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E-ELT PROGRAMME

TOP LEVEL REQUIREMENTS FOR THE ELT-MOS

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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 Multi Object Spectrograph (MOS) capabilities for the E-ELT. This might refer to one or more instruments. For the sake of simplicity, however, we will refer in this document to an ELT-MOS.

The Top Level Requirements are derived from the Science Case of the E-ELT and the astronomical community. 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 (PST). 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 Issue 6 (E-ESO-SPE-313-0066)

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 Issue 1 (E-TRE-ESO-080-0806)

RD2 Science Working Group input to the E-ELT Instrument Plan
ESO-193215 Issue 1 (E-PLA-ESO-080-0770)
RD3 The E-ELT Design Reference Mission
ESO-191370 Issue 2 (E-TRE-ESO-080-0717)
RD4 The E-ELT Design Reference Science Plan
ESO-192959 Issue 2 (E-TRE-ESO-080-0840)
RD5 E-ELT-MOS White Paper: Science Overview & Requirements
arXiv:1303.0029 (2013)
RD6 E-ELT Programme OPTIMOS-DIORAMAS: Science Analysis
ESO-194378 Issue 1 (E-SPE-DIO-531-1024)

3 Science Case for ELT-MOS

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 form an important part of the Science Case for the E-ELT [RD1]. The E-ELT has also been designed to have excellent image quality over a 10 arcmin field of view (FoV) (although the infrastructure required for adaptive optics (AO) guide stars and other sensors limits the FoV to ~ 7 arcmin). Multi-object spectroscopy exploits both these capabilities. The need for such an instrument was recognized and strongly emphasized by the E-ELT Science Working Group (SWG) in its recommendation regarding the E-ELT's first generation of instruments [RD2].

In this document we derive the Top Level Requirements for an ELT-MOS, a multi object 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 drives the requirements for ELT-MOS. Although not a complete list, this set is nevertheless representative of the science to be enabled by ELT-MOS and is based on extensive discussion by the PST and on the E-ELT-MOS White Paper [RD5]. We provide brief descriptions of these cases, as well as the instrument requirements derived from them.

We note that throughout this document the term spatial resolution refers to the ability to distinguish sources located at the given angular distance. This implies the ability of AO to concentrate the light on such scales and to provide the minimum perturbation to the adjacent resolution elements. The spatial resolution range involved here (40 to 100 mas) - and the corresponding spaxel size in the range from 20 to 50 mas assuming a Nyquist sampling - is in fact much smaller than the average seeing condition by about an order of magnitude and it is, at the same time, much larger than the diffraction limited capabilities of the E-ELT by the same factor. While it is worth noting that this is a kind of novel regime in AO applications one should be careful in assessing the performance requirements. The usual indication of the Strehl ratio, in fact, runs the risk of being inadequate, as it gauges the amount of energy concentrated into the central spike of the point spread function (PSF), which accounts for a minimum fraction of the area covered by the spaxel. Furthermore, the concentration of the energy in the spaxel area still lacks the information on how much light is spread in the adjacent spaxels. An ideal PSF, from this viewpoint, is the one in which the largest fraction of energy is included in the spatial resolution required (twice the spaxel size) and the remaining light is spread around in such a way that its density is significantly small, especially in the case of scrutinizing complex clumpiness in an area smaller than 1". A good metric could be defined by the fraction of energy collected in the spatial resolution area (2x2 spaxels) and by the average ratio between the energy in this element and the one in a similar area within the original seeing disk. Desirable values could lie in the range of 30% to 50% and a ratio > 200 respectively.

3.1 Primordial galaxies and the reionisation of the Universe

3.1.1 Outline of the science case

The redshift interval from ~ 10 through ~ 6-6.5 is becoming the next extragalactic frontier. The re-ionization history in this interval, when the Universe is believed to have transitioned from half-ionized to fully ionized, together with the properties of the first galaxies responsible for this ionization, are largely unknown.

Current evidence seems to support a quite fast decrease of the Lyα emission from galaxies beyond z~7, an indicator that the Intergalactic Medium (IGM) is increasingly neutral at these redshifts. Extending such observations of the Lyα properties of continuum-selected galaxies to fainter sources and higher redshifts (up to z~13) will constrain the reionisation state of the Universe as a function of cosmic time. Other emission lines, or the continuum, can also be used to identify and study galaxies at very high redshifts. Such continuum and absorption UV line studies at z > 7 are out of the reach of 8-10m class telescopes.

A near-IR spectroscopic study of Lyman break galaxies (LBGs), up to z ~13 and down to m_{AB} ~30, aimed at measuring Lyα and bright UV emission lines such as CIII]190.9nm or HeII 164.0nm, and for the brighter objects, measurement of the continuum or interstellar absorption lines, would allow studying the star formation rate, stellar populations, the interstellar medium (ISM) and the properties of possible outflows in the first galaxies in the universe. Spatially resolved spectroscopy for the brighter sources (m_{AB}<28) will allow resolution of their expected clumpy structure, determination of the geometry and sizes of outflows, and observations of spatially-resolved stellar population gradients within the galaxy.

3.1.2 Derived requirements for the science case

This science case naturally splits in two sub-cases: “high multiplex” and “high definition”.

1. For Lyα detection in LBGs (high *multiplex* case), the surface density for sources with $H_{AB} \leq 30$ with $6.5 \leq z \leq 9.5$ is ~ 10 arcmin $^{-2}$, giving ~ 400 sources/patrol field (assuming a 7 arcmin diameter field ~ 38.5 arcmin^2). These sources are expected to be compact. Low-performance AO is sufficient and the optimal FoV of the individual apertures has been shown to be ~ 0.9” x 0.9” (a patrol of 40 arcmin^2 with a FoV of 0.9” x 0.9” each; Navarro et al. 2010). Spectral resolution should be large enough to work between the night sky lines, i.e. R ≥ 3,000. The short wavelength end should allow observations of Lyα at z=7, i.e. 0.95 μm, preferably reaching z=6, 0.85 μm. Pushing the long wavelength limit beyond H and into the K band would in principle allow studies of galaxies with redshifts up to 19. If CIII] transpires to be a key emission line for redshift determination at z > 7, then the importance of following it out to z ~ 10 provides a further argument for extending the wavelength range into the K-band. Assuming a Lyα flux for a z>7 H_{AB} = 29 magnitude LBG ~ 10^{-19} erg/cm^2/s (based on an extrapolation from z ~ 7.5 galaxies) a S/N ~ 10 (per resolution element) requires a few tens of hours of integration. This case can be completed with one or a few ELT pointings.

FoV (sub-apertures)	0.9”x0.9”
Spatial resolution	not required
Spectral R	≥ 3,000
Wavelength Range	0.95 - 1.8 μm (goal 0.85-2.45 μm)

Multiplex	400
Sensitivity	Lyα flux ~ 10^{-19} erg/cm^2/s, S/N = 10, t_{exp}~ 20 h

Table 1a. Summary of requirements for Science Case 1.1

2. For continuum detections/absorption lines (high *definition* case) at brighter magnitudes J_{AB}~27-28, the surface density is ~ 1-2 arcmin^{-2} giving ~ 40 - 80 sources/patrol field. Spatially resolved information is desirable, as sources are compact and clumpy. The basic requirement is to concentrate the light into 50 – 100 mas scales for each target over the patrol and hence provide a few angular resolution elements across the target (z > 7 sources have half light radii 100 – 200 mas). The choice of spaxel scale is a tradeoff between sensitivity and resolution and is also tied to the level of AO-correction specified. Simulations suggest that the optimal spaxel scale is around 40-90mas and show that a FoV of 2”x2” contains most of the H-band light for a galaxy at z ~ 7. Resolving Lyα profiles requires a spectral resolution of at least R=4,000 to marginally sample the narrowest lines, with the optimal requirement being R=5,000 to separate the IGM from effects in the host galaxy and its close environment. Wavelength requirements are as for the Lyα case above. Simulations show that S/N ~ 3 - 5 can be reached for J_{AB}~27 targets within ~ 40 h of integration time (depending on IFU sampling and target size).

FoV (sub-apertures)	2”x2”
Spatial resolution	40-90 mas
Spectral R	5,000
Wavelength Range	0.95 - 1.8 µm (goal 0.85-2.45 µm)
Multiplex	40 (goal 80)
Sensitivity	J_{AB} = 27, S/N ~ 3-5, t_{exp}~ 40 h

Table 1b. Summary of requirements for Science Case 1.2

Of these two sub-cases, the first one is deemed to be of higher priority, as it contains most of the science for this case.

3.2 Chemodynamics of high redshift galaxies

3.2.1 Outline of the science case

The extension of the study of the kinematics and chemical abundances of intermediate mass galaxies beyond redshift ~2 will represent a significant step forward in understanding galaxy formation and evolution, since dynamical and chemical evolution are intimately coupled. Also, the cosmic star formation density peaks between redshifts 2 to 4. However, intermediate mass galaxies at these distances are out of the reach of the current facilities.

It is therefore important to study, for a relatively large sample of intermediate mass galaxies, their total and stellar masses, spatially-resolved gas metallicity gradients, and gas inflows/outflows. These quantities can be derived from the dynamical state of the galaxies and their haloes, from emission line ratios (such as the R23 index), and from shifts between emission and absorption lines. They will allow detecting merging signatures, and the study of the evolution of fundamental scaling relations, such as stellar and baryonic mass versus velocity or angular momentum, and stellar and baryonic mass versus metallicity.

3.2.2 Derived requirements for the science case

Achieving these objectives requires spatially resolved spectroscopy of the targets and of their satellite galaxies (for the study of the haloes) at a wavelength range where the widely used optical diagnostic lines ranging from [OII]$\lambda\lambda$372.7nm though [SII]$\lambda\lambda$672.4nm or, at least, Hα/[NII] can be observed. With adequate spectral resolution, [OII] can be used for density determinations instead of [SII], but Hα/[NII] is required for constructing the diagnostic diagram (i.e., [OIII]/Hβ vs. N2 = [NII]/Hα; Baldwin, Phillips, & Terlevich [BPT]) for segregating AGN from star forming and composite galaxies, for correcting R23 for extinction via the Hβ/Hα ratio, and for obtaining reliable star formation rates. Moreover, the [NII] line helps breaking the R23 degeneracy by providing an additional metallicity indicator (the N2 index). At higher redshifts, when the Hα/[NII] system leaves the K band, the ratio Hγ/Hβ could then be used for extinction corrections and star formation rate determinations, but these lines are nearer than Hβ/Hα, and the extinction correction is more uncertain. Also, since the underlying stellar absorption is higher in the blue, Hγ is more affected, and even after a careful correction, higher associated uncertainties remain, especially bearing in mind that this line is much fainter than Hα.

Then, reaching the K band is required for achieving a maximum redshift of ~ 2.7 for the full set of lines (including Hα/[NII]) for proper chemodynamical studies), and a maximum redshift of ~ 3.8 for dynamical studies using [OIII], in this case with limited metallicity estimations using Hγ/Hβ for extinction corrections and SFR determinations, or up to ~ 5.6 for dynamical studies only using [OII]. The essential requirements are then YJ-, H- and K-bands (not simultaneously, but one band per observation). Limiting the spectral range to the H-band would reduce the maximum redshift below redshift 2 (for Hα/[NII]), and to less than ~ 2.6 (using the fainter and more uncertain Hγ/Hβ ratio). It is therefore more important achieving K as the reddest wavelength, than Y as the bluest one. It is important to note that the estimation of stellar masses and less extinction affected star formation rates require at least additional NIR and UV imaging or multicolour imaging for spectral energy distribution derivation and fitting.

Estimates of the number of targets of interest in the ~7 arcmin diameter patrol field range from ~ a few tens to around a hundred galaxies. The relevant spatial scale for studying distant galaxy structures is the diameter of the target galaxies. Given that the size of galaxies at redshifts 2-4 is of 1-2”, one needs a FoV of 2”x2” and a spatial resolution in the range 50-75 mas is required for achieving a minimum of 20 elements of resolution across the galaxy diameter. Finally, at least R = 4,000 – 5,000 is needed to resolve the brightest OH sky lines and identify emission lines between them. This case requires reaching a S/N ~ 5 in the emission lines at an equivalent continuum K_{AB} ~ 28, which translates in an exposure time of ~ 24 h (Puech et al. 2010, MNRAS, 402, 903).

FoV (sub-apertures)	2”x2”
Spatial resolution	50 – 75 mas
Spectral R	4,000 – 5,000
Wavelength Range	1.0 – 2.45 µm
Multiplex	20 – 100
Sensitivity	Emission line with equivalent continuum K_{AB} ~ 28, S/N~5, t_{exp} ~ 24h

Table 2. Summary of requirements for Science Case 2

3.3 IGM tomography

3.3.1 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 ionizing photons and expel metals and energy through powerful winds, which determine the physical state of the gas in the IGM. The interplay between galaxies and the IGM is therefore central in the field of galaxy formation. This happens on scales of order of 1 Mpc or less, or about 2 arcmin at z~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 arc minutes, 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 would give important clues about the formation of structures at high redshift and allow us to characterize 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~2. Therefore, in principle, scales from ~2 arcmin to 1 degree should be investigated. About 900 randomly distributed targets per square degree would be required to recover the matter distribution with this resolution.

3.3.2 Derived requirements from the science case

Quasars are not numerous enough to reach 900 background sources per square degree so LBGs have to be targeted at the same time down to a typical magnitude of R~24.8. To cover 900 targets per square degree simultaneously implies a multiplex of 10, assuming a patrol field of 7’ diameter.

This case requires observations of the Lyα forest. Thus, coverage down to 0.42 μm is essential, with coverage to 0.37 μm desirable. For the reconstruction, the focus would be Lyα at z=2.5, and so actually very 'blue' – 0.42 μm. The red boundary for the case comes from the bonus science from high S/N LBG spectra. The LBGs obviously need to be at higher z than the reconstruction redshift, and so lots of the useful features are in the red or NIR. In addition, observing the objects redwards of the Lyα emission would allow us to study the metals in the IGM (in the case of quasars), and the quasars themselves if the IR is accessible. $R \geq 5{,}000$ is required, although $R = 10{,}000$ would be helpful to avoid metal lines (but this will likely reduce the wavelength range). The spectral resolution needed for the tomographic inversion itself is low, and the driver for spectral resolution is to disentangle contamination from intervening metal systems and also the need to divide out the LBG spectrum to derive the Ly-alpha optical depths. The FoV per target should be large enough for the observations of somewhat extended sources (LBGs) at 0.42 μm (~2”x2”). To reach a $S/N \geq 8$ at $R_{AB} = 24.8$ requires exposure times of 8-10 hours per field, giving an ambitious programme of ~750 h to cover one square degree.

FoV (sub-apertures)	2”x2”
Spatial resolution	not required
Spectral R	5,000 (10,000 goal)
Wavelength Range	0.42 – 1.0 μm (0.37 – 1.0 μm goal)
Multiplex	10
Sensitivity	R_{AB} = 24.8, S/N = 8, t_{exp} ~ 10 h

Table 3. Summary of requirements for Science Case 3

3.4 Resolved stellar populations beyond the Local Group

3.4.1 Outline of the science case

This is one of the “classic” E-ELT science cases. Its key goal is to probe the evolved populations of galaxies at distances between 1 and 5 Mpc. These samples will yield clues as to the star formation histories and the build up of early and late type galaxies. The different stellar densities as a function of galactocentric distance dictate different observational strategies, as detailed below.

3.4.2 Derived requirements from the science case

As others, this science case also splits naturally in two sub-cases: “high multiplex” and “high definition”.

1. *High multiplex.* For the outer halo regions, with low stellar densities (~ 10 sources arcmin^{-2} or ~ 400 sources/patrol field) and extended structures, only low performance AO is needed and a resolving power of ~ 5,000 should suffice. One also assumes the use of the CaT as a metallicity diagnostic, together with the Mg I b triplet and the G-band, which means the optical band. To get to the tip of the RGB in, say, the Sculptor group and Centaurus A, one needs to reach I_{Vega}=24. A S/N ~ 30 is also required, which translates into an exposure time of ~ 10 hr.

Spatial resolution	not required
Spectral R	≥5,000
Wavelength Range	0.4 - 1.0 µm
Multiplex	>400
Sensitivity	I_{Vega}= 24, S/N = 30, t_{exp} ~ 10 h

Table 4a. Summary of requirements for Science Case 4.1

2. *High definition.* For the denser disk regions, spatial resolution becomes important and higher order AO corrections will be necessary. Therefore, the use of spectral diagnostics in the J-band is proposed. In order to maximize survey efficiency, spatial sampling of 20 – 40 mas in the J band would be desirable, although coarser sampling with 80 mas pixels but twice the area would also be acceptable in order to match HST/JWST imaging. The latter would be more in line with the other ELT-MOS cases. A FoV 1”x1” would provide adequate spatial pixels for good background subtraction combined with multiple stars per IFU. The number of IFUs required (10 – 20) is driven by the need to efficiently build up large sample sizes per target galaxy in order to sample the full range of spatial structures. The requirement for blue cut-off is at 0.8 µm to include the CaT, which is currently the most reliable metallicity indicator for the targets of interest. To get to the tip of the RGB one needs to reach H_{Vega}= 24. A S/N ~ 15 is also required, which translates into an exposure time of ~ 35 hr.

FoV (sub-apertures)	1”x1”
Spatial resolution	80 mas (20 – 40 mas as a goal)
Spectral R	5,000
Wavelength Range	1.0 - 1.8 µm (0.8 - 1.8 µm as a goal)
Multiplex	10 – 20
Sensitivity	H_{Vega}= 24, S/N = 15, t_{exp} ~ 35 h

Table 4b. Summary of requirements for Science Case 4.2

3.5 Galaxy archaeology with metal-poor stars

3.5.1 Outline of the science case

One the key questions in the Local Group (LG) is whether galaxies were formed from the early primordial gas, or if they formed from gas that had already been partially enriched, thus providing a metallicity ‘floor’. This has important cosmological implications. In the standard hierarchical scenario the first structures to form are dwarf galaxies, which subsequently merge to form larger structures like the Galaxy and other massive disc galaxies. If the metallicity distribution functions (MDFs) of LG dwarfs display a clear metallicity ’floor’, then either the hierarchical galaxy formation model is wrong, or the present-day ‘surviving’ dwarf galaxies formed later (in which case, they are not the relics of the primordial dwarfs).

The current limiting factor in extragalactic studies is that only giant stars are bright enough to have high quality, high-resolution spectroscopy with an 8-m class telescope. Unfortunately, the statistics available from the analysis of extragalactic red giant branch (RGB) stars is not sufficient to determine the metal-poor tail of the MDF robustly in their host galaxies. There are simply not enough giant-branch stars in most of the LG dwarf galaxies to sample these rare populations and to observe these faint stars in extragalactic systems we need the sensitivity of the E-ELT. One then needs large samples of stars at the main-sequence turn-off (MSTO), in multiple nearby galaxies. This means large multiplex, high-resolution, absorption-line spectroscopy down to I_{Vega} ~ 24.

Optical band

Together with the opportunity to provide accurate elemental abundances an ELT-MOS is also crucial to constrain the kinematics of stellar populations in nearby galaxies. Current measurements indicate that dwarf galaxies are dark matter dominated. However, we still lack accurate measurements of the radial velocity profile of the different stellar populations. Recent findings suggest the presence of secondary kinematic features (Fabrizio et al. 2012), but we still lack detailed 3D radial velocity maps, since these results are based on small samples of bright red giants. The simultaneous use of low- and medium-resolution spectra down to I_{Vega} ~ 27 mag will provide the unique opportunity to use MSTO stars as stellar tracers in a significant fraction of more distant LG galaxies.

Near-IR band

The current and next generation of Integral Field Units (IFUs) (e.g., KMOS, MUSE) available at 8-10m telescopes will allow us to increase by an order of magnitude the number of targets in stellar systems for which we can provide accurate measurements of radial velocity and abundances. The simultaneous use of high spatial-resolution images collected with HST and with ELT-CAM and 2D spectra will provide the opportunity to apply the integral field spectroscopy to extract spectra of stars below the confusion limit (see Kamann et al. 2012, A&A 549,A71; Soto et al. 2012, A&A 540, A48). This approach becomes even more compelling if we also account for the fact that it has been applied to crowded fields, such as the innermost regions of Galactic globular clusters. Integral field spectroscopy is bound to play an increasing role in this direction, allowing a direct study of stellar populations in the innermost, crowded fields (Galactic Bulge, GB; Nuclear Bulge, NB).

The GB and the NB play a crucial role in constraining the formation and the evolution of the Galactic spheroid. Recent numerical simulations indicate that the Milky Way formed inside-out, which means that the bulge harbours the oldest Galactic populations (Debattista et al. 2006, ApJ, 645, 209). This theoretical framework is soundly supported by recent photometric investigations (Zoccali et al. 2003, A&A, 399, 931) suggesting that stellar populations in the Galactic Bulge are either old (10 Gyr) or intermediate-age (a few Gyr). On the other hand, the NB together with the super-massive black hole in the Galactic centre, harbours very young stars (a few Myr, Serabyn & Morris,1996, Nature, 382, 602; Figer et al. 2004, ApJ, 601, 319), compact star clusters, and massive molecular clouds (Launhardt et al. 2002, A&A, 384, 112). Although current knowledge of the innermost components of the Galactic spheroid is quite solid, we still lack quantitative constrains concerning its kinematic structure and chemical enrichment history. Moreover, current predictions suggest that a presence of a bar-like structure is crucial to support the high rate of star formation present in the NB. It is the bar-like structure to drag the gas and the molecular clouds from the inner disk into the NB (Athanassoula, 1992, MNRAS, 259, 345; Kim et al. 2011, ApJ, 735, L11). Thus, quantitative constraints on this phenomenon will have an impact on our understanding of the formation and the evolution of classical bulges and pseudo-bulges. The latter are considered disk-like stellar components slowly evolving in galaxy centres, whereas the former ones are considered the aftermath of galaxy mergers (Kormendy & Kennicut, 2004, ARA&A, 42, 603).

3.5.2 Derived requirements from the science case

As others, this science case also splits naturally in two sub-cases: “high multiplex” and “high definition”.

1. ***Optical band, high multiplex.*** High-resolution spectroscopy is required at R ≥ 20,000 (optimal), R ≥ 15,000 (essential) to determine accurate chemical abundances/metallicities, but only selected wavelength regions are required. For stellar kinematics, low and medium spectral resolutions are needed. The optimum optical regions for high-resolution spectroscopy are well understood from the extensive work already completed with, e.g., VLT-FLAMES and VLT-UVES. Abundance estimates are required for: Fe, α-elements (e.g. Mg, Ca), C (from the G-band), N (from the A-X CN band), Li, Ba, Eu, and Sr. Thus, the optimal spectral ranges required are 380-520 nm and 640-676 nm, with an essential requirement on the bluewards range of 410-460 nm. If these were obtained simultaneously then that would save a factor of two in total observing time. With a field of view of 7 arcmin diameter the typical mean density of main sequence stars in nearby dwarf galaxies is ~ 400 (Bono et al. 2014). For abundance studies I_{Vega}= 24 with a S/N ~ 30 translates into an exposure time ~ 40 h, while for stellar kinematics I_{Vega}= 27 with a S/N ~ 5 translates into an exposure time ~ 60 h.

Spatial resolution	not required
Spectral R	1,000, 5,000, and ≥ 15,000 (≥ 20,000 goal)
Wavelength Range	0.41 – 0.46 μm (0.38 – 0.52 μm goal) and 0.60 – 0.68 μm (high R) 0.4 – 0.9 μm (low R)
Multiplex	~ 400
Sensitivity	I_{Vega}= 24, S/N = 30, t_{exp} ~ 40 h I_{Vega}= 27, S/N = 5, t_{exp} ~ 60 h

Table 5. Summary of requirements for Science Case 5.1

2. ***Near-IR band, high definition.*** The GB and NB are characterized by high reddening (A_K~1 – 3 mag, i.e. from 10 to 30 mag in the optical) and by high differential reddening. Accurate elemental abundances and radial velocities of the unevolved stellar populations (MSTO) require a NIR multi-IFU instrument with a large field of view, possibly extending into the K-band. This gives the opportunity to collect high-resolution (R ~ 10,000) spectra down to H_{Vega} ~ 22.5 (old MSTO in the NB) and to collect medium-resolution (R ~ 5,000) spectra down to H_{Vega} ~ 25 (highly reddened thin disk regions, red clump and horizontal branch stars in nearby reddened galaxies, e.g., NGC 6822). These regions are also affected by stellar crowding, which means that the IFUs should also have high-spatial resolution (~ 50 – 100 mas). A multiplexity of the order of a dozen is required to trace in a field of 7 arcmin diameter both the cluster and the field populations (Davies et al. 2009, ApJ, 696, 2014; Najarro et al. 2009, ApJ, 691, 1816). The FoV requirement stems from the need of having a combined total of ~ 50 arcsec^2 summed over all IFUs. H_{Vega}= 25 with a S/N ~ 10 translates into an exposure time ~ 15 h.

FoV (sub-apertures)	2”x2”
Spatial resolution	50 – 100 mas
Spectral R	5,000 and 10,000 (15,000 goal)
Wavelength Range	1.0 – 1.8 µm (1.0 – 2.45 µm goal)
Multiplex	~ 12
Sensitivity	H_{Vega} = 25, S/N = 10, t_{exp} ~ 15 h

Table 5. Summary of requirements for Science Case 5.2

3.6 Characterization of exo-planetary atmospheres

3.6.1 Outline of the science case

The era of the characterization of exo-planets has already started a decade ago with the atmospheric characterization of hot and strongly irradiated Jupiters like HD209458 (Charbonneau et al. 2002). Such observations have been reported now for over 30 exo-planets to date (Seager & Deming 2010), including hot Jupiters, hot Neptunes (e.g. Stevenson et al. 2010), and even super-Earths (Demory et al. 2012). The presence of water, carbon monoxide and methane molecules, of haze revealed by Rayleigh scattering, observation of day-night temperature gradients, constraints on vertical atmospheric structure and atmospheric escape have been evidenced in the past decade (Seager & Deming 2010).

In the context of low-resolution transmission or secondary eclipse spectroscopy, one important limitation for the ultimate performances from space is related to the correction of the instrumental systematics (Gillon et al. 2012, Deming et al. 2013). From the ground, one has to deal in addition with the variability of the telluric lines. The simultaneous observation of one or various reference star(s) during the spectro-photometric transit or secondary eclipse is therefore extremely important to calibrate these effects and recover practically photon-limited performances (Bean et al. 2010; Crossfield et al. 2013). The ELT-MOS instrument at the E-ELT offers this opportunity and could play an important role for the characterization of exo-planetary atmospheres.

In that perspective, the goal is to use the ELT-MOS to simultaneously observe one or more reference stars during the planetary transit or secondary eclipse at medium resolution. This technique has already been applied to the Super-Earth GJ1214b with VLT/FORS2 (Bean et al. 2010) the warm Iced Giant GJ3470b with Keck/MOSFIRE and Gemini/GMOS (Crossfield et al. 2013) and Hot Jupiters (Stevenson et al. 2013), reaching an ultimate photometric precision down to 10^{-4} in the optical and near-infrared bands. It enables a fine correction of the telluric variations during the transit or secondary eclipse to retrieve the transmission or emission spectra of exo-planets. It has been also successfully tested during the VLT/KMOS commissioning. In the E-ELT perspective, JWST will be of course an important competitor for transit and eclipse spectroscopy but will probably suffer from instrumental systematics correction and a smaller collecting aperture in comparison to ELT-MOS. This technique completely relies on our ability to properly remove the telluric lines with the ELT-MOS and therefore to deal with the instrumental and atmospheric biases during the observations.

3.6.2 Derived requirements from the science case

Key targets for this type of study are M-dwarfs offering a more favourable contrast to characterize exoplanetary atmospheres. Characterizing atmospheres of giant and telluric exoplanets will require a photometric precision of 10^{-5} to probe the presence of metal oxides, of molecules such as H2O, CO, NH3, CO, CO2 as well as the presence of haze. Ultimately, the detection of biomarkers of telluric planets, that is of atmospheric compounds in strong chemical disequilibrium just as oxygen and methane, requires a spectrophotometric precision of 10^{-6}, defined as a goal for the ELT-MOS.

This science case will then require: 1. the important collecting capability offered by the E-ELT; 2. medium spectral resolution to properly remove the sky lines; 3. a wavelength coverage from 0.5 to at least 1.6 µm (with 2.45 µm as a goal) to cover spectral features of metal oxides, molecules such as H2O, CH4, NH3, CO, CO2, O2, O3 and Rayleigh scattering. In addition, simulations by Xavier Bonfils show that a possible technical solution requires also: 4. the ability to defocus the telescope to mitigate the influence of seeing variations; 5. a significant FoV to collect the light of the completely defocused PSF; 6. a centering accuracy to properly control the differential effect between the science target and the reference star with the ability to adjust it in real time. For a photometric precision of 10^{-6} the above-mentioned parameters need to have values of 1.6” for the defocusing, 6” x 6” for the FoV, and a 20mas centering accuracy. This technique relies as well on the availability of reference stars of similar magnitude to the target stars, mostly limiting its use to the case of M stars fainter than 10th mag.

Spatial resolution	not required
Spectral R	5,000 – 10,000
Wavelength Range	0.5 - 1.6 µm (0.5 - 2.45 µm as a goal)
Multiplex	≥2, possibly slitless spectroscopy or IFU to avoid flux losses
Photometric precision	10^{-5} (goal 10^{-6})

Table 6. Summary of requirements for Science Case 6

4 Derived science requirements

The requirements derived from the science cases discussed above are summarized here.

4.1 Compilation of requirements from the science cases

	FoV (sub-apertures)	Spatial resolution	Spectral R	Wavelength range	Multiplex	Sensitivity	Other
Primordial galaxies and the reionisation of the Universe	0.9”x0.9”	not required	≥3,000	0.95 – 1.8 µm (goal 0.85 –2.45 µm)	400	Lyα flux ~ 10^{-19} erg/cm^2/s, S/N = 10, t_{exp}~ 20 h	
“ “	2”x2”	40-90mas	5,000	0.95 – 1.8 µm (goal 0.85 – 2.45 µm)	40 (goal 80)	J_{AB} = 27, S/N ~ 3-5, t_{exp}~40h	
Chemodynamics of high redshift galaxies	2”x2”	50-75mas	4,000 – 5,000	1.0 – 2.45 µm	20 – 100	Emission line with equivalent continuum K_{AB} ~ 28, S/N~5, t_{exp}~24h	
IGM tomography	2”x2”	not required	5,000 (10,000 goal)	0.42 – 1.0 µm (0.37 – 1.0 µm goal)	10	R = 24.8, S/N = 8, t_{exp}~10h	
Resolved stellar populations beyond the Local Group		not required	≥5,000	0.4 – 1.0 µm	>400	I_{Vega}= 24, S/N = 30, t_{exp} ~ 10 h	
“ “	1”x1”	80 mas (20 – 40 mas goal)	5,000	1.0 - 1.8 µm (0.8 - 1.8 µm goal)	10 – 20	H_{Vega}= 24, S/N = 15, t_{exp}~35h	
Galaxy archaeology with metal-poor stars: optical band		not required	1,000, 5,000 and ≥ 15,000 (≥ 20,000 goal)	0.41 – 0.46 µm (0.38 – 0.52 µm goal) and 0.60 – 0.68 µm (high R) 0.4 – 0.9 µm (low R)	~ 400	I_{Vega}= 24, S/N =30, t_{exp}~40h I_{Vega}= 27, S/N = 5, t_{exp} ~ 60h	
“ “: near IR band	2”x2”	50-100mas	5,000 and 10,000 (15,000 goal)	1.0 – 1.8 µm (1.0 – 2.45 µm)	~ 12	H_{Vega} = 25, S/N =10, t_{exp}~15h	

Characterization of exo-planetary atmospheres		not required	5,000 – 10,000	0.5 - 1.6 μm (0.5 - 2.45 μm goal)	≥2, possibly slitless spectroscopy or IFU to avoid flux losses		Photometric precision 10^{-5} (goal 10^{-6})

4.2 Science requirements for instrument ELT-MOS

FoV (subapertures)	The FoV per target needs to cover the ~ 1”x1” to 6”x6” range. The smallest value comes from the “high multiplex” version of the reionisation of the Universe and the “high definition” version of the resolved stellar populations cases. The largest value is needed by the characterization of exo-planetary atmospheres case for the photometric precision goal of 10^{-6}. Most of the other cases require a 2”x2” FoV.
Spatial resolution	The spatial resolution ranges from relatively coarse (low performance AO), typically for the “high multiplex” cases, to medium, 40 – 100 mas, with a goal of 20 – 40 mas for the “high definition” version of the resolved stellar populations case. No case requires sampling the diffraction limit of the E-ELT in the near-IR band (4 mas).
Spectral R	The required resolving power covers the 1,000 – 15,000 range, with a goal of 20,000. The largest values (10,000 – 15,000) are required to determine chemical abundances/metallicities in the galaxy archaeology case (both optical and near-IR) and to characterize exo-planetary atmospheres. The former case has also a goal of 20,000. The lowest value is needed by the galaxy archaeology case. Most of the other cases require values between 3,000 and 5,000.
Wavelength range	The spectral coverage has to extend over the 0.4 – 2.45 μm range. The chemodynamics case is the only one, which has as a requirement to reach the K band, while all the others stop at 1.8 μm, with three having a goal of 2.45 μm. The low end is needed for IGM tomography, the “high multiplex” sub-case of resolved stellar populations, the optical sub-case of galaxy archaeology, and characterization of exo-planetary atmospheres. A large maximum wavelength (1.8 μm) is important to study high redshift sources (reionisation of the Universe and chemodynamics of high-z galaxies) and also for the “high definition” sub-case of resolved stellar populations and characterization of exo-planetary atmospheres.
Multiplex	Three cases can be divided into a “high definition, low multiplex” and “low definition, high multiplex” type. The former requires observations of ~ a few tens of channels at fine spatial resolution (high performance AO), while the latter needs only

	integrated-light observations of ~ 400 objects (low performance AO). The other three cases span the ≥2 – 100 multiplex range.
Other requirements	A possible solution for the exo-planetary atmosphere case has the following additional requirements for a goal of a 10^{-6} photometric precision: a FoV of 6” x 6”, the ability to defocus the telescope down to 1.6” and a centering accuracy of 20mas.

5 Appendix

5.1 Sources of targets

We list here the possible sources of targets for ELT-MOS for the various cases.

5.1.1 Primordial galaxies and the reionisation of the Universe

Deep imaging in multiple bands is needed in order to select the targets via the dropout technique. Usually at least three bands are used, spanning the Lyα line at the redshift or interest. A galaxy at high-z (e.g. z>7) will be blank in bands shortward of Lyα due to absorption by the IGM, and brighter in the bands redward of Lyα. A third band redward of Lyα helps distinguish lower-z red interlopers (e.g. elliptical galaxies at z~2 where the Balmer break can mimic the Lyman break at higher z). These will typically have red colours in the bands redward of the break, whereas high-z star-forming galaxies will be relatively blue. In addition, deep optical imaging is essential to obtaining a clean sample of high-redshift sources by removing the lower redshift contaminants. Another potential contaminant is cool (hence red) stars. High-resolution imaging will be beneficial for star/galaxy separation. Therefore some improvement compared to natural seeing would certainly be beneficial. The HST resolution of ~0.15-0.18” has proven sufficient for clean separation resulting in <2% contamination by stars (Finkelstein et al 2010, Bouwens et al 2011).

Imaging depth

The 2012 Hubble Ultra-deep field HUDF12 reaches depths (5σ, AB) of Y=30.0, J=29.5, J=29.5 H=29.5 (Ellis et al 2013, Schenker et al submitted). This is sufficient to detect sources to z~9 (with completeness depending on luminosity), and possibly even up to z~12. These depths match those of the targets for spectroscopy discussed above.

Note that in order to reliably detect a break, imaging in the bands below the Lyman break (where the source is blank) should ideally go deeper than the redder bands in which the source is detected. Schenker et al require that the high-z candidates are blank (<2σ) in all bands below the break, i.e. [for z~7] B, V, and i. For the Y-drops [z~8], they add the z-band. Visible depths (5σ in HUDF are B=29.7, V=30.2, z=29.1 (McLure et al. 2013, MNRAS, 432, 2696).

Imaging area

To these depths, Schenker et al. find 47 and 27 candidates at z~7 and z~8 respectively in an area of 4.6 arcmin^2. In the full E-ELT patrol field (7 arcmin diameter) this would give 8.4 times more candidates, i.e. ~390 and 220 at z~7 and 8 respectively (and even more at lower z ~6). This agrees with the numbers discussed below. Therefore imaging that covers only one or a few ELT field(s) should be sufficient for this case.

Other facilities

The E-ELT Design Reference Mission (DRM) version of this case [RD3] assumes that IR imaging will come from VISTA, HST and JWST. The MOS white paper [RD5] says that work must be done in the meantime to extend deep imaging with HST, e.g. Frontier Fields, followed by JWST. The JWST NIRCAM FoV is 2.2'x4.4', thus the ELT FOV can be covered with a reasonably small number (about 4) NIRCAM pointings. This will cover the NIR bands and the optical down to 0.6□m.

Sufficiently deep B and V band optical imaging might be provided by the Large Synoptic Survey Telescope (LSST) but not automatically within the currently planned surveys: the LSST Deep drilling fields would reach a stacked depth of ugrizy (co-added) = 28.0, 28.7, 28.9, 28.4, 28.0, 27.0 (Jones et al AAS 247.07), each covering ~9.6 deg^2. However with a reasonably large amount of dedicated 8m time it would be feasible to reach the required limits in the optical. This argues for retention/implementation of a moderately wide-field optical imager on VLT.

Conclusions

Existing or expected imaging facilities (HST, JWST, VLT & other 8m telescopes) already go deep enough and cover (or will cover) enough area to provide sufficient targets for this case.

5.1.2 Chemodynamics of high redshift galaxies

Target selection for this case requires both an imaging survey and a redshift survey to find suitable galaxies in the range $1 < z < 6$.

In order to define a complete sample by mass, the target selection should be based on photometry in NIR bands. A pre-imaging survey down to H(AB)=25-26 is required in order to be complete for sub-M* galaxies at z=4 (Puech et al. 2010, MNRAS, 402, 903). The imaging survey must cover sufficient area to fill bins in redshift and mass with a substantial number of galaxies. To find 100 suitable galaxies at z~4 requires covering about 40 arcmin^2 to a depth of H(AB)=26. The Euclid deep fields will reach this depth over a much larger area (~40 deg^2) so will provide more than enough targets, assuming at least part of the Euclid Deep field area is in the South. If the case were extended to z ~ 5 then to find 100 galaxies in that bin requires roughly double the sky area, i.e. ~100 arcmin^2, and a deeper limit H(AB)=27-28. This could in principle be provided by a Euclid ultra deep field (if scheduled – which is very uncertain). JWST could also do it in ~10 NIRCAM pointings, which is not unreasonable.

The HAWKI ETC suggests that in order to reach H(AB)=26 mag over 40 arcmin^2 (required for the z~4 case) would take ~ 30 h of exposure time (in one HAWKI pointing since the FoV is well matched), assuming good natural seeing of 0.5" in H. For the z~5 case, reaching H(AB)=28 over 100 arcmin^2 would not be possible (>1000 h per pointing, for 3 pointings). So getting the targets for the z~4 case is difficult but possibly just doable with an 8-10m, while the pre-imaging for the z~5 case is not and requires Euclid or JWST as mentioned above.

Note that colour selection would *not* be used as this could introduce uncontrollable biases. Instead, a blind and complete redshift survey would be required prior to the dynamical measurements so that the wavelengths of emission lines are known: only those sources with emission lines in clear regions with respect to night sky emission lines would be selected for dynamical studies. This requires a redshift survey up to z~5 and with high spectroscopic completeness down to H~26-28. Such a survey is itself not trivial and would probably require an ELT MOS (high multiplex version since the density of all sources with $z \geqq 2$ and $H \leqq 28$ is ~ 17 arcmin^{-2} so in a MOS FoV there would be ~ 680 objects). The failure rate without a previous spectroscopic redshift survey will be of order 50%, because only those objects with emission lines free from OH sky lines are useful (Evans et al 2010, SPIE, 7735, 178).

5.1.3 IGM tomography

This case requires a multi-band survey down to r = 24.8 over approximately 1 deg^2. There are already some fields targeted for LBGs at ESO by the Durham group and others.

5.1.4 Resolved stellar populations beyond the Local Group

Excellent HST/ACS imaging is already available; examples include the ANGST (3-filter) survey, which observed 69 galaxies in the Local Volume, at a depth of several magnitudes below the tip of the RGB, and the GHOSTS survey of stellar populations in the outskirts of disk galaxies (14 galaxies within 17 Mpc with F606W and F814W). Thus, large catalogues of evolved stars in galaxies beyond the Local Group already exist, but spectroscopy with any currently available facility is unfeasible. Spectroscopy of small samples with JWST/NIRSPEC would be possible, albeit at a lower spectral resolution than required by the science cases above. Good ground-based imaging of galaxies out to a few Mpc is also available, with further imaging being possible with existing wide-field imagers.

5.1.5 Galaxy archaeology with metal-poor stars

Optical: current 8m telescopes; near-IR: HAWKI, JWST.

5.1.6 Characterization of exo-planetary atmospheres

Samples from radial velocities surveys (HARPS-S, HARPS-N, Keck/NIRSPEC…) and transiting surveys (TESS, ChEOPS, PLATO). This requires bright targets and, in the context of the search for bio-markers, low-mass stars.

5.2 Exo-planets in nearby galaxies

This case has not been developed fully. However, it was deemed to be interesting enough to be kept in the document for the time being.

5.2.1 Outline of the science case

Although more than 1,000 exo-planets are known to exist, they are all confined to a few parsecs from the Sun. We have no idea of the dependence of the environment on planet formation and evolution. A fundamental question is therefore whether exo-planets exist also in other galaxies, and whether they are similar to those found in the Milky Way. With an accuracy of 5 m/s a giant planet population may be detected around G and K dwarf stars (a 10m/s accuracy would limit detection to hot Jupiters, not enough to be comprehensive for a proper comparison with our Galaxy). Scaling the HARPS performance one finds that 1h exposure with a MOS would provide a 5 m/s accuracy on an 18th mag star. However, dwarf stars in nearby galaxies are fainter than 22th. Even an instrument 10 times more sensitive than HARPS might not be able to bridge this gap.

Open issues and questions:

- Three possible options were discussed at PST meetings: 1. this case can be done with smaller R and so it does not drive anything new; 2. R needs to be high but HIRES will have a MOS-mode, in which case this would belong to the HIRES TLR; 3. the requirements for this case are beyond the E-ELT capability. For all three options it looks like the case as it is now does not belong to this document.

- Is it interesting to do this for other nearby stellar systems (e.g. metal-poor open clusters) if it cannot be done for nearby galaxies? There are enough "old" open clusters (about a dozen) to build a comprehensive planet search program with the ELT. To be really efficient the accuracy should be at least down to few m/s (say 3) and this would put a significant pressure on the design. One does not get to that level without serious optimizations. For example, one would need a resolution above 50,000.

5.2.2 Requirements from the science case

Resolution higher than 50,000 is absolutely needed. None of the currently existing instruments has demonstrated an exo-planet survey capability with a resolution below this value.

Spectral R	> 50,000
Spectral resolution	TBD
Wavelength Range	TBD
Multiplex	TBD

Table 7. Summary of requirements for this Science Case