the EMSS (see Sect. 6.4.5). Together with the fact that an understanding of astronomical sources usually requires data taken over a broad range of frequencies, there is a strong motivation for the creation of *virtual observatories*: infrastructures which connect archives containing astronomical data from a large variety of instruments and which can be accessed electronically. In order for such virtual observatories to be most useful, the data structures and interfaces of the various archives need to become mutually compatible. Intensive activities in creating such virtual observatories are ongoing; they will doubtlessly play in increasingly important role in the future.

11.3 Challenges

Understanding galaxy evolution. One of the major challenges for the next few years will certainly be the investigation of the very distant Universe, studying the evolution of cosmic objects and structures at very high redshift up to the epoch of reionization. To relate the resulting insights of the distant Universe to those obtained more locally and thus to obtain a consistent view about our cosmos, major theoretical investigations will be required as well as extensive observations across the whole redshift range, using the broadest wavelength range possible. Furthermore, the new astrometry satellite Gaia will offer us the unique opportunity to study cosmology in our Milky Way. With Gaia, the aforementioned stellar streams, which were created in the past by the tidal disruption of satellite galaxies during their merging with the Milky Way, can be verified. New insights gained with Gaia will certainly also improve our understanding of other galaxies.

Dark matter. The second major challenge for the near future is the fundamental physics on which our cosmological model is based. From observations of galaxies and galaxy clusters, and also from our determinations of the cosmological parameters, we have verified the presence of dark matter. Since there seem to be no plausible astrophysical explanations for its nature, dark matter most likely consists of new kinds of elementary particles. Two different strategies to find these particles are currently being followed. First, experiments aim at directly detecting these particles, which should also be present in the immediate vicinity of the

Earth. These experiments are located in deep underground laboratories, thus shielded from cosmic rays. Several such experiments, which are an enormous technical challenge due to the sensitivity they are required to achieve, are currently running. They will obtain increasingly tighter constraints on the properties of WIMPs with respect to their mass and interaction cross-section. Such constraint will, however, depend on the mass model of the dark matter in our Galaxy. As a second approach, the Large Hadron Collider at CERN will continue to search for indications for an extension of the Standard Model of particle physics, which would predict the presence of additional particles, including the dark matter candidate.

Dark energy. Whereas at least plausible ideas exist about the nature of dark matter which can be experimentally tested in the coming years, the presence of a non-vanishing density of dark energy, as evidenced from cosmology, presents an even larger mystery for fundamental physics. Though from quantum physics we might expect a vacuum energy density to exist, its estimated energy density is tremendously larger than the cosmic dark energy density. The interpretation that dark energy is a quantum mechanical vacuum energy therefore seems highly implausible. As astrophysical cosmologists, we could take the view that vacuum energy is nothing more than a cosmological constant, as originally introduced by Einstein; this would then be an additional fundamental constant in the laws of nature. From a physical point of view, it would be much more satisfactory if the nature of dark energy could be derived from the laws of fundamental physics. The huge discrepancy between the density of dark energy and the simple estimate of the vacuum energy density clearly indicates that we are currently far from a physical understanding of dark energy. To achieve this understanding, we might well assume that a new theory must be developed which unifies quantum physics and gravity—in a manner similar to the way other 'fundamental' interactions (like electromagnetism and the weak force) have been unified within the standard model of particle physics. Deriving such a theory of quantum gravity turns out to be enormously problematic despite intensive research over several decades. However, the density of dark energy is so incredibly small that its effects can only be recognized on the largest length-scales, implying the necessity of further astronomical and cosmological experiments. Only astronomical techniques are able to probe the properties of dark energy empirically. We have outlined in Sect. 8.8 the most promising ways of studying the properties of dark energy, and the new facilities described above will allow us to make essential progress over the next decade.

Inflation. Although inflation is currently part of the standard model of cosmology, the physical processes occurring during the inflationary phase have not been understood up to now. The fact that different field-theoretical models of inflation yield very similar cosmological consequences is an asset for cosmologists: from their point-of-view, the details of inflation are not immediately relevant, as long as a phase of exponential expansion occurred. But the same fact indicates the size of the problem faced in studying the process of inflation, since different physical models yield rather similar outcomes with regard to cosmological observables. Perhaps the most promising probe of inflation is the polarization of the cosmic microwave background, since it allows us to study whether, and with what amplitude, gravitational waves were generated during inflation. Predictions of the ratio between the amplitudes of gravitational waves and that of density fluctuations are different in different physical models of inflation. A successor of the Planck satellite, in form of a mission which is able to measure the CMB polarization with sufficient accuracy for testing inflation, will probably be considered.

Baryon asymmetry. Another cosmological observation poses an additional challenge to fundamental physics. We observe baryonic matter in our Universe, but we see no signs of appreciable amounts of antimatter. If certain regions in the Universe consisted of antimatter, there would be observable radiation from matter-antimatter annihilation at the interface between the different regions. The question therefore arises, what processes caused an excess of matter over antimatter in the early Universe? We can easily quantify this asymmetry—at very early times, the abundance of protons, antiprotons and photons were all quite similar, but after proton-antiproton annihilation at $T \sim 1\,\mathrm{GeV}$, a fraction of $\sim 10^{-10}$—the current baryon-to-photo ratio—was left over. This slight asymmetry of the abundance of protons and neutrons over their antiparticles in the early Universe, often called baryogenesis, has not been explained in the framework of the standard model of particle physics. Furthermore, we would like to understand why the densities of baryons and dark matter are essentially the same, differing by a mere factor of ~ 6.

The aforementioned issues are arguably the best examples of the increasingly tight connection between cosmology and fundamental physics. Progress in either field can only be achieved by the close collaboration between theoretical and experimental particle physics and astronomy.

Sociological challenges. Astronomy has become Big Science, not only in the sense that our facilities are getting more expensive, in parallel to their increased capabilities, but also in terms of the efforts needed to conduct individual science projects. Although most research projects are still carried out in small collaborations, this is changing drastically for some of the most visible projects. One indication is the growing average number of authors per publication, which doubled between 1990 and 2006 from 3 to 6, with a clearly increasing trend. Whereas many papers are authored by less than a handful of people, there is an increasing number of publications with long author lists: the typical H.E.S.S. publication now has $\gtrsim$200 authors, the Planck papers of order 250. One consequence of these large collaborations is that a young postdoc or PhD student may find it more difficult to find her or his name as lead author, and thus to become better known to the astrophysical community. We need to cope with this non-reversible trend; other scientific communities, like the particle physicists, have done so successfully.

Is cosmology on the right track? Finally, and perhaps too late in the opinion of some readers, we should note again that this book has assumed throughout that the physical laws, as we know them today, can be used to interpret cosmic phenomena. We have no real proof that this assumption is correct, but the successes of this approach justify this assumption in hindsight. Constraints on possible variation of physical 'constants' with time are getting increasingly tighter, providing additional justification. If this assumption had been grossly violated, there would be no reason why the values of the cosmological parameters, estimated with vastly different methods and thus employing very different physical processes, mutually agree. The price we pay for the acceptance of the standard model of cosmology, which results from this approach, is high though: the standard model implies that we accept the existence and even dominance of dark matter and dark energy in the Universe.

Not every cosmologist is willing to pay this price. For instance, M. Milgrom introduced the hypothesis that the flat rotation curves of spiral galaxies are not due to the existence of dark matter. Instead, they could arise from the possibility that the Newtonian law of gravity ceases to be valid on scales of 10 kpc—on such large scales, and the correspondingly small accelerations, the law of gravity has not been tested. Milgrom's *Modified Newtonian Dynamics (MOND)* is therefore a logically possible alternative to the postulate of dark matter on scales of galaxies. Indeed, MOND offers an explanation for the Tully–Fisher relation of spiral galaxies.

There are, however, several reasons why only a few astrophysicists follow this approach. MOND has an additional free parameter which is fixed by matching the observed rotation curves of spiral galaxies with the model, without invoking dark matter. Once this parameter is fixed, MOND cannot explain the dynamics of galaxies in clusters without needing additional matter—dark matter. Thus, the theory has just enough freedom to fix a problem on one length- (or mass-)scale, but apparently fails on different scales. We can circumvent the problem again by postulating warm dark matter, which would be able to fall into the potential wells of clusters, but not into the shallower ones of galaxies, thereby replacing one kind of dark matter (CDM) with another. In addition, the fluctuations of the cosmic microwave background radiation cannot be explained without the presence of dark matter.

In fact, the consequences of accepting MOND would be far reaching: if the law of gravity deviates from the Newtonian law, the validity of General Relativity would be questioned, since it contains the Newtonian force law as a limiting case of weak gravitational fields. General Relativity, however, forms the basis of our world models. Rejecting it as the correct description of gravity, we would lose the physical basis of our cosmological model—and thus the impressive quantitative agreement of results from vastly different observations that we described in Chap. 8. The acceptance of MOND therefore demands an even higher price than the existence of dark matter, but it is an interesting challenge to falsify MOND empirically.

This example shows that the modification of one aspect of our standard model has the consequence that the whole model is threatened: due to the large internal consistency of the standard model, modifying one aspect has a serious impact on all others. This does not mean that there cannot be other cosmological models which can provide as consistent an explanation of the relevant observational facts as our standard model does. However, an alternative explanation of a single aspect cannot be considered in isolation, but must be seen in its relation to the others. Of course, this poses a true challenge to the promoters of alternative models: whereas the overwhelming majority of cosmologists are working hard to verify and to refine the standard model and to construct the full picture of cosmic evolution, the group of researchers working on alternative models is small[2] and thus hardly able to put together a convincing and consistent model of cosmology. This fact finds its justification in the successes of the standard model, and in the agreement of observations with the predictions of this model.

We have, however, just uncovered an important sociological aspect of the scientific enterprise: there is a tendency to 'jump on the bandwagon'. This results in the vast majority of research going into one (even if the most promising) direction—and this includes scientific staff, research grants, observing time etc. The consequence is that new and unconventional ideas have a hard time getting heard. Hopefully (and in the view of this author, very likely), the bandwagon is heading in the right direction. There are historical examples to the contrary, though—we now know that Rome is not at the center of the cosmos, nor the Earth, nor the Sun, nor the Milky Way, despite long epochs when the vast majority of scientists were convinced of the veracity of these ideas.

[2]However, there has been a fairly recent increase in research activity on MOND. This was triggered mainly by the fact that after many years of research, a theory called TeVeS (for Tensor-Vector-Scalar field) was invented, containing General Relativity, MOND and Newton's law in the respective limits—though at the cost of introducing three new arbitrary functions.