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E-ELT PROGRAMME

TOP LEVEL REQUIREMENTS FOR ELT-HIRES

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Contents

Abbreviations

See applicable document AD1 (see section 2.1 herein for references of applicable documents).

1 Scope

The scope of this document is to define the Top Level Requirements for the E-ELT instrument: high resolution spectrograph (ELT-HIRES).

The Top Level Requirements are derived from the Science Case of the E-ELT. For particular instruments, they were developed during the concept phase for the instruments (between 2007 and 2010), as well as in the process of defining the Design Reference Mission and Design Reference Science Plan for the E-ELT.

The Top Level Requirements are developed by the E-ELT project with the help of its Project Science Team. They can be refined by the Consortium contracted to deliver the instrument, and are the basis for setting up the Technical Specifications for the instruments.

2 Related documents

2.1 Applicable documents

The following applicable documents form a part of the present document to the extent specified herein. In the event of conflict between applicable documents and the content of the present document, the content of the present document shall be taken as superseding.

AD1 Common definitions and acronyms;
ESO-193178 v6

2.2 Reference documents

The following Reference Documents provide background information as to the present document. Under no circumstance shall the content of Reference Documents be construed as applicable to the present one, in part or in full.

RD1 E-ELT Science Case;
ESO-191903 v1

RD2 Science Working Group input to the E-ELT Instrument Plan;
ESO-193215 v1

RD3 A Community Science Case for E-ELT HIRES
arXiv:1310.3163

RD4 The E-ELT Design Reference Mission;
ESO-191370 v2

RD5 The E-ELT Design Reference Plan;
ESO-192959 v2

3 Science Case for ELT-HIRES

The unique photon collecting area of the E-ELT is one of its key defining characteristics. The scientific advances to be expected from the sensitivity of a 40-m telescope forms an important part of the Science Case for the E-ELT [RD1]. High resolution spectroscopy in particular exploits this capability.

The need for such an instrument was already recognized and emphasized by the E-ELT Science Working Group (SWG) in its recommendation regarding the capabilities of the E-ELT's first generation of instruments [RD2].

In this document we derive the Top Level Requirements for ELT-HIRES, a high resolution spectrograph for the E-ELT. As has been well established, many of the sciences cases for the E-ELT [RD1] require such an instrument. In this section we assemble that sub-set of science cases that drive the requirements for ELT-HIRES. Although not a complete list, this set is nevertheless representative of the science to be enabled by ELT-HIRES. We provide brief descriptions of these cases, as well as the instrument requirements derived from them.

3.1 Solar system

3.1.1 Outline of the science case

High-resolution spectroscopic mapping of planetary disks has been shown to be a powerful way of studying the atmospheric circulation of planets. Several atmospheric regions can be probed, depending on the wavelength range.

In the visible range, winds at the cloud top (P = 0.1 – 0.5 bar) can be monitored through Doppler velocimetry using Fraunhofer solar lines as illustrated in the case of Venus (Machado et al., 2012, Icarus, 221, 248). The zonal winds reach speeds of 140 m/s at mid-latitudes. The atmospheric circulation of Venus, dominated by super-rotation near the cloud base, is believed to be the result of planetary-scale waves due to thermal tides forced by solar heating (Yamamoto & Takahashi, 2012, Icarus, 217, 702). In the case of Jupiter, zonal winds show an alternate structure following the belts and zones with opposite directions and amplitudes of +/-100 m/s or more (Ingersoll et al., 2004, in 'Jupiter', F. Bagenal et al. eds., 105). The ELT-HIRES observations will be precious as a follow-up of the JUNO mission (in operation from 2016) and in preparation of the JUICE (Jupiter and Icy Satellite Explorer) mission selected by ESA, to be launched in 2022 for operation in 2030. In the case of Saturn, which exhibited an enormous storm in 2011, these observations will help as a follow-up the Cassini mission, in operation until 2017, which has revealed the extraordinary complexity of Saturn's atmospheric dynamics.

In the near-IR, different atmospheric levels can be probed. On Venus, the distribution, short-term variability and rotational temperature of the O_2 $a^1\Delta_g$ airglow band at 1.27 μm can be mapped in the upper mesosphere of Venus (P < 0.1 mbar) from the ground (Bailey et al., 2008, PSS, 56, 1385; Ohtsuki et al., 2008, PSS, 56, 1391). On the giant planets, mapping H_2 (2.12 μm) and H_3+ (2.09 μm) allows us to probe even higher levels (P < 1 μbar) and to investigate the energetics and dynamics of upper atmospheres and ionospheres, as well as the coupling with magnetospheres (Drossart et al., 1989, Nature, 340, 539; Chaufray et al., 2011, Icarus, 211, 1233). Finally, the deep troposphere of Venus is only accessible in a few near-IR windows on the night side between 1.0 and 2.5 μm. Windows are centred in the J (1.00, 1.18, 1.27 μm), H (1.74 μm) and K bands (2.3 μm). They have been used to retrieve the abundances of minor species (CO, H_2O, HDO, OCS, SO_2, HF) and to infer the tropospheric D/H ratio, over 100 times higher than the terrestrial value (Bézard et al., 1990, Nature, 345, 509). Accurate velocimetry will allow us to track the tropospheric circulation of Venus below the clouds at a pressure level of several bar.

ELT-HIRES operating in the visible and near-IR range will allow us to monitor the planetary atmospheric winds of planets over a wide range of altitudes, and thus to retrieve a 3D picture of their atmospheric dynamics. In the case of Venus, typical scales for planetary dynamics are in the range of hours (McGouldrick et al., 2012, Icarus 217, 615; Encrenaz et al., 2013, A&A 559, 65). On small disks (Uranus, Neptune, Titan, Io), in the near-IR range, ELT-HIRES will allow the same kind of study with a spatial resolution of several tens of pixels per diameter. The case of Titan is of special interest as its atmosphere, like that of Venus, appears to be dominated by super-rotation.

Regarding the atmospheric mapping of small bodies using CRIRES in the K band has made possible the detection of minor atmospheric species (CO, CH_4) on Pluto and Triton (Lellouch et al., 2010, A&A, 512, L8; 2011, A&A 530, L4). With ELT-HIRES in the K band, it will be possible to map CO and CH_4 on both objects; these measurements will allow us to constrain the nature of surface-atmosphere interactions and possible seasonal transport. In the same way, it will be possible to map Io in the SO line at 1.7 μm, detected by De Pater et al. (2002, Icarus, 156, 296) at the Keck telescope, and thus to isolate the volcanic cores and to monitor their variability. In the case of TNOs, the sensitivity advantage of the E-ELT will make it possible to search for an atmosphere on the most favourable objects.

3.1.2 Requirements derived from the science case

The observations related to atmospheric dynamics require the visible and near-IR wavelength range, i.e. 0.4 – 2.4 μm, with a resolving power of 100,000 in V, and 30,000 in the J, H bands and 60,000 in the K band. In the near-IR range, diffraction limited spatial resolution is required in order to map features on planets and small bodies. As far as the trade-off between simultaneous spectral coverage and field of view of the IFU is concerned, the large range of scientific objectives argues for flexibility and versatility, and hence for an intermediate solution: a field of view of 0.2 x 0.2 $arcsec^2$ and a simultaneous wavelength coverage of $\lambda / \Delta\lambda = 20$.

Note that Venus has no satellites that could be used as NGS.

Regarding atmospheric chemistry, a resolving power of 60,000 in the K band (Lellouch et al. 2010; 2011) is needed for three reasons: to separate transitions from different atmospheric species, to derive rotational temperatures from the relative intensities of a given rotovibrational band, and for separating planetary lines from terrestrial absorption.

Spectral resolution	100,000 in V 30,000 in J, H 60,000 in K
Wavelength range	Total: 0.4 – 2.4 μm Simultaneous: $\lambda / \Delta\lambda = 20$
Spatial resolution	Near-IR: diffraction limited, on-axis; differential movement between target and NGS; LGS
Entrance aperture	Optical: 1 Near-IR: IFU with 200 mas field of view

Table 1: Summary of requirements of this science case.

3.2 Detection and characterisation of exoplanet atmospheres

3.2.1 Outline of the science case

The vast majority of extrasolar planets are located too close to their host stars to be separated by direct imaging. Therefore, the presence of a planet is currently detected indirectly by small variations of the combined radiation coming from the system. The two most common indirect exoplanet detection techniques – the radial velocity and transit methods – have led to the discovery of about 1000 systems. When combined, these techniques enable the determination of the planetary mass and radius and hence of the mean density. But such constraints are available only for a small fraction of exoplanets. Furthermore, measurements of the bulk properties tell us little about the physical conditions, such as temperature and pressure, or about the chemistry of planetary surfaces and atmospheres.

The first constraints on exoplanet atmospheres came from transit spectrophotometry. It allowed detecting atomic and molecular absorption in planetary atmospheres by comparison of the eclipse curves in the continuum and in the centres of strong absorption features (e.g. Vidal-Madjar et al., 2003, Nature, 422, 143; Swain et al., 2008, Nature, 452, 329). This method is mainly applied to low-resolution spectra and relies heavily on the photometric stability of the instrument. An extension of this technique to high-resolution spectroscopy was proposed by Snellen et al. (2010, Nature, 465, 1049). In this method a small spectroscopic contribution ($\sim 10^{-4}$ relative to the stellar continuum) of the planet is detected by taking advantage of the strong Doppler shifts due to planet orbital motion (up to 150 km/s). The planetary contribution shifts significantly relative to the nearly stationary stellar and telluric lines. Tracing this Doppler trail allows the determination of the masses of both the planet and its host star. The strength and shape of the planetary absorption lines, as measured by, e.g., the cross-correlation function, provides information on the chemistry and wind patterns in the planetary atmosphere.

Detection of CO in transmission reported for the transiting exoplanet HD 209458 b (Snellen et al., 2010, Nature, 465, 1049) was followed by the detection of this molecule in the dayside spectra of another transiting planet, HD 189733 b (Rodler et al., 2012, ApJ, 735, L25), and in the spectrum of the non-transiting planet τ Boo b (Brogi et al., 2012, Nature, 486, 502). The last example demonstrated that the high-resolution Doppler-trail technique can be applied to non-transiting systems, representing the only direct possibility to derive masses and orbital inclinations for these exoplanets.

Another interesting direction to gather information about exoplanet atmospheres is to study the optical stellar spectrum reflected off the planet. Detection of reflected light constrains the albedo of an exoplanet and hence its atmospheric physics. It also allows the determination of the orbital velocity and hence the mass of a non-transiting exoplanet. Several attempts to observe reflected light with current 4 – 8-m class telescopes were unsuccessful. However, simulations show that such reflected light studies are well within reach of ELT-HIRES (Martins et al., 2013, MNRAS, 436, 1215).

Currently, the high-resolution detections of exoplanet atmospheric signatures are accomplished in the near-IR, e.g. using CRIRES@VLT or NIRSPEC@Keck, by analyzing cross-correlation functions built by combining a few dozen individual lines belonging to a single molecular species. Application of the same technique to the transmission and dayside spectra obtained with ELT-HIRES will enable analysis of several molecular species (CO, CO_2, H_2O, CH_4) simultaneously for the Jupiter-size exoplanets. Furthermore, the increase in the S/N possible with E-ELT will allow the reconstruction, at least for the brightest systems, of a high-resolution planetary spectrum. A study of individual spectral lines formed at different atmospheric heights opens possibilities to derive the temperature-pressure profile of exoplanetary atmosphere. The shape of absorption lines measured at high resolution may reveal signatures of the planet's rotation, atmospheric circulation, and winds. Orbital modulation of the planetary signal can be used to study longitudinal variations of the chemistry and physical properties. Detection of biomarker molecules (e.g. O_2) for the Earth-size exoplanets orbiting mid-M dwarfs should be possible with high-resolution spectroscopy at E-ELT (Snellen et al., 2013, ApJ, 764, 182) provided that the data collected over several transits can be combined.

Additional constraints on the planetary parameters and atmospheres can be inferred from high-resolution spectropolarimetry. A centre-to-limb variation of scattering polarization may be detectable during transits due to symmetry breaking by the planet's shadow. In addition, scattering linear polarization may arise in the centres of strong molecular lines formed in a planetary atmosphere. Circular polarization has been detected in the spectrum of the earthshine and interpreted as the signature of a biomarker (chlorophyll) on the Earth's surface (Sterzik et al., 2012, Nature, 483, 64). The essential advantage of polarimetric observations, compared to detecting planetary signatures in the intensity spectra, is that the stellar and telluric contributions are expected to be very weak in polarization, yielding significantly higher planet/star intensity contrasts. Furthermore, precise circular polarization measurements in spectral lines may allow diagnosing the presence of magnetic fields on exoplanets, which is known to be an essential aspect of a planet's habitability.

3.2.2 Requirements derived from the science case

The key requirement of this science case is achieving a spectral resolution of at least 100,000. This is absolutely essential for separating telluric and exoplanet contributions, for isolating individual molecular lines, and for probing a large range of atmospheric heights in planetary atmospheres.

The simultaneous wavelength coverage needs to be 0.38 – 2.4 μm. The blue limit is motivated by the inclusion of the Ca II H&K lines, which are relevant for monitoring stellar activity and useful for observations of the exospheres of evaporating highly-irradiated exoplanets (Fossati et al., 2013, ApJ, 766, 20). The extension to these wavelengths also benefits the reflected light science case because the scattering-dominated albedo is expected to increase towards the blue (Evans et al. 2013, ApJ, 772, L16). The red limit is determined by the strong CO band at 2.3 μm. Numerous interesting molecular diagnostic features can be found between these wavelength limits.

A high stability of the spectrum on the detector of better than 50 m/s over the timescale of a night is required in order to be able to take exposures on target continuously without having to take wavelength calibrations during transits. The detectors should be stable, well calibrated in terms of the pixel-to-pixel sensitivity variations, non-linearity, and capable of handling high photon fluxes, with the ability to achieve a S/N per pixel of > 1000 in the extracted spectrum using daytime calibrations.

ELT-HIRES should allow the observation of very bright stars at high cadence, i.e. with exposure times as low as ~1 s.

Adaptive optics is not required for this science case.

A second fibre (or even more, to be placed over a patrol field of $\gtrsim$ 1 arcmin) may be used for differential spectrophotometry or for simultaneous monitoring of telluric lines using a nearby early-type star if available.

High-resolution linear and circular spectropolarimetric capability is desirable.

Spectral resolution	100,000
Wavelength range	Total: 0.38 – 2.4 μm Simultaneous: 0.38 – 2.4 μm
Spatial resolution	Seeing limited
Entrance aperture	1 (goal: 2)
Calibration	Wavelength: 50 m/s (goal: 10 m/s) For a source of suitable brightness it shall be possible to achieve S/N > 1000 per pixel in the 1D extracted spectrum from a single exposure using daytime calibrations.
Stability	50 m/s/night (goal: 10 m/s/night)

Polarimetry	Goal: polarimetric sensitivity ~10^{-4}, wavelength range 0.8 – 2.4 µm (goal: 0.38 – 2.4 µm)
Other	Minimum allowed exposure time: 1 s Fast detector read-out mode Minimal downtime between successive exposures

Table 2: Summary of requirements of this science case.

3.3 Protoplanetary disks

3.3.1 Outline of the science case

The study of extrasolar planets and their formation scenarios is one of the key science cases for the E-ELT, as it addresses some of the fundamental questions of Mankind: Is our Solar System unique? Is Earth unique? A first hint to the answers to these questions has appeared during the last two decades of extrasolar planet research – the exoplanetary systems that have been discovered so far are characterized by a huge diversity as far as parameters such as planetary mass, orbital distance, and eccentricities are concerned. Those findings impose challenging questions on the formation of planets and planetary systems, and indicate a high sensitivity of the formation process on initial conditions, and that a multitude of physical processes may be at work.

ELT-HIRES, in synergy with ALMA, will provide direct observational tests of the early phases of planet formation. The evolutionary phases of young stellar objects (YSOs), inferred from their spectral energy distributions, are described in the traditional classification scheme via the transition of the circumstellar material from a thick and massive envelope to a tenuous circumstellar disk (Lada & Wilking, 1984, ApJ, 287, 610). Circumstellar disks are commonly observed around young stellar objects (e.g. Beckwith & Sargent, 1996, Nature, 383, 139). Disks around T Tau stars disappear after timescales of 10^6 – 10^7 years, and most of the very low-mass stars have lost their disks after 5 – 9 Myr (Haisch et al., 2001, 553, L153; Bouwman et al., 2006, ApJ, 653, L57; Hernández et al., 2007, ApJ, 671, 1784). Those disk clearing times form an upper limit for the timescales at which planet formation occurs. The formation of planets is believed to occur through the coagulations of µm-sized dust particles which leads to the formation of planetesimals and rocky cores of planets. Although this scenario faces several challenging problems, it has been shown that dust trapping in pressure maxima in disks (arms and vortices) can efficiently trap large particles, allowing grains to grow and stay in the disk for long times (Pinilla et al., 2012, A&A, 538, 114). Observational evidence of a dust-trapped blob in the disk around the star Oph IRS 48 using ALMA has been given recently by van der Marel (2013, Science, 340, 1199).

Once planetesimals have been formed, the subsequent gas accretion leads to the formation of giant gas planets. The standard scenario describes the formation of Jupiter-sized planets via a two-stage process – an initial accretion of a central rocky core of a few Earth masses followed by accretion of gas from the surrounding accretion disk (Boss, 1996, ApJ, 469, 906). The transport of angular momentum and material via tidal torques created by the planet on the disk leads to the formation of a gap in the disk (e.g. Goldreich & Tremaine, 1980, ApJ, 241, 425). The gravitational interaction of a Jupiter-sized planet with the gaseous disk leads to an orbital migration of the protoplanet toward the star (e.g. Mordasini et al., 2009, A&A, 501, 1139). Two main types of gas-disk migration have been identified. Type I migration occurs during the formation of low-mass planets, where the surface density profile of the disk is only weakly altered by the planet. As a result, the migration rate is proportional to the mass of the planet. Type II migration occurs during the formation of massive planets, where the planets strongly perturb the gas disk.

The structure and the dynamics of the gap created by a protoplanet in an accretion disk has been modelled by Kley (1999, MNRAS, 303, 696) who calculated the accretion of mass onto the protoplanet by use of the hydrodynamic equations for a flat, two-dimensional and non self-gravitating protostellar accretion disk. According to their comprehensive models, the accretion of mass onto a planet occurs from regions exterior and interior to the planet, and on timescales of a few 10^5 years, for typical disk viscosities. The size of the gap depends on the planetary mass. For instance, Jupiter-mass planets produce gaps 0.3 AU wide at an orbital distance of 1 AU (Takeuchi et al., 1996, ApJ, 460, 832). Disks with a gap, either resulting from the formation of a planet, or, alternatively, by photo-evaporation from inside out, are the final stages of protoplanetary disk.

Planet formation does, however, compete with various other physical processes that lead to the dissipation of circumstellar disks. Among these processes, viscous accretion of disk material onto the star, protostellar winds and jets, magnetic disk winds, and photo-evaporation. MHD winds may occur over a very narrow range of disk radii (X-winds, Shu et al., 1994, ApJ, 429, 781) or over a wide range of disk radii (magnetocentrifugal disk winds, Königl & Pudritz, 2000, in Protostars and Planets IV, 759). At closest distance to the star (R < 1 AU), various physical processes are believed to dominate planetary formation processes, and stellar and disk evolution in general. Magnetic field lines create accretion columns onto the star and channel jets and winds (Pudritz et al., 2007, in Protostars and Planets V, 277), which in turn set the timescale for the disk dispersal and the final properties of the star (Shu et al. 1994). Dynamical effects such as orbital migration caused by tidal interactions between the disk and the protoplanet can lead to mergers and thus significantly alter the mass of a planet (e.g. Lin & Papaloizou, 1993, in Protostars and Planets III, 749; Lin & Ida, 1997, ApJ, 477, 781), and its orbital parameters. Disentangling the various effects requires very high spectral resolution and an IFU. The importance of an IFU and the difficulties and pitfalls of single slit observations are described in some detail below. As shown below, the highest spectral resolution of R = 20,000 available with ELT-IFU will not be sufficient to disentangle the various physical effects that govern protoplanetary disks.

Young stellar objects need to lose angular momentum, and the physical processes involved are outflows and disk winds. Jets and outflows from YSOs have been intensively studied in the past, and the optical and near-IR spectroscopy of Herbig-Haro objects provides detailed insight into the physics of the shocks that occur when the outflowing material hits the ambient interstellar material (e.g. Gredel, 1994, A&A, 292, 580). High angular resolution studies obtained with STIS/HST of the optical forbidden [OI], [NII] and [SII] lines, along with the Hα lines of the jet arising from DG Tau (Bacciotti et al., 2002, ApJ, 576, 222) provide evidence of rotation in the initial channel of the jet flow. The kinematic relationship between the disk and the jet in the DG Tau system has been derived via high-angular sub-mm CO observations (Testi et al., 2002, A&A, 394, L31). First observational evidence of a disk wind of the rotating molecular disk around the Herbig Ae star HD 163296 has been given by Klaassen et al. (2013, A&A, 555, 73), based on CO 2-1 and 3-2 observations taken during ALMA science verification.

High resolution optical line studies provide important diagnostics of disk winds and accretion and insight into the evolution and dispersal of circumstellar disks. The study of optical and near-IR emission lines such as [OI], Hα, CaII, Paβ or Brγ provide a measure of the accretion luminosities that occur during the early stages of YSO evolution (Antoniucci et al., 2011, A&A, 534, 32). Hydrogen emission lines observed toward T Tau stars are generally very broad (>> 100 km/s), and are well explained to arise from disk gas accreted onto the star in magnetospheric accretion columns. Optical forbidden lines are generally characterized by two components. There is a high-velocity component, which has been shown to trace collimated jets (e.g. Hartigan et al., 2004, ApJ, 609, 261). A second component is seen with lower radial velocity shifts with respect to the star. Its origin is unclear but the suggestion has been made that the low velocity component arises from the disk wind, mostly because the peak velocities of various forbidden lines are inversely proportional to the respective critical densities – which is exactly what is expected in a disk wind, where the flow accelerates as it rises from the disk. The peak velocity differences are of the order of few km/s which sets the required spectral resolution for these kinds of studies. From their comprehensive study of the [OI] low-velocity component from T Tau stars using high-resolution UVES data, Rigliaco et al. (2013, ApJ, 772, 60) presented their working hypothesis that the narrow line component traces the wind from the outer disk, whereas the broad [OI] component arises from photo-dissociated OH in the upper layer of the inner disk. The low-velocity component is blueshifted by a few km/s only with respect to the stellar velocity.

Yet even at the spatial resolution of the E-ELT, the most interesting regions of the disk, which are located at a few stellar radii only, are not resolved. Spectro-astrometric methods afford the possibility to obtain information on significantly smaller scales than the resolution limit of an observation. The method is based on the fact that the accuracy in the determination of the centroid of an emission line is limited by the observed S/N only, and is routinely applied to obtain mas precision from seeing limited observations at 8 m-class ground-based telescopes. For instance, Whelan et al. (2005, Nature, 435, 652) have analysed their high-resolution VLT/UVES observations of the brown dwarf ρ Oph 102 to show that the forbidden optical [OI] and [SII] lines arise from regions displaced from the brown dwarf by 0.01 – 0.1 arcsec, with an accuracy reaching 30 mas, or 4.5 AU. Their analysis resulted in outflow characteristics that are very similar to that of young stars, albeit at smaller scales. The use of an IFU affords the possibility to reach even higher astrometric precisions toward spatially unresolved objects, down to 0.01 pixel precisions. This has been convincingly demonstrated by Goto (2012, ApJ, 748, 6) who have resolved the kinematics of ionized gas at scales of one stellar diameter (0.01 AU) in the evaporating disk around TW Hya. The authors applied 2D spectro-astrometry to the Brγ emission as obtained from their VLT/SINFONI observations. The authors showed convincingly that the centroid of the Brγ emission is displaced to the North with respect to TW Hya at the blue side of the emission line, and to the South at the red side. Spectro-astrometry in combination with an IFU avoids some of the problems that may arise from slit vignetting and wavelength calibration. The work done with SINFONI is at the limit of what can be done today at 8 m-class telescopes. With the higher spectral and spatial resolution that is available with an IFU mode of ELT-HIRES, 2D spectro-astrometric studies will become possible for the known Class II objects in Taurus, ρ Oph and the Gould Belt.

The understanding of the complexity of the dissipation processes that occur in protoplanetary disks, which include planet formation, requires high angular resolution studies of young disks (1 Myr) at high spectral resolution. Even with the E-ELT, the regions will not be spatially resolved, but will require us to adopt methods such as spectro-astrometry to disentangle the various physical processes that compete in the dissipation processes of protoplanetary disks. The use of an IFU is not an extravagance but a must, as it avoids problems that arise from slit vignetting and systematic effects from wavelength calibration. ELT-HIRES will provide the complementary tool to ALMA to study the physical processes related to the dissipation of circumstellar disks in great detail. Planet formation proceeds via complex channels, and detailed high angular and high spectral resolution studies of young disks are required in order to develop a reliable theory of planet formation.

Magnetic fields have a very strong governance of the physical processes described above, and provide one of the dominant forces that shape the formation of extrasolar planets. Magnetic fields are likely to transport angular momentum via magneto-centrifugal acceleration of outflows from the disk surface, for instance via the Balbus-Hawley instability (e.g. Armitage, 2011, ARAA, 49, 195; and references therein). Insight into magnetospheric accretion processes is gained by means of multi-wavelength studies and time-resolved spectropolarimetric observations obtained at spectral resolutions of typically R > 50,000. Using spectropolarimetric methods, the structure of the magnetic fields close to a star or a protoplanetary disk may be reconstructed at spatial scales well below the resolution limit. An example is described by Donati et al. (2011, MNRAS 417, 1747) who obtained spectra of classical T Tau stars covering the 0.37 – 1 μm range at a spectral resolution of R = 65,000 in circular and linear polarisation. The authors were able to construct maps of the large-scale magnetic field, as well as maps of the accretion-powered emission at the surfaces of a star. Until now only few studies of the brightest stars exist, yet real population studies are critical. The ELT-HIRES polarimeter will be fundamental to further our understanding of the impact of magnetic fields on the evolution of protoplanetary disks.

The details of inner accretion processes in higher-mass pre-main-sequence objects have also been addressed by means of spectropolarimetry during the previous decade (e.g. Vink et al. 2002, MNRAS 337, 356). Especially intriguing is the perspective to reveal systematic differences when going to higher and higher stellar masses. For this, the polarisation properties of hydrogen lines and the immediate continuum signal have to be analysed, and patterns in the Stokes Q-U-space have to be interpreted. Based on spectropolarimetry, Mottram et al. (2007, MNRAS 377, 1363) have proposed that Herbig Ae stars show a similar behaviour to T Tau stars, and magnetospheric accretion might dominate and give rise to characteristic loops in Stokes Q-U space. Early-type Herbig Be stars, on the other hand, show a different behaviour, and a characteristic depolarisation effect in the lines is seen. In this particular paper, it was interpreted as a signature of disk accretion, different from the common accretion along magnetospheric accretion funnels in lower-mass stars. The exact cause of these line (de-)polarisation effects, however, is not clear yet. The authors mentioned above propose a pure scattering model where line photons are scattered on electrons in the inner circumstellar disk, and the geometries and sizes of the line-emitting regions and the size of an inner hole in the disk are governing the (de-)polarisation effects. A different explanation was proposed by Harrington & Kuhn (2009, ApJS, 180, 138) who suggest that the polarisation effects are governed by partial absorption of light in the (inner) circumstellar disk. In both interpretations, the analysis of the polarised continuum and line emission allows us to assess the geometry of the most inner part of the circumstellar disks and the accretion material between the disk and the central object. Still, the work by Harrington & Kuhn (2009) makes it obvious that the spectropolarimetry has to be coupled with high spectral resolution to fully reveal the intricate details of the line polarisation changes along the line profile and in order to facilitate a sound interpretation of these effects. It should be noted, however, that these particular spectropolarimetric studies do not depend on the accuracy of the absolute calibration of the polarimetric measurement system in terms of absolute polarisation degree and polarisation angle purity. The science is derived from a relative comparison of the polarimetric properties of the emission lines to the immediate continuum, and is therefore relatively robust with regard to polarimetric calibration issues (e.g. Vink, 2012, AIP Conf. Proc. 1429, 147).

3.3.2 Requirements derived from the science case

The key science described here aims to understand the various physical processes that compete in the dissipation of protoplanetary disks. It is thus required to obtain spatially resolved information on the interaction regions between the disk, the star, and the winds. Current observational constraints suggest that the wind launching mechanism occurs at distances of a few AU from the central star. At 100 pc, 1 AU corresponds to 10 mas, thus a field of view of 0.1 arcsec is required to study these processes in nearby star forming regions.

High resolution optical line studies (R ~ 100,000) provide important diagnostics of disk winds and accretion and insight into the evolution and dispersal of circumstellar disks. Optical forbidden lines and the near-IR lines explore a different parameter space, in general. As discussed above, the peak velocities of various forbidden lines are inversely proportional to the respective critical densities, a behaviour that is expected in a disk wind where the flow accelerates as it rises from the disk. The peak velocities are different by a few km/s which sets the required spectral resolution for this kind of studies. In contrast, the near-IR and the hydrogen recombination lines are generally used to derive physical parameters of the hot plasma near the central star – for instance, the Paα/Brγ ratio is sensitive to the temperature and the density of the emitting gas, and Brγ is generally used to derive the accretion luminosity, while the CaII IR triplet lines are used to determine surface accretion.

In order to disentangle molecular hydrogen emission from the inner (spatially unresolved) part of the disk requires spectro-astrometric observations which in turn require high spectral resolution (R ~ 100,000) (e.g. Beck et al., 2008, ApJ 676, 472).

Spectral resolution	100,000
Wavelength range	Total: 0.4 – 2.4 μm
Spatial resolution	Near-IR: diffraction limited, on-axis
Entrance aperture	Optical: 1 Near-IR: IFU with 100 mas field of view
Calibration	Sky subtraction: goal
Polarimetry	Yes

Table 3: Summary of requirements of this science case.

3.4 Stellar structure and evolution

3.4.1 Outline of the science case

3.4.1.1 Precise chemical composition of solar-type stars

Atmospheres of solar-type stars with parameters similar to the Sun are reasonably well understood. Nevertheless, abundance analyses of these objects rarely attain a precision of better than 0.1 dex, especially when fainter halo and cluster stars are considered. A number of recent studies demonstrated that a higher precision in the abundance determination helps to uncover signatures of key hydrodynamical processes and hence to better understand the structure and evolution of solar-type stars and even of the Sun itself. For example, atomic diffusion operates in dwarf and sub-giant stars and modifies the surface abundances by 0.05 – 0.2 dex (Korn et al., 2007, ApJ, 671, 402). Similarly, the (multiple) dredge up of CNO processed material in giants alters the surface light element abundances and isotopic ratios. There is evidence of a difference, at the level below 0.1 dex, of the volatile and refractory element abundances in the Sun and most solar-like stars (Meléndez et al., 2009, ApJ, 704, L66). This may be related to cleansing of the solar proto-planetary nebula from refractories by planetary formation, providing an indirect indicator of the presence of rocky planets. Intriguingly, the solar refractory vs. volatile abundance anomaly was also found for a solar twin in M67 (Önehag et al., 2011, A&A, 528, 85), possibly suggesting that the Sun originates from this cluster. These and other studies rely heavily on very precise relative and absolute abundances to establish the evolutionary status of stars, probe poorly understood mixing and circulation processes in their envelopes, and examine connections between stellar abundances and planetary companions. However, these studies are currently feasible only for a very limited sample of nearby field stars and only for a few individual cluster members. The dramatic gain in sensitivity provided by E-ELT will enable precise chemical abundance studies of large and unbiased samples of solar-type stars.

3.4.1.2 Spectroscopic parameters of M dwarf stars

M dwarfs are by far the most common type of star in our Galaxy and are currently the most promising targets for finding Earth-size planets in habitable zones. Despite a growing interest in M dwarfs, accurate information about their properties, including masses, radii and atmospheric parameters, is still lacking owing to difficulties with the theoretical modelling of their atmospheres, and to the observational challenge of studying overcrowded optical spectra of these stars at moderate spectral resolutions. Disentangling profiles of individual atomic and molecular lines in the spectra of these stars requires a high S/N and a resolution of ~150,000, which is challenging to obtain for faint objects even with the largest currently available telescopes. Near-IR wavelength regions are less affected by molecular blends, offering prospects for precise abundance analyses of M dwarfs (e.g. Önehag et al., 2012, A&A, 542, 33). But some lines in the optical are still indispensable as temperature and activity indicators. In this context ELT-HIRES will provide a unique opportunity to study the entire optical to near-IR spectra of thousands of M dwarfs at very high resolution. This observational material will allow precise determination of the atmospheric parameters and abundances for large samples of M dwarfs and will enable exploration of different populations of these stars beyond the immediate neighbourhood of the Sun.

3.4.1.3 Convection and 3D structures in stellar atmospheres

Modelling of stellar surfaces and atmospheres is being extended from relatively simple 1D hydrostatic models to sophisticated 3D hydrodynamic and magneto-hydrodynamic calculations. There is growing evidence that such models are necessary for obtaining precise abundances and parameters of stars (e.g. Pereira et al., 2013, A&A, 554, 118). It is critical that predictions of hydrodynamical models are thoroughly tested not only for the Sun, but also for a variety of late-type stars of different temperatures, evolutionary stages, and metallicities. Observations of spectral line shapes in high-resolution stellar spectra allow us to verify 3D inhomogeneities and velocity distributions predicted by hydrodynamical models. Uniquely for ELT-HIRES, the extension of the line profile analyses to atomic and molecular spectral lines across the entire optical to near-IR wavelength range will allow us to probe dynamics and inhomogeneities at different heights in stellar atmospheres. Furthermore, additional information about the centre-to-limb variation of the line intensities and profile shapes can be retrieved from very high S/N observations of the spectral variations during exoplanet transits across stellar disks.

High-resolution diffraction limited IFU spectroscopy in the near-IR would enable direct spatially resolved studies of stellar surface structures. This observing mode can be used to study giant convection cells, surface inhomogeneities, and immediate circumstellar environments for stars with large angular diameters. Such observations can provide novel observables to constrain models of stellar atmospheres, chromospheres and coronae, in particular to test 3-D MHD simulations of convection. Very high (> 10^5) spectroscopic resolution and high wavelength stability is essential for this science case in order to resolve convective radial velocity shifts and line profile changes across stellar disks.

Given the E-ELT's diffraction limit of ~6 mas at 1 µm, only about 40 M and K giants appear to be suitable for direct spatially-resolved spectroscopy. However, it is possible to detect global radial velocity patterns (e.g. stellar rotation, pulsation) even for stars with angular diameters significantly smaller than the E-ELT's diffraction limit using the principles of spectro-astrometry. Considering rotation Doppler shifts as an example, one can find that for a star with an angular diameter 5 times smaller than the diffraction limit, the observable range of Doppler shifts is about 2% of the projected rotational velocity. This translates to a radial velocity shift of 40 m/s even for such slow rotators as the Sun. Moreover, the line-dependent radial velocity shifts may allow one to use spectro-astrometry for probing the vertical structure of stellar atmospheres. If the diffraction limited PSF is adequately sampled, it is possible to use ELT-HIRES in its IFU mode for spectro-astrometric investigations of global velocity patterns in > 1000 stars, including many nearby dwarf stars of both early and late spectral types.

3.4.2 Requirements derived from the science case

The science cases described above require full optical/near-IR wavelength coverage, preferably simultaneously in order to be able to cope with time variable phenomena in active stars such as M dwarfs. This is needed to cover the full range of useful diagnostic atomic and molecular features, and to inter-calibrate and benchmark near-IR model atmosphere and abundance analyses against those carried out in the optical. The specific limits of 0.38 µm in the blue and 2.4 µm in the red are set by the Ca II K line and the CO band, respectively. The former is essential for the analysis of metal poor stars and as a magnetic activity indicator. The latter is useful (along with the atomic lines in the K band) for the derivation of atmospheric parameters and rotational velocities of late K and M dwarfs.

The spectral resolution required for the studies of weak lines, especially those in the spectra of metal-poor stars, and for resolving blends in the spectra of M dwarfs is 100,000 – 150,000. On the other hand, a resolution closer to 200,000 is necessary for the analyses of spectral line broadening and asymmetries produced by convective motions and/or magnetic fields.

Most of the stellar physics science cases impose modest stability requirements (~10 m/s).

Spatially resolved spectroscopy of stellar surfaces requires a diffraction limited IFU working in the near-IR. It should have a FoV extending to 15 – 20 mas to cover the stars with the largest angular diameters. At the same time, doing spectro-astrometry for smaller stars requires sampling the diffraction limited PSF with ~3 spatial resolution elements.

Spectral resolution	150,000 (goal: 200,000)
Wavelength range	Total: 0.38 – 2.4 μm Simultaneous: goal: 0.38 – 2.4 μm
Spatial resolution	Near-IR: diffraction limited, on-axis
Entrance aperture	Optical: 1 Near-IR: IFU with 20 mas field of view (goal: 3 spaxel sampling of the diffraction limited PSF)
Calibration	Wavelength: 50 m/s (goal: 10 m/s) Sky subtraction: goal
Stability	10 m/s/night
Other	Minimum allowed exposure time: 1 s Fast detector read-out mode Minimal downtime between successive exposures

Table 4: Summary of requirements of this science case.

3.5 Stellar magnetic fields

3.5.1 Outline of the science case

It is known (e.g. Bagnulo et al., 2012, A&A, 538, 129) that essentially all types of stars can harbour (surface) magnetic fields, from white dwarfs, fully convective dwarfs and protostars, to very massive stars having predominantly radiative envelopes. One or several dynamo mechanisms generate the magnetic fields, but these mechanisms are not understood. Indeed, we still do not understand the 11-year sunspot cycle of our own Sun. Stellar magnetic fields also have a dramatic impact on the circumstellar environment from the early stages when they influence protoplanetary disks and jets through planet formation and migration to being the source of interplanetary space weather that influences planetary atmospheres. Indeed, we still do not understand the underlying mechanism(s) that lead to magnetic fields on the Sun erupting violently and producing flares and coronal mass ejections that impact life and technology on Earth and in space.

Sensitive, high spectral resolution spectropolarimetry can now be performed to levels corresponding to average field strengths of about 0.1 Gauss (Snik et al., 2011, ASP Conf. Ser, 437, 237) on bright stars. By measuring the Zeeman signals as a function of the stellar rotation (Zeeman-Doppler Imaging), maps of the stellar magnetic field can be inferred for Ap, active late-type, T Tau stars and even solar analogues (Semel, 1989, A&A, 225, 456; Donati et al., 2003, MNRAS, 345, 1145; Petit et al., 2008, MNRAS, 388, 80; Kochukhov & Wade, 2010, A&A, 513, 13). Such maps can then in turn be used to study the evolution of stellar magnetic fields with the ultimate goal of understanding how dynamo mechanisms maintain magnetic fields in the universe.

Current spectropolarimeters have to average the information from all spectral lines to achieve sufficient S/N for the magnetic field measurements (e.g. Kochukhov et al., 2010, A&A, 524, 5). With the E-ELT, it will be possible to measure the magnetic fields in individual spectral lines, or at least in a combination of lines that have very similar sensitivities to certain atmospheric parameters. This will enable us to measure the magnetic field as a function of temperature, which will allow us to disentangle magnetic fields in dark starspots and bright plages. By measuring magnetic fields at different heights in a stellar atmosphere, using lines with different formation heights, the structure of the field with height in the atmosphere can be explored. This is a crucial observation to understand the formation of stellar chromospheres, coronae and stellar winds.

The light-collecting power of the E-ELT will also provide the opportunity to study magnetic fields on faint objects such as massive stars in the Magellanic Clouds, brown dwarfs and maybe even free-floating exoplanets. Near-IR polarimetric capability will also allow us to study magnetic fields of obscured protostars and accretion disks.

The Hanle effect, which modifies resonant scattering polarisation, is sensitive to even weaker magnetic fields than the Zeeman effect is, and it allows the measurement of magnetic fields in stellar winds (e.g. Ignace et al., 2004, ApJ, 609, 1018).

3.5.2 Requirements derived from the science case

The most common approach to measuring stellar magnetic fields employs the Zeeman effect in spectral lines, which changes the line shape and introduces intricate linear and circular polarisation signatures. The full set of Stokes parameters is required, but circular polarisation (V) is given priority over linear polarisation (Q, U). Since the polarisation signal is roughly proportional to the first derivative (circular polarisation) and second derivative (linear polarisation) of the spectral line in intensity with respect to wavelength, Zeeman polarimetry requires a higher spectral resolution than high-resolution intensity spectroscopy. Experience with instruments such as HARPSpol indicates that a spectral resolution of 100,000 is adequate, and a resolution of 150,000 would be desirable.

As sensitive polarimetry at high spectral resolution is photon starved and magnetic field signatures may change on timescales of hours or less, the complete spectrum must be recorded simultaneously. The required wavelength range for Zeeman effect observations is driven by two factors: 1) the decrease with wavelength in the number of spectral lines exhibiting useful Zeeman signatures and 2) the increase in Zeeman sensitivity of spectral lines with wavelength. In the blue, one wants to observe at least the CaII H and K lines and the CN molecular band at 0.37 μm as proxies for stellar magnetic fields and, in the red, the extremely sensitive TiI lines around 2.2 μm. The near-IR spectrum is also important when probing particularly cool and embedded (e.g. pre-main sequence) stars where little light is received at visible wavelengths. On the other hand, the Hanle effect is most prominent in the UV where the scattering polarisation of spectral lines is large.

Given typical amplitudes of stellar polarisation signatures, this science case requires an accuracy of 10^{-3} in measuring Stokes parameter profiles and a sensitivity of 10^{-5}.

Spectral resolution	100,000 (goal: 150,000)
Wavelength range	Total: 0.37 – 2.4 μm Simultaneous: 0.37 – 2.4 μm
Spatial resolution	Seeing limited
Entrance aperture	1
Calibration	Wavelength: 30 m/s For a source of suitable brightness it shall be possible to achieve S/N > 100 per pixel in the 1D extracted spectrum from a single exposure.
Polarimetry	I, Q (priority), U, V Polarimetric accuracy: 10^{-3} Polarimetric sensitivity: 10^{-5} (without photon noise contribution, using multi-line diagnostic)

Table 5: Summary of requirements of this science case.

3.6 Galactic archaeology

3.6.1 Outline of the science case

Nearby stellar systems are fundamental laboratories in which to constrain the dependence of chemical enrichment on environment. This applies not only to the Milky Way satellites, but also to giant and dwarf galaxies in the Local Group. Detailed knowledge of their properties requires a good sampling of the different galactic components (disks, halo, bulge), and therefore ubiquitous stellar tracers. In this context the red giant branch (RGB) stars play a crucial role, since they trace both old and intermediate-age stellar populations. The typical brightness of the tip of the RGB (TRGB) is $M_I \sim -4$ mag. This means that a high-resolution spectrograph reaching good S/N ratio in a few hours at a limiting magnitude of R ~ 21 mag can trace the TRGB in a significant fraction of nearby stellar systems.

The key advantage of an optical, high-resolution (R ~ 100,000) spectrograph covering the UBV region is that it is able to provide homogeneous measurements of the most popular diagnostics for tracing the chemical enrichment of different stellar populations in the Local Group. This applies not only to FeI and FeII, but also to α-elements and to s and r-elements, and in turn to different polluters (SN type I and II, AGB stars, Novae). In this context the wavelength interval between 0.37 and 0.44 μm is quite important, since this range includes both Hγ, and the CaII H and K lines, which are crucial for investigating cluster and field white dwarfs, as well as extremely metal-poor stars. ELT-HIRES can also play a crucial role in stellar cosmo-chronology, since it provides an independent method to estimate individual stellar ages. The idea is to use long-lived radioactive isotopes such as ^{232}Th (with a half-life of 14 Gyr) and ^{238}U (half-life 4.5 Gyr). The Th lines can be easily detected, but there is only one U line in the optical regime and it is located at 0.3859 μm (UII). Current estimates for cluster stars (Cayrel et al., 2001, Nature, 409, 691; Sneden et al., 2003, ApJ, 591, 936; Frebel & Kratz, 2009, IAUS, 258, 449) are still limited by the achievable S/N.

In this context the transition from Population III to Population II stars plays a crucial role, not only for the formation and initial evolution of the Milky Way, but also for the impact that the metal-free stellar structures have had on the early chemical enrichment of the interstellar medium. During the last few years high-resolution investigations of extremely metal-poor stars revealed that not all of them are C enriched (Frebel et al., 2006, ApJ, 652, 1585), but also C and N normal (Caffau et al., 2012, A&A, 542, 51).

Turning to the abundances of the primordial elements, we note that current empirical evidence indicates that the Spite plateau might not be a universal law. Indeed, the spread in current abundances steadily increases when moving into the metal-poor ([Fe/H < –3) and into the extremely metal-poor ([Fe/H < –5) regime. Lithium is typically destroyed during the pre-main sequence phase and in the approach to the main sequence, but it can also be produced during the AGB phase (hot bottom burning). The use of un-evolved stars will help to constrain the interplay between production and destruction.

The measurements of both primordial helium content and the helium-to-metal enrichment ratio ($\Delta Y / \Delta Z$) are still affected by large uncertainties. The helium lines are not easily detected in low-mass stars and when they can be measured (extreme horizontal branch stars) they are either affected by gravitational settling and by radiative levitation (Behr et al., 2003, ApJS, 149, 67) or they trace peculiar evolutionary channels (Moehler et al., 2011, A&A, 526, 136). However, during the last few years the helium abundance has been measured in a few warm horizontal branch stars by using the line at 0.5876 μm (Villanova et al., 2009, A&A, 499, 755; Villanova et al., 2012, ApJ, 748, 62). This approach appears very promising not only to constrain the primordial helium content, but also to shed new light on the nature of multiple populations in globular clusters.

More recently He lines have also been identified in field RR Lyrae stars at 0.5876 μm (HeI) and 0.4686 μm (HeII). They appear to be connected with the passage of the shock front during the phases of maximum compression (Preston, 2009, A&A, 507, 1621; 2011, AJ, 141, 6). The analysis of these lines and those at 0.4026 μm and 0.4471 μm is still in its infancy, but they have the potential to become a crucial diagnostic to constrain Big Bang Nucleosynthesis by using stellar absorption lines.

3.6.2 Requirements derived from the science case

Measuring CNO and Li in the Galactic Spheroid (bulge, disk, halo) requires a resolution of at least 50,000, although 100,000 would be optimal.

The wavelength range required for this case ranges from the Uranium line at 0.3859 µm to several optical lines like the Li doublet at 0.6708 µm, There are also several s and r-elements with lines between 0.5 and 0.8 µm.

The Helium lines detected in RR Lyrae stars are both in the UV and in the optical regime (0.4 – 0.59 µm). These lines appear to be formed by the passage of the shock soon after the phases of maximum compression (rising branch). The typical time scale for the rising branch is at most of the order of one hour. The outermost layers during these phases are far from being in local thermal equilibrium. For these reasons the UV and optical wavelength coverage is required simultaneously. Moreover, simultaneous UV-optical coverage provides the opportunity to obtain the most relevant lines for constraining chemical enrichment (CNO, α-elements, s and r- elements) in a single exposure.

A limiting magnitude of R ~ 20 – 21 mag would imply main sequence turn-off stars at a distance of 20 – 30 kpc, i.e. a good fraction of the low-reddening regions of the Galactic Bulge and a significant fraction of the inner halo. Current knowledge concerning extremely metal-poor stars in nearby stellar systems is still in its infancy, but these systems are fundamental to constrain possible differences caused by the environment.

The above limiting magnitude is also crucial to observe AGB stars in nearby galaxy clusters (Cen A, Sculptor), and in turn to constrain the production of Li in metal-rich AGB stars in ellipticals.

The spectroscopy of extremely metal-poor stars is limited by the candidates. Current spectroscopic surveys are biased toward evolved (brighter) extremely metal-poor targets. This limitation is even more severe in the Bulge, due to its intrinsic crowding.

Spectral resolution	50,000 (goal: 100,000)
Wavelength range	Total: 0.38 – 0.8 µm Simultaneous: 0.38 – 0.8 µm
Spatial resolution	Seeing limited
Entrance aperture	1
Calibration	Wavelength: ~100 m/s
Sensitivity	S/N = 70 for R = 21 mag in 3 h

Table 6: Summary of requirements of this science case.

3.7 Intergalactic medium

3.7.1 Reionisation and pristine gas

3.7.1.1 Outline of the science case

Within 300,000 years of the hot Big Bang, the Universe had expanded and cooled sufficiently to allow ions and free electrons to recombine, leaving the baryons almost completely neutral. Within one billion years, however, essentially all of the hydrogen in the Universe was once again ionised. The re-ionisation of hydrogen is believed to have been caused by ultraviolet photons from the first stars and galaxies, most of which are too faint to be observed directly, even with JWST.

High resolution spectroscopic observations of the intergalactic medium (IGM) seen in absorption against distant background QSOs have revealed that the reionisation process was complete by z ~ 5 – 6. Determining how and when reionisation proceeded in the early Universe is one of the hottest topics in astrophysics and requires high resolution and high S/N spectroscopic observations of QSOs and GRBs at z ~ 7 and beyond. QSOs at z ~ 7 are now being identified (Mortlock et al., 2011, Nature, 474, 616), and near-IR surveys such as those carried out by VISTA now and by Euclid in the future promise to uncover quasars out to z ~ 8 – 10 and beyond. A robust characterisation of the IGM ionisation state at z ~ 6 – 7 will require dozens of high-quality sight lines. Multiple lines of sight will be needed to determine the clumpiness of the IGM ionisation state and the degree to which reionisation is complete at a given redshift. The spectra must be observed at high resolution is to be able to detect the narrow transmission peaks that are the first features to appear in the Lyman-α forest.

QSO and GRB absorption line spectroscopy may also provide us with clues as to the nature of the stars that caused the reionisation of the Universe. Observations of Damped Lyman-α absorption systems (DLAs) are a powerful tool to measure the metal content of the Universe at high redshift. The most metal-poor DLAs, with $Z \sim 1/3000\ Z_{Sun}$ or [Fe/H] ~ −3.5, are particularly interesting as they are believed to have undergone minimal pollution from stars, and even more metal-poor systems may shed light on the properties of the very first population of stars in the Universe.

However, observations of these very metal poor (VMP) DLAs are extremely challenging with current facilities. It has taken several years to build up even modest samples of VMP DLAs with well determined abundances. Yet, there are burning questions waiting to be answered. In particular, with only two known examples of carbon-enhanced metal-poor DLAs it is impossible to draw general conclusions on the early generations of stars that seeded this gas. Also, the relative abundances of Fe-peak elements (i.e. Ti/Fe, Cr/Fe, Co/Fe, Ni/Fe, Zn/Fe) depend more sensitively on the masses, explosion energies and mass-cuts of the core-collapse supernovae that created them than the relative abundances of the more common alpha-capture elements. At present, however, absorption lines from these rarer species are too weak to be detected in individual VMP DLAs, and existing data are too few to give a definite result even with stacking techniques (e.g. Cooke et al., 2013, MNRAS, 431, 1625).

One of the most exciting prospects for ELT-HIRES is the detection of elements synthesized by the first stars in the Universe, the massive, metal-free Population III. Individual Pop III stars are expected to be too faint to detect directly, even with JWST. Evidence for Pop III stars, however, may be found from their nucleosynthetic yields, as potentially observed in the abundance patterns of VMP DLA systems. At higher redshifts, the elements produced by Pop III stars are less likely to have been diluted by those from subsequent generations of Pop II stars. Relative abundances have already been measured for a small number of low-ionization metal absorbers at z ~ 6 (Becker et al., 2012, ApJ, 744, 91) and suggest that chemical enrichment at z ~ 6 is already dominated by conventional Pop II nucleosynthesis. A comprehensive search for metals from Pop III stars, therefore, must extend to fainter ($m_z \sim 21$ mag), more numerous background quasars, and to higher redshifts. The known metal absorption lines at z ~ 6 are typically narrow (b < 10 km/s), and weaker than those in lower-redshift DLAs.

3.7.1.2 Requirements derived from the science case

The absorption lines to be studied for this case can be as narrow as a few km/s. Therefore, a spectral resolution of 100,000 is in principle needed to be able to deblend the individual components of an absorption system, and to measure the thermal and dynamical broadening of the absorbers. However, spectral resolution has to be traded off against the continuum S/N achievable for the faint tail of the QSO population at $z > 6$. It is estimated that a resolution of 50,000 represents the best compromise.

The requirement for the spectral coverage is given by the need to probe different metals (to reconstruct the chemical enrichment pattern tracing the different possible stellar progenitors) in different ionisation states. In particular, both low- and high-ionisation lines are needed to correct abundances for ionisation effects and to investigate the reionisation process. The primary low-ionisation lines are Si II, O I, and C II with rest-wavelengths in the range 0.1260 – 0.1334 μm. Coverage out to $z = 10$ thus requires a wavelength range out to 1.5 μm. Fe II λ1608 at $z = 10$ requires a spectral coverage out to 1.8 μm, while observing the high-ionisation doublet C IV λλ1548,1551 at $z = 10$ implies $\lambda = 1.7$ μm. It would also be highly desirable to observe the strong lines of singly ionised Fe and Mg, Fe II λλ2344–2600 and Mg II λλ2796–2803, as well as the neutral transitions Fe I λλ2484,2523,2967,2984, Si I λ2515, S I λ1807 and Mg I λλ2026,2853. These all require extension to 2.4 μm to be observed out to $z = 7.6$.

Spectral resolution	50,000 (goal: 100,000)
Wavelength range	Total: 0.6 – 1.8 μm (goal: 0.4 – 2.4 μm)
Spatial resolution	Seeing limited
Entrance aperture	1
Calibration	Sky subtraction: yes
Sensitivity	S/N = 50 for J_{AB} = 21 mag in 5 h

Table 7: Summary of requirements of this science case.

3.7.2 Tomography

3.7.2.1 Outline of the science case

The IGM at high redshift, as revealed by Lyα absorption systems, contains most of the baryons in the Universe. The IGM is therefore the reservoir of baryons for galaxy formation. In turn galaxies emit ionising photons and expel metals and energy through powerful winds, which affect the physical state of the gas in the IGM. The interplay between galaxies and its surrounding medium is therefore central in the field of galaxy formation. This happens on scales of the order of 1 Mpc or less, or about 2 arcmin at $z \sim 2.5$. At larger scales, the gas is in the linear regime and probes large-scale structures.

By detecting absorption systems on lines of sight separated by a few arcmin it is possible to study the topology of the IGM in the linear regime and to correlate the position of the galaxies with the density peaks. This gives important clues about the formation of structures at high redshift and allows us to characterise the interactions between galaxies and the IGM.

Structures in the spatial distribution of the IGM at moderate overdensities are expected to occur on scales larger than the Jeans scale, which corresponds to a transverse separation of about 0.5 – 2 arcmin at $z \sim 2$.

It is important to note that while the 3D distribution of the IGM at high redshift will be addressed also by other facilities like SKA, ELT-HIRES has the unique capability of mapping the *three-dimensional distribution of metals* within the cosmic web, by simultaneously detecting the metal absorption lines associated with Lyα systems, provided that the wavelength coverage extends to the near-IR. Such three-dimensional metallicity maps would provide key insights into the metal enrichment processes on large scales in the Universe.

3.7.2.2 Requirements derived from the science case

This case requires observations of the Lyα forest and of its associated metal lines. Thus, coverage down to at least 0.4 μm is essential, with coverage to 0.37 μm desirable. The far UV is not needed. Near-IR coverage will allow observations of the metal lines associated with the Lyα absorbers in order to trace the global metal enrichment and α/Fe enhancement. Accessing the strong Mg and Fe lines at 0.23 – 0.28 μm out to z ~ 3.6 requires the wavelength range to extend to 1.3 μm.

3D reconstruction requires probing the IGM with tens to hundreds of lines of sight. Therefore a multiplex of the order of a few to ten is desirable to increase the observing efficiency. The angular scale to be probed (~1 arcmin) implies that the patrol FoV for the multiplex is ~10 $arcmin^2$.

Since QSOs are not numerous enough to reach the required source density of ~1 $arcmin^2$, Lyman Break Galaxies (LBGs) will have to be used as targets. LBGs reach the required cumulative source density at R ~ 24 mag (Steidel et al., 2009, “Astro2010: The Astronomy and Astrophysics Decadal Survey”, Science White Papers, no. 286).

The spectral resolution required for this case is derived from the need to match the velocity dispersion of individual star clusters in the LBGs, ~30 km/s (i.e. R ~ 10,000). This resolution is also needed to resolve the Jeans length of the IGM along the line of sight, and is a good match to the resolution across the line of sight. This resolution is also sufficient for setting the continuum level. However, when using LBGs as background sources, deblending the metal lines originating in the LBGs from those in the IGM may require a higher resolution of ~20,000.

Spectral resolution	10,000 (goal: 20,000)
Wavelength range	Total: 0.4 – 1.3 μm (goal: 0.37 – 1.3 μm)
Spatial resolution	Seeing limited
Entrance aperture	1 (goal: 10)
Calibration	Sky subtraction: yes
Sensitivity	S/N = 15 for R = 24 mag in 5 h

Table 8: Summary of requirements of this science case.

3.8 Extragalactic transients

3.8.1 Outline of the science case

Gamma-ray burst (GRB) afterglows provide an alternative to quasars for probing the ISM in high-redshift galaxies, as well as the IGM. These afterglows typically outshine quasars by several orders of magnitude, and thereby serve as convenient background sources against which to study the intervening gas along the line-of-sight. If the data are of sufficient quality, physical properties of the ISM can be derived, including metallicity, dust-to-gas ratio, ionisation state, and extinction laws. As long-duration GRBs are believed to arise from massive stars, they are typically well-embedded in their host galaxies, and provide a sensitive probe of the host-galaxy ISM, complementary to quasars that probe intervening systems at much larger impact parameters. Furthermore, GRBs are also expected to arise from early stellar populations in proto-galaxies, thereby offering the chance to pinpoint the location of these galaxies, and offer a fleeting view of the ambient conditions. As GRB afterglows fade by several magnitudes per day, the time-window for carrying out these observations is particularly narrow, necessitating rapid follow-up.

The relatively recent discovery of a particularly luminous class of supernovae ($M_V \sim -22 - -23$ mag) may offer some respite in response times as they tend to have light curves that are relatively long-lived. Transients belonging to this category have already been detected out to z ~ 1.5, and their potential has already been demonstrated. However, as the underlying nature of these objects is currently unknown, the expected rate calculations at higher redshifts are highly uncertain.

Although high-resolution spectroscopy will only be feasible for a subset of GRBs (e.g. those that are exceptionally bright at intermediate redshifts), follow-up of larger samples (tens to hundreds) of afterglows and host galaxies will be possible with ELT-IFU, thereby providing a holistic view of GRBs, their immediate environs, and the IGM along various sightlines.

3.8.2 Requirements derived from the science case

The primary requirements are on spectral resolution, wavelength range and response times.

High-resolution (R ~ 50,000) spectroscopy allows for clean separation of narrow components, permitting metal column densities to be measured. These can be compared with studies of metal-line systems associated with DLAs along the line-of-sight to bright background quasars.

Simultaneous high resolution and broad wavelength coverage is a powerful combination for a number of reasons: it allows accurate redshifts to be derived from a large number of lines for the GRB (and therefore its peak absolute brightness), as well as any intervening systems; it allows constraints to be placed on the ionisation state of the UV-absorbing gas by covering wavelength regions that contain both high and low ionisation species of different elements, e.g. CIV λλ 1550,1548; CII λ1334; AlII λ 1670; AlIII λ 1854. In addition, a wide wavelength range can accommodate bursts occurring in a wide range of redshifts, with different associated line diagnostics. Finally, given the short decay time of GRBs, wide *simultaneous* wavelength coverage is essential for obtaining high S/N.

The limited time window to perform observations such as those described above imposes a requirement on response times between triggering of observations and the commencement of on-source integration.

Spectral resolution	50,000 (goal: 100,000)
Wavelength range	Total: 0.4 – 2.4 μm Simultaneous: 0.4 – 1.3 μm (goal: 0.4 – 2.4 μm)
Spatial resolution	Seeing limited
Entrance aperture	1
Calibration	Sky subtraction: yes
Other	Rapid response mode: total response time $\lesssim$ 10 min

Table 9: Summary of requirements of this science case.

3.9 Fundamental physics

The observational evidence for the acceleration of the Universe demonstrates that our canonical theories of gravitation and particle physics are incomplete, if not incorrect. The recent LHC detection of a Higgs-like particle shows that fundamental scalar fields are part of Nature's building blocks. A pressing follow-up question is whether this field has a cosmological role, or indeed if there are cosmological counterparts. The next generation of ground-based and space-borne astronomical facilities must therefore carry out precision consistency tests of our current paradigms and search for new physics beyond them.

The E-ELT will play a leading role in this endeavour. While several of its instruments are expected to contribute (cf. ELT-CAM's tests of gravity in the strong field regime and ELT-IFU's characterization of type Ia supernovae at redshifts z > 2), it is clear that the high resolution and stability of ELT-HIRES make it a unique tool for fundamental physics. In addition to the intrinsic merit of these science cases, they also provide key synergies with other facilities such as ALMA, Euclid, the SKA and possible future space-borne gravitational wave detectors (such as DECIGO and BBO).

3.9.1 The redshift drift: watching the Universe expand in real time

3.9.1.1 Outline of the science case

Cosmic acceleration is the most profound enigma of modern physics: even the most conservative available explanation requires 70% of the Universe to be in the form of a fluid, never seen in the laboratory, which among other things makes gravity repulsive. Any possible explanation points towards entirely new physics, and consequently its discovery has sparked intense interest in mapping the expansion history of the Universe.

Observables that depend on the expansion history include distances and the linear growth of density perturbations: SNIa surveys, weak lensing, redshift space distortions and baryon acoustic oscillations in the galaxy power spectrum can all be used as probes of the acceleration. ESA's Euclid mission, currently scheduled for launch in 2020, is expected to use some or even all them to map the expansion history of the Universe at z < 2 (Laureijs et al., 2011, arXiv:1110.3193). However, all of these methods are geometric in the sense that they seek to deduce the evolution of the expansion by mapping out our present-day past light-cone. None of these actually probe the global dynamics of the Friedman-Robertson-Walker metric.

The redshifts of cosmologically distant objects drift slowly with time (Sandage, 1962, ApJ, 136, 319). This redshift drift rate provides direct measurement of the Universe's expansion history, with the key conceptual advantage of being a non-geometric, completely model-independent test, uniquely probing the global dynamics of the metric (Liske et al., 2008, MNRAS, 386, 1192). Rather than mapping our (present-day) past light-cone, it directly measures evolution by comparing past light-cones at different times. A further (practical) advantage is that once a first epoch of observations is made, the redshift drift signal grows linearly with time.

The observational challenge is that the drift rate is expected to be extremely small: ~6 cm/s/decade at z = 4 for a Planck-like standard cosmology (Liske et al. 2008). Nevertheless, the Lyα forest of absorption lines seen towards background QSOs is a promising target (Loeb, 1998, ApJ, 499, L111): the lines are numerous, ubiquitous, reasonably narrow (~10 – 30 km/s) and likely to be sufficiently immune to peculiar accelerations.

Redshift drift measurements by ELT-HIRES are crucial to probe the 'redshift desert' (2 < z < 5), characterizing dark energy beyond the regime where it is dynamically important: CMB results on w_0, H_0 and Ω_m can be improved by factors of ~3, 3 and 2, respectively (Martinelli et al., 2012, PhysRevD, 86, 123001): these improvements are not due to a better sensitivity of the redshift drift, but simply due to key degeneracies being broken. Recently, the HI 21 cm line has been reconsidered as another probe of the redshift drift (Darling, 2012, ApJ, 761, L26). The SKA may enable redshift measurements both at $z < 1$ and at $z > 8$ (SKA White paper, arXiv:1301.4124, 45) while intensity mapping experiments such as CHIME may probe the range $0.8 < z < 2.5$ (Yu et al., 2013, arXiv:1311.2363). Furthermore, Yagi et al. (2012, JCAP, 4, 31) argue that future space-based gravitational wave observatories such as the proposed DECIGO and BBO can measure it at $z \sim 0.5$ using gravitational wave detections of neutron star binaries. Although detailed feasibility studies of these methods remain to be done, we have an opportunity to directly map the expansion history of the Universe, all the way from the low-redshift accelerated phase to deep into the matter era (beyond $z = 4$) with no model-dependent assumptions beyond those (practical ones) of homogeneity and isotropy.

3.9.1.2 Requirements derived from the science case

The main conclusion that emerged from the Phase A study (Liske et al. 2008) is that, given the number of known, bright (V ~ 15 – 17 mag), high-redshift (z ~ 2 – 4) QSOs, a 39-m E-ELT with 25% total efficiency could detect the redshift drift of the Lyα forest with ~4000 h observing time by monitoring the 10 – 20 most suited targets over a period of ~20 yr. The extremely high S/N spectra of the target QSOs will offer other unique scientific opportunities (including measurements of α discussed below). The discovery of just a few very bright (V ~ 15.5 – 16.2 mag) quasars at z ~ 2.7 – 3.2 could substantially reduce the observing time required and/or the duration of the test. Future southern all-sky surveys may well identify such objects: their optical colours are very similar to stars, so previous surveys may have missed them.

At z ~ 2 – 4 the difference in the predicted redshift drift of a $(\Omega_M,\Omega_\Lambda) = (0.3,0.7)$ and (0.3, 0.0) universe is ~0.6 cm/s/yr (Liske et al. 2008). Being able to distinguish between these models with 3σ significance in 10 yr thus requires an instrument lifetime of 10 yr (goal: 20 yr) and an overall radial velocity precision and accuracy of ~2 cm/s (goal: 1 cm/s). This value refers to the *total* precision and accuracy of the experiment, i.e. summed over all observations of all absorption lines towards all QSOs included in the experiment. The main requirement on ELT-HIRES is that it shall not induce any systematic errors that would prevent us from achieving this level. Furthermore, given the very large amount of observing time required to achieve this level even when photon noise is the only source of error, ELT-HIRES is required not to increase the total radial velocity random error by more than 1% (goal: 0.5%) compared to the photon-noise-only case.

Fundamentally, the experiment consists of comparing the positions of spectral features at different times. Given the long timescales involved it is unfeasible to perform this comparison in detector space, and it must be performed in wavelength (or frequency, velocity, redshift or some equivalent) space instead (we will assume velocity space in the following). However, given the relative faintness of QSOs, photon noise will limit the radial velocity precision (of an entire QSO spectrum) to ~0.5 m/s in any single exposure, even in the best cases (using the scaling relations of Liske et al. 2008). Since each spectrum is composed of ~10^2 spectral features, the photon-noise limited precision with which the radial velocity of an individual spectral feature in a single QSO observation can be determined is ~5 m/s. The requirement not to degrade this precision by more than 1% (goal: 0.5%) thus translates to a requirement on the instrument-induced random error on the radial velocity of a single spectral feature in a single, fully calibrated exposure of no more than 0.7 m/s (goal: 0.5 m/s).

Furthermore, in order to be able to compare the positions of spectral features at different wavelengths and at different times (both are required to achieve the necessary overall precision), any instrument-induced bias in the radial velocity of a single spectral feature in a single, fully calibrated exposure is required not to vary by more than 2 cm/s (goal: 1 cm/s) as a function of the position on the detector and as a function of time over all timescales up to the lifetime of the instrument. Put differently, the short-term, exposure-to-exposure instrument-related reproducibility of the radial velocity of a single spectral feature in a single exposure shall not be degraded by more than 2 cm/s (goal: 1 cm/s) when sampling longer timescales up to the lifetime of the instrument. Note that for this experiment a radial velocity bias that is completely constant as a function of time and position on the detector is essentially irrelevant.

Again, the main requirement on ELT-HIRES is that it shall allow the precision of a radial velocity measurement to increase as the square-root of the S/N and as the square-root of the number of spectral features used (i.e. the error shall remain photon-noise dominated) down to a level of 2 cm/s (goal: 1 cm/s). In particular, this includes the ability to ‘stack’ lines from the same spectrum. Note that this implies that the error on the radial velocity of a single spectral feature must be uncorrelated with the error of other features in the same spectrum (and in other spectra). This is non-trivial as the wavelength calibration may introduce radial velocity errors that are correlated across a large wavelength range in a single exposure.

Laser frequency combs can likely provide the necessary wavelength calibration information per exposure (Murphy et al., 2007, MNRAS, 380, 839). Prototype systems have been demonstrated several times (Steinmetz et al., 2008, Science, 321, 1335; Wilken et al., 2010, MNRAS, 405, L16; Murphy et al., 2012, MNRAS, 422, 761; Wilken et al., 2012, Nature, 485, 611).

It has also been emphasised (Liske et al. 2008) that, if the specific scientific goal is the best possible constraint on Ω_Λ from global dynamics, then observing the Lyα forest over a large redshift range is important. Specifically, one needs to be able to observe down to z = 2 (goal: 1.9), where the drift is expected to change sign, and up to z = 5, where the high density of the Lyα lines begins to affect the sensitivity of the Lyα forest to radial velocity shifts. This sets the blue end of the required wavelength range to 0.37 µm (goal: 0.35 µm), and the red end to 0.73 µm. The requirement for the blue end may be alleviated if low-redshift (i.e. z < 2) measurements were performed by SKA or CHIME, where the drift is smaller in magnitude but opposite in sign to that at z ~ 3.

Lyα forest lines have widths ≥ 7 km/s, so only a moderate resolving power of R ~ 45,000 is needed to resolve them. However, R ≥ 100,000 is likely required to achieve the required wavelength calibration precision and accuracy (Murphy et al. 2007).

This science case is very much photon starved. The precision of a redshift drift measurement is directly related to the S/N of the data. Achieving the highest possible throughput is therefore essential.

Spectral resolution	100,000
Wavelength range	Total: 0.37 – 0.73 µm (goal: 0.35 – 0.73 µm)
Spatial resolution	Seeing limited
Entrance aperture	1
Calibration	Wavelength: 0.7 m/s (goal: 0.5 m/s), stable to within 2 cm/s (goal: 1 cm/s) over the lifetime of the instrument Sky subtraction: yes
Sensitivity	S/N = 400 for V = 16 mag in 1 h
Other	Instrument lifetime: 10 yr (goal: 20 yr)

Table 10: Summary of requirements of this science case.

3.9.2 Fundamental constants: mapping the dark universe

3.9.2.1 Outline of the science case

Nature is characterized by a set of physical laws and fundamental dimensionless couplings, which historically we have assumed to be spacetime-invariant. For the former this is a cornerstone of the scientific method, but for the latter it is only a simplifying assumption without further justification. We have no 'theory of constants', that describes their role in physical theories or even which of them are really fundamental. Indeed, our current working definition of a fundamental constant is simply: any parameter whose value cannot be calculated within a given theory, but must be found experimentally.

Fundamental couplings are known to run with energy, and in many extensions of the standard model they will also roll in time and ramble in space (i.e., they will depend on the local environment). In particular, this will be the case in theories with additional spacetime dimensions, such as string theory.

A detection of varying fundamental couplings will be revolutionary: it will automatically prove that the Einstein Equivalence Principle is violated (and therefore that gravity can't be purely geometry), and that there is a fifth force of nature. Moreover, even improved null results are important, as these rule out otherwise viable dark energy models.

In theories where a dynamical scalar field yields, say, a variation of the fine-structure constant α, the other gauge and Yukawa couplings are also expected to vary. In particular, in Grand Unified Theories the variation of α is related to that of the energy scale of Quantum Chromodynamics, whence the nucleon masses necessarily vary when measured in an energy scale that is independent of QCD (such as the electron mass). It then follows that a variation of the proton-to-electron mass ratio μ is also expected, although the relative size of both variations will be model-dependent.

Recent astrophysical evidence from quasar absorption systems suggests a parts-per-million spatial variation of α at redshifts 2 – 3 (Webb et al., 2011, PhysRevL, 107, 191101), with no corresponding variation seen in μ. Although no known theoretical model can explain such a result without considerable fine-tuning, it should also be said that there is also no identified systematic effect that can explain it. Nevertheless it is clear, in particular from the ongoing analysis of a dedicated UVES Large Programme (Molaro et al., 2013, A&A, 555, 68; Rahmani et al., 2013, MNRAS, 435, 861) that current measurements are limited both by S/N and by the ability to identify and control systematics.

High-resolution ultra-stable spectrographs such as ESPRESSO and ELT-HIRES will be needed to clarify the issue. Measurements of these couplings (whether they are detections or upper bounds) also constrain the dynamics of the dark sector of the Universe: a reconstruction using α measurements from ELT-HIRES can be more accurate than using a next-generation 3000 supernova dataset (Amendola et al., 2012, PhysRevD, 86, 063515), its key advantage being the much larger redshift lever arm.

The importance of having measurements of several dimensionless couplings (such as α and μ) or combinations thereof cannot be overstated, as these can provide unique tests of unification scenarios. These tests typically require measurements with accuracy better than parts-per-million, and with currently available data they can only reliably be done using atomic clock measurements at $z = 0$ (Ferreira et al., 2012, PhysRevD, 86, 125025). ELT-HIRES will make similarly precise tests possible in the early Universe.

3.9.2.2 Requirements derived from the science case

The transition frequencies of the ubiquitous narrow metal absorption lines from quasar absorption systems are sensitive to α (Bahcall et al., 1967, PhysRevL, 19, 1294) and those of the relatively rare H_2 absorbers are sensitive to μ (Thompson, 1975, ApL, 16, 3). In both cases, the different transitions have different sensitivities, so, observationally, one expects relative velocity shifts between different transitions in an absorber, in a single spectrum, if the constants indeed vary. A relative variation in α or μ of 1 part per million leads to velocity shifts of ~20 m/s between typical combinations of transitions.

Tripling the resolving power from the currently typical R ~ 50,000 to ~150,000 would not improve the precision by a factor of 3 because, in most metal-ion absorption profiles, many velocity components exist, with widths ≥ 1 km/s each, and are closely blended together; i.e. the sharpest features in most absorption systems are already resolved at R ~ 50,000.

Avoiding systematic errors is the critical step for improving on current measurements. To achieve this, future instruments must enable much more accurate calibration than is currently possible with UVES. In addition, improved laboratory measurements of the restframe wavelengths of the relevant transition will also be needed (Berengut et al. 2011, in From Varying Couplings to Fundamental Physics, 9).

The required wavelength range is determined by the desire to cover as great a range in redshift as possible. In particular, we would like to get as close to the transition to a Λ-dominated Universe at z ~ 0.7 as possible. In addition, we would like to observe the large number of H_2 transitions at rest wavelengths of 0.0913 – 0.11 μm towards the very brightest quasars which lie at relatively low redshifts (z ~ 2). Thus a very blue lower end of the wavelength range (goal: 0.33 μm) is desirable. This goal may be relaxed if (a) reliable radio/millimetre-wave molecular absorbers (such as methanol) can be identified at z ~ 1 – 2.5, and (b) more bright quasars with H_2 absorbers are identified at redshifts z ≥ 3 beyond the few currently known. The upper end of the required wavelength range is determined by the need to observe the MgII doublet at 0.28 μm, which acts as an 'anchor' in α measurements, up to a redshift of 2 (goal: 2.2).

It is worth bearing in mind that ESPRESSO at the VLT should achieve these requirements well before the E-ELT is built, although only in the optical, but not in the near-IR. Nevertheless, the E-ELT will have the best chance of finding a new effect below the noise level of all other telescopes by virtue of its larger collecting area. ELT-HIRES does have a further advantage over ESPRESSO in its near-IR coverage, which may allow precise measurements well beyond z = 4 (although relatively little work exists in this area, it has much unexplored potential).

Again, this science case is limited by S/N, requiring the maximum possible throughput, in particular at the blue end of the required wavelength range. Note that even a null result will provide significant constraints on cosmological models (Amendola et al. 2012) if the sensitivity and wavelength range requirements are met.

Spectral resolution	100,000 (goal: 120,000)
Wavelength range	Total: 0.37 – 0.84 μm (goal: 0.33 – 0.9 μm)
Spatial resolution	Seeing limited
Entrance aperture	1
Calibration	Wavelength: 2 m/s (goal: 1 m/s) Sky subtraction: yes
Sensitivity	S/N = 400 for V = 16 mag in 1 h

Table 11: Summary of requirements of this science case.

3.9.3 The CMB temperature: mapping the bright Universe

3.9.3.1 Outline of the science case

When one finds direct evidence for new physics, it will only be believed once it is seen through multiple independent probes. It is therefore crucial to develop a set of possible consistency tests – in other words, astrophysical observables whose behaviour will also be non-standard as a consequence of varying couplings or dynamical dark energy.

One of the most remarkable measurements in cosmology is the intensity spectrum of the cosmic microwave background radiation: at z = 0 one finds a very precise black-body spectrum. However, this tells us nothing about the behaviour of the CMB at non-zero redshift. The CMB temperature-redshift relation, $T(z) = T_0\ (1+z)$, is a robust prediction of standard cosmology but it assumes adiabatic expansion and photon number conservation. This is violated in many scenarios, including string theory inspired ones as well as models where α varies. Phenomenological deviations from this law are only constrained to percent level.

The distance duality relation, $d_L(z) = (1+z)^2\ d_A(z)$, is an equally robust prediction of standard cosmology; it assumes a metric theory of gravity and photon number conservation, but again is violated if photon number is not conserved. In fact, in many such models (including varying-α ones) the temperature-redshift relation and the distance duality relation are not independent: a direct relation exists between the violations of the two laws. Exploiting this link recently led to a 40% improvement on the current constraints (Avgoustidis et al., 2012, JCAP, 2, 13).

Moreover, it has also been established that in a fairly broad set of models the redshift dependence of the relative deviation of the T(z) law follows that of the relative change in alpha, although the proportionality factor between the two is model-dependent (Avgoustidis et al., 2013, arXiv:1305.7031). Given that, at least in the simplest models, the evolution of α and μ is monotonic, it follows that one should ideally test the T(z) law deep in the matter era, where any deviations to the standard behaviour are expected to be largest.

The current percent-level constraints do not have a strong impact on theoretical models, Progress in the number and sensitivity of low-redshift T(z) measurements will come from using clusters in the Planck SZ catalogue and also from ALMA, but ELT-HIRES will be the key instrument for improving the high-redshift spectroscopic measurements and thus (due to the large redshift lever arm) ultimately provide a crucial consistency check for any claims of α or μ variations at the level of the claimed α dipole. Such constraints will also be important for Euclid science (Avgoustidis et al. 2013).

3.9.3.2 Requirements derived from the science case

The CMB temperature at $z > 0$ can be measured spectroscopically by using the excitation of interstellar atomic (like CI) or molecular species (like CN or CO) that have transition energies in the sub-millimetre range and can be excited by CMB photons. When the relative populations of the different energy levels are in radiative equilibrium with the CMB radiation, the excitation temperature of the species equals that of the black-body radiation at that redshift. The detection of these species in diffuse gas, where collisional excitation is negligible, provides one of the best thermometers for determining the black-body temperature of the CMB in the distant Universe (Bahcall & Wolf, 1968, ApJ, 152, 701).

While the measurements involving atomic species are limited by 'theoretical' uncertainties in physical parameters in the clouds, and while CN (an excellent thermometer in the Galaxy) has not been detected at high redshift, CO has been recently detected in diffuse gas at high redshift, and these measurements are currently limited by S/N. At present there are five measurements in the redshift range $z \sim 1.7 – 2.7$ with uncertainties of order 0.7 K (Noterdaeme et al., 2011, A&A, 526, L7). These can be improved significantly by ELT-HIRES. The number of currently known systems where these measurements can be made is very limited, and thus identifying additional lines of sight in which CO can be detected is highly desirable.

The specific requirements are similar to those for μ measurements, already discussed above. First, one needs high resolution (R > 100,000) to be able to adequately model the absorption systems from which the T(z) measurements are derived. Furthermore, good throughput down to very short wavelengths is needed in order to be able to observe the electronic transitions of CO around 0.14 μm and thus probe T(z) at $z \sim 2$. Although the E-ELT will be able to perform T(z) measurements at redshifts higher than those of current measurements (if suitable absorption systems can be found), we nevertheless need to improve the existing constraints on T(z) in the currently known systems at $z \sim 1.7 – 2.7$ (goal: 1.5 – 4).

Note that these measurements are not necessarily costly in terms of telescope time, since in many such systems μ can also be measured. This would be important in case a deviation from the standard behaviour were detected: if a variation of μ is found one will also expect a breakdown of the standard T(z) law – by an amount that is precisely calculable, though somewhat model-dependent – and thus being able to measure both in the very same system would be an ideal consistency test.

Spectral resolution	100,000 (goal: 120,000)
Wavelength range	Total: 0.37 – 0.57 μm (goal: 0.34 – 0.82 μm)
Spatial resolution	Seeing limited
Entrance aperture	1
Calibration	Wavelength: 2 m/s (goal: 1 m/s) Sky subtraction: yes
Sensitivity	S/N = 400 for V = 16 mag in 1 h

Table 12: Summary of requirements of this science case.

4 Derived science requirements

4.1 Compilation of requirements from the science cases

	Spectral resolution	Wavelength range	Spatial resolution	Entrance aperture	Calibration
Solar System	100,000 in V 30,000 in J, H 60,000 in K	Total: 0.4 – 2.4 μm Simultaneous: λ / Δλ = 20	Near-IR: diffraction limited, on-axis; differential movement between target and NGS; LGS	Optical: 1 Near-IR: IFU with 200 mas FoV	
Exoplanet atmospheres	100,000	Total: 0.38 – 2.4 μm Simultaneous: 0.38 – 2.4 μm	Seeing limited	1 (goal: 2)	Wavelength: 50 m/s (goal: 10 m/s) Shall be possible to reach S/N > 1000
Protoplanetary disks	100,000	Total: 0.4 – 2.4 μm	Near-IR: diffraction limited, on-axis	Optical: 1 Near-IR: IFU with 100 mas FoV	(Goal: sky subtraction)
Stellar structure and evolution	150,000 (goal: 200,000)	Total: 0.38 – 2.4 μm (Goal: Simultaneous: 0.38 – 2.4 μm)	Near-IR: diffraction limited, on-axis	Optical: 1 Near-IR: IFU with 20 mas FoV (goal: 3 spaxel sampling of the diffraction limited PSF)	Wavelength: 50 m/s (goal: 10 m/s) (Goal: sky subtraction)
Stellar magnetic fields	100,000 (goal: 150,000)	Total: 0.37 – 2.4 μm Simultaneous: 0.37 – 2.4 μm	Seeing limited	1	Wavelength: 30 m/s Shall be possible to reach S/N > 100
Galactic archaeology	50,000 (goal: 100,000)	Total: 0.38 – 0.8 μm Simultaneous: 0.38 – 0.8 μm	Seeing limited	1	Wavelength: ~100 m/s
Reionisation and pristine gas	50,000 (goal: 100,000)	Total: 0.6 – 1.8 μm (goal: 0.4 – 2.4 μm)	Seeing limited	1	Sky subtraction

IGM tomography	10,000 (goal: 20,000)	Total: 0.4 – 1.3 μm (goal: 0.37 – 1.3 μm)	Seeing limited	1 (goal: 10)	Sky subtraction
Extragalactic transients	50,000 (goal: 100,000)	Total: 0.4 – 2.4 μm Simultaneous: 0.4 – 1.3 μm (goal: 0.4 – 2.4 μm)	Seeing limited	1	Sky subtraction
Redshift drift	100,000	Total: 0.37 – 0.73 μm (goal: 0.35 – 0.73 μm)	Seeing limited	1	Wavelength: 0.7 m/s (goal: 0.5 m/s), stable to within 2 cm/s (goal: 1 cm/s) over the lifetime of the instrument Sky subtraction
Fundamental constants	100,000 (goal: 120,000)	Total: 0.37 – 0.84 μm (goal: 0.33 – 0.9 μm)	Seeing limited	1	Wavelength: 2 m/s (goal: 1 m/s) Sky subtraction
CMB temperature	100,000 (goal: 120,000)	Total: 0.37 – 0.57 μm (goal: 0.34 – 0.82 μm)	Seeing limited	1	Wavelength: 2 m/s (goal: 1 m/s) Sky subtraction

Table 13: Summary of requirements from all science cases.

	Stability	Sensitivity	Polarimetry	Other
Solar System				
Exoplanet atmospheres	50 m/s/night (goal: 10 m/s/night)		Goal: Polarimetric sensitivity: 10^{-4} Wavelength range: 0.8 – 2.4 μm (goal: 0.38 – 2.4 μm)	Minimum allowed exposure time: 1 s; fast detector read-out mode; minimal downtime between successive exposures
Protoplanetary disks			Yes	
Stellar structure and evolution	10 m/s/night			Minimum allowed exposure time: 1 s; fast detector read-out mode; minimal downtime between successive exposures
Stellar magnetic fields			I,Q,U,V Polarimetric accuracy: 10^{-3} Polarimetric sensitivity: 10^{-5}	
Galactic archaeology		R = 21 mag t_{exp} = 3 h S/N = 70		
Reionisation and pristine gas		J_{AB} = 21 mag t_{exp} = 5 h S/N = 50		
IGM tomography		R = 24 mag t_{exp} = 5 h S/N = 15		
Extragalactic transients				Rapid response mode: total response time $\lesssim$ 10 min
Redshift drift		V = 16 mag t_{exp} = 1 h S/N = 400		Instrument lifetime: 10 yr (goal: 20 yr)
Fundamental constants		V = 16 mag t_{exp} = 1 h S/N = 400		
CMB temperature		V = 16 mag t_{exp} = 1 h S/N = 400		

Table 14: Summary of requirements from all science cases (continued).

4.2 Science requirements for ELT-HIRES

Spectral resolution	The highest spectral resolution is required by the stellar structure and evolution case: R = 150,000 (goal: 200,000). Most of the other cases require R > 50,000 – 100,000. The only exception is the IGM tomography case, which does not need such high resolution, and only requires R > 10,000.
Wavelength range	The wavelength range in which ELT-HIRES shall be able to observe is 0.37 – 2.4 μm (goal: 0.33 – 2.4 μm). The blue end of this range is motivated by the need of the stellar cases to observe the Ca H and K lines, and by the need of the fundamental physics cases to cover a wide redshift range and in particular to push to relatively low redshifts. Furthermore, to be able to cope with various forms of variability on the timescales of hours and less, all of the stellar cases, as well as the exoplanet atmospheres case, require (or at least set as a goal) that a broad wavelength range is recorded simultaneously. In particular, the stellar magnetic fields and exoplanet cases require a simultaneous wavelength range of 0.37 – 2.4 μm, at a resolution of 100,000. The stellar structure and evolution case sets the simultaneous coverage of this range at a resolution of 150,000 as a goal.
Spatial resolution	Many science cases have point sources as their targets and hence do not require any spatial resolution. However, the solar system and protoplanetary disk cases, and to a lesser extent the stellar structure and evolution case, largely rely on spatially resolved information on their targets, and thus require, at wavelengths $\gtrsim$ 1 μm, diffraction limited spatial resolution on-axis. Observations of solar system objects involve differential motion between the science target and the natural guide star. For some solar system objects no natural guide stars are available.
Entrance aperture	Most science cases require an entrance aperture that can accommodate a single point source science target. However, the exoplanet atmospheres and IGM tomography cases set as a goal the simultaneous acquisition of the spectra of 2 and 10 point source science targets, respectively. In the former case the motivation is the desire for simultaneous monitoring of the atmosphere by observing a second target. In the latter case the density of potential science targets on the sky is high enough so that multiplexing increases the observing efficiency. The solar system, protoplanetary disk and stellar structure and evolution cases all require an IFU operating at near-IR wavelengths and at diffraction limited spatial resolution. The size of the field of view shall be 200 mas. The stellar structure and evolution case sets 3 spaxel sampling of the diffraction limited core of the PSF as a goal, albeit for a smaller field of view of 20 mas.
Wavelength precision and accuracy	The fundamental physics science cases, and in particular the redshift drift case, require the ability to compare the positions of spectral features in wavelength space with great precision and accuracy: the vacuum wavelength (as provided by the wavelength calibration system) of an unresolved, unconfused, intrinsically stable line of optimal brightness shall be reproducible from one fully calibrated exposure to the next to within 0.7 m/s (goal: 0.5 m/s) rms over 90% (goal: 99%) of the available spectral range. The bias (i.e. the quasi-constant offset) between the observed wavelength and the line's true wavelength shall be < 1 m/s. Furthermore the bias shall vary by no more than 2 cm/s (goal: 1 cm/s) as a function of position on the detector and time for the lifetime of the instrument.
Stability	Both the exoplanet atmospheres and the stellar structure and evolution cases need to be able to observe their targets quasi-continuously for as long as a given target is observable during a night without having to interrupt for (wavelength) calibration exposures. To ensure that the spectra from individual exposures can nevertheless be compared and/or combined, the position of

	the spectrum on the detector must be stable: the position on the detector of an unresolved, unconfused, intrinsically stable line of optimal brightness shall be reproducible from uncalibrated exposures taken up to 8 h apart to within 10 m/s rms over 90% (goal: 99%) of the available spectral range.
Sky subtraction	For single science targets, a sky spectrum shall be recorded simultaneously with the spectrum of the science target. This is only a goal for observations carried out in IFU mode.
Polarimetry	Polarimetry (i.e. the ability to measure all four Stokes parameters) is required by the protoplanetary disks and stellar magnetic fields cases, and is a goal for the exoplanet atmospheres case. Polarimetric sensitivity is defined as the smallest polarisation signal that a polarimeter can detect above a background. It is therefore related to the final noise level in Q/I, U/I and V/I and is expressed as a fraction of the intensity. The required polarimetric sensitivity is 10^{-5}. Once a signal larger than the polarimetric sensitivity level is detected, its magnitude needs to be quantified. The metric for how well this can be performed is the polarimetric accuracy. The polarimetric accuracy is the accuracy of the measured polarisation as compared to the actual polarisation of the light incident on the telescope, in the absence of noise and other spurious polarisation signals. This can be further divided into the position of the zero point for the measurement of Q, U and V (often called the absolute polarimetric accuracy) and the measurement scale (the relative polarimetric accuracy). The required relative polarimetric accuracy is 10^{-3}.
Other	Both the exoplanet atmospheres and the stellar structure and evolution cases need to be able to obtain rapid sequences of short exposures of very bright targets. Exposure times as short as 1 s shall hence be possible. Furthermore, these cases require a fast detector read-out mode and more generally minimal down-time between exposures. For a source of suitable brightness it shall be possible to achieve S/N > 1000 per pixel in the 1D extracted spectrum from a single exposure using daytime calibrations. The extragalactic transients case requires a rapid response mode with a total response time of $\lesssim$ 10 min. The redshift drift case requires an instrument lifetime of 10 yr (goal: 20 yr).

Table 15: Final top level requirements for ELT-HIRES.