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ELT-HIRES, the high resolution spectrograph for the ELT: results from the Phase A study

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ABSTRACT

We present the results from the phase A study of ELT-HIRES, an optical-infrared High Resolution Spectrograph for ELT, which has just been completed by a consortium of 30 institutes from 12 countries forming a team of about 200 scientists and engineers. The top science cases of ELT-HIRES will be the detection of life signatures from exoplanet atmospheres, tests on the stability of Nature's fundamental couplings, the direct detection of the cosmic acceleration. However, the science requirements of these science cases enable many other groundbreaking science cases. The baseline design, which allows to fulfil the top science cases, consists in a modular fiber-fed cross-dispersed echelle spectrograph with two ultra-stable spectral arms providing a simultaneous spectral range of 0.4-1.8 μm at a spectral resolution of $\sim 100,000$. The fiber-feeding allows ELT-HIRES to have several, interchangeable observing modes including a SCAO module and a small diffraction-limited IFU.

Keywords: EXTREMELY LARGE TELESCOPES, HIGH RESOLUTION SPECTROSCOPY, EXOPLANETS, STARS AND PLANETS FORMATION, PHYSICS AND EVOLUTION OF STARS, PHYSICS AND EVOLUTION OF GALAXIES, COSMOLOGY, FUNDAMENTAL PHYSICS

1. INTRODUCTION

At first light in 2024, the European Extremely Large Telescope (ELT) will be the largest ground-based telescope at visible and infrared wavelengths. The flagship science cases supporting the successful ELT construction proposal were the detection of life signatures in Earth-like exoplanets and the direct detection of the cosmic expansion re-acceleration and it is no coincidence that both science cases require observations with a high-resolution spectrograph.

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Over the past few decades high-resolution spectroscopy has been a truly interdisciplinary tool, which has enabled some of the most extraordinary discoveries spanning all fields of Astrophysics, from Exoplanets to Cosmology. Astronomical high-resolution spectrometers have allowed scientists to go beyond the classical domain of astrophysics and to address some of the fundamental questions of Physics. In the wide-ranging areas of research exploiting high-resolution spectroscopy, ESO has a long and successful tradition, thanks to the exquisite suite of high-resolution spectrographs offered to the community of Member States. UVES, FLAMES, CRIRES, X-shooter and HARPS have enabled European teams to lead in many areas of research. ESPRESSO, which is now joining this suite of very successful high-resolution spectrographs, holds the promise of truly revolutionising some of these research areas. The scientific interest and high productivity of high-resolution spectroscopy is reflected by the fact that more than 30% of ESO publications can be attributed to its high-resolution spectrographs.

However, it is becoming increasingly clear that, in most areas of research, high-resolution spectroscopy has reached or is approaching the "photon-starved" regime at 8-10m class telescopes. Despite major progress on the instrumentation front, further major advances in these fields desperately require a larger photon collecting area. Due to its inherently "photon-starved" nature, amongst the various astronomical observing techniques, high-resolution spectroscopy most desperately requires the collecting area of Extremely Large Telescopes.

When defining the ELT instrumentation,[1] ESO commissioned two phase-A studies for high-resolution spectrographs, CODEX[2] and SIMPLE,[3] which were started in 2007 and completed in 2010. These studies demonstrated the importance of optical and near-IR high-resolution spectroscopy at the ELT and ESO thus decided to include a High-REsolution Spectrograph (HIRES) in the ELT instrumentation roadmap. Soon after conclusion of the respective phase A studies the CODEX and SIMPLE consortia realized the great scientific importance of covering the optical and near-infrared spectral ranges simultaneously. This marked the birth of the HIRES initiative (http://www.hires-eelt.org) that started developing the concept of an X-Shooter-like spectrograph, but with high resolution, capable of providing R 100.000 in the 0.37-2.4 μm wavelength range. Following a community workshop in September 2012 the HIRES Initiative has prepared a White Paper summarizing a wide range of science cases proposed by the community[4] and also prepared a Blue Book with a preliminary technical instrument concept.[5]

With the start of construction of the ELT, the HIRES Initiative has decided to organize itself as the HIRES Consortium and has recruited additional institutes, which expressed their interest in HIRES. The consortium, strongly motivated by the unprecedented scientific achievements that the combination of such an instrument with the ELT will enable, was commissioned to perform a Phase A study by ESO. The Phase A study started in march 2016 and successfully concluded in may 2018.

2. THE HIRES CONSORTIUM

The HIRES Consortium is composed of institutes from Brazil, Chile, Denmark, France, Germany, Italy, Poland, Portugal, Spain, Sweden, Switzerland and United Kingdom (Table 1). For each country, one institute ("Coordinating Institution") coordinates the contributions from all other institutes of that country ("Other Consortium Members"). The Italian National Institute for Astrophysics (INAF) is the lead technical Institute and Alessandro Marconi, from the University of Florence and INAF, is the PI of the consortium.

The consortium structure is schematically represented in Figure 1. The HIRES project is coordinated by the Principal Investigator (PI; A. Marconi) who is also the contact person between ESO and the HIRES consortium. The Board of co-Investigators (co-Is) is composed of one representative per country (see Table 1; all decisions concerning the overall scientific performance and exploitation of the instrument and all matters concerning the organization of the consortium are taken by the PI and the Board. During the meetings with the Board the PI is assisted by the Project Scientist (PS; R, Maiolino) and by the Project Manager (PM; L. Valenziano). The PS chairs the Science Advisory Team (SAT) and is responsible for finalising the top level requirements and providing the link between the science and technical team. The SAT is composed of a science team at large and of a core science team. The science team at large is composed of 4 working groups, each with a coordinator and a deputy.

- Exoplanets and Circumstellar Disks (Coordinator E. Palle, Deputy C. Lovis)
- Stars and Stellar Populations (C. Allende, A. Korn)

Table 1. Consortium composition. The first column indicates the member countries and the corresponding co-I, member of the executive board. The second column indicates the coordinating institutes (consortium members) while the third column lists the associated members from each country.

Country	Coordinating Institution	Other Consortium Members
Brazil (J. Renan de Medeiros)	Board of Observational Astronomy, Federal University of Rio Grande do Norte	Instituto Mauá de Tecnologia
Chile (L. Vanzi)	Pontificia Universidad Catolica de Chile, Centre of Astro Engineering	Universidad de Chile, Department of Astronomy; Universidad de Concepcion, Center of Astronomical Instrumentation; Universidad de Antofagasta
Denmark (J. Fynbo)	Niels Bohr Institute, University of Copenhagen	Department of Physics and Astronomy, Aarhus University
France (I. Boisse)	Laboratoire d'Astrophysique de Marseille	Institut de Planétologie et d'Astrophysique de Grenoble, Université Grenoble Alpes; Laboratoire Lagrange, Observatoire de la Côte d'Azur; Observatoire de Haute Provence, CNRS, Aix Marseille Université, Institut Pythéas
Germany (K. Strassmeier)	Leibniz-Institut für Astrophysik Potsdam (AIP)	Institut für Astrophysik, Universität Göttingen (IAG); Zentrum für Astronomie Heidelberg, Landessternwarte (ZAH); Thüringer Landesternwarte Tautenburg (TLS); Hamburger Sternwarte, Universität Hamburg (HS)
Italy (A. Marconi - PI)	Istituto Nazionale di Astrofisica (INAF) - Lead Technical Institute	
Poland (A. Niedzielski)	Faculty of Physics, Astronomy and Applied Informatics, Nicolaus Copernicus University in Torun	
Portugal (N. C. Santos)	Instituto de Astrofísica e Ciências do Espaço (IA) at Centro de Investigaço em Astronomia/Astrofísica da Universidade do Porto (CAUP)	Instituto de Astrofísica e Ciências do Espaço (IA) at Faculdade de Ciências da Universidade de Lisboa
Spain (R. Rebolo)	Instituto de Astrofísica de Canarias	Instituto de Astrofísica de Andalucía-CSIC; Centro de Astrobiología
Sweden (N. Piskunov)	Dept. of Physics and Astronomy, Uppsala University	
Switzerland (F. Pepe)	Département d'Astronomie, Observatoire de Sauverny, Université de Genève	Universität Bern, Physikalische Institut
United Kingdom (M. Haehnelt)	Science and Technology Facilities Council	Cavendish Laboratory & Institute of Astronomy, University of Cambridge; UK Astronomy Technology Centre; Centre for Advanced Instrumentation - Durham University; Institute of Photonics and Quantum Sciences, Heriot-Watt University

- Formation and Evolution of Galaxies and Intergalactic Medium (V. D'Odorico, E. Zackrisson)
- Cosmology and Fundamental Physics (J. Liske, C. Martins)

Each working group is composed of about 15 members beyond coordinator and deputy. The PS, as chair, the coordinators and deputies of each working group constitute the core science team. The science team is responsible

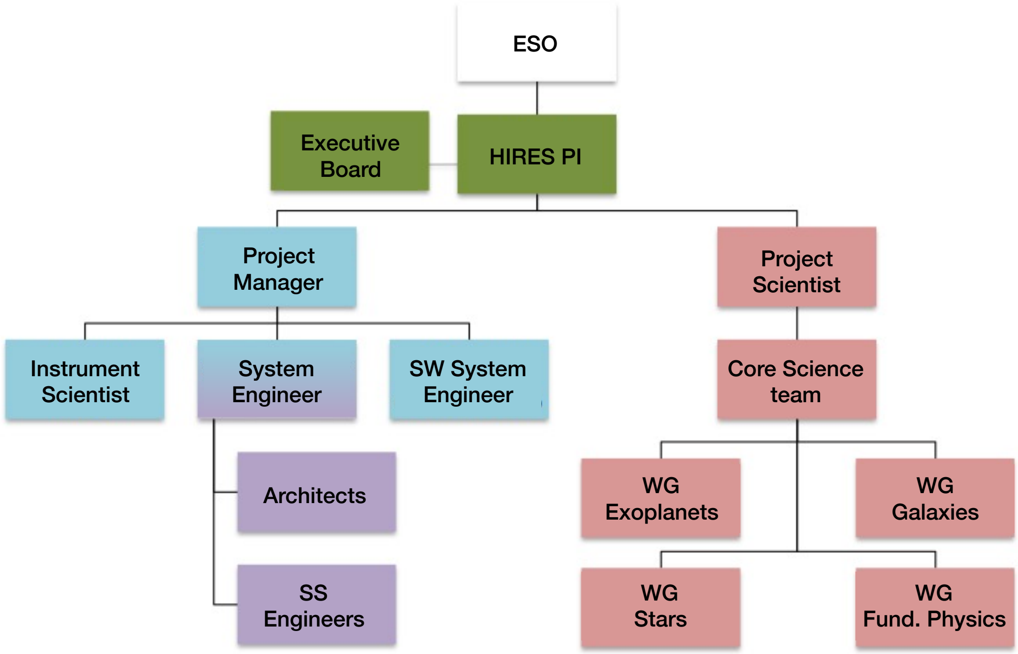

Figure 1. Consortium structure. Different colors denote different areas of activity (red - science team, green - executive board, blu - project office, magenta - technical team)

for all matters that concern the science cases for the instrument, for instance for the prioritisation of the key science cases that will allow to help defining the baseline design of the instrument.

The Project Office (PO) is coordinated by the PM (L. Valenziano, deputies: E. Stempels, P. Par-Burrman) and includes the Instrument Scientist (IS; Livia Origlia, deputies, P. Amado, M. Weber, F. Bouchy), the System Engineer (SE; M. Riva, deputies: A. Cabral, S. Becerril, B. Chazelas), the Software System Engineer (SSE; P. Di Marcantonio, deputies: T. Chen, M. Monteiro). The project office coordinates the activities of the various Work Packages (WP):

- Front End (Coordinator A. Cabral)
- Fibre link (A. Fragoso)
- Calibration (P. Huke)
- Visible Spectrograph (B. Chazelas)
- Infrared Spectrograph (P. Parr-Burman)
- Polarimeter (I. Di Varano)
- Software (P. Di Marcantonio)

Finally, system architects are

- Optical: E. Oliva
- Mechanical: I. Hughes
- Electronical: I. Coretti
- Software: T. Chen, P. Di Marcantonio
- Thermal & Vacuum: S. Becerril
- Detector: N. Bezawada
- PSF: T. Morris

3. SCIENCE GOALS

During the course of the phase-A study, the HIRES Science Advisory Team (SAT), chaired by the Project Scientist, has defined the science priorities for HIRES and determined the corresponding Top Level Requirements. The SAT includes more than 60 experts in high-resolution spectroscopy, across multiple disciplines, mostly from Europe, but involves also a significant fraction of experts from outside Europe. As specified in the previous section, the SAT is organized in four Working Groups and is chaired by the Project Scientist. Each WG has identified the top priority science cases within their respective scientific areas, as well as the associated requirements in terms of instrument capabilities. These science cases, briefly described below, have been prioritized as described in the following section. Many other science cases are possible with HIRES but they will not be mentioned here (see, e.g., the community white paper[4]).

3.1 Exoplanets & Protoplanetary Disks

The study of exoplanet atmospheres for a wide range of planetary objects, from gas giants to rocky planets, and from hot to temperate planets, is a primary objective in the field for the next decade. In particular, the detection of components such as CO_2 or O_2 in Earth- or super-Earth sized planets is considered to be truly transformational, as they may be regarded as signatures of habitability.

- HIRES will be able to probe the atmospheres in transmission during the transit of an exoplanet in front of its host star. As an example, it will be possible to detect CO_2 absorption in Trappist-b with a S/N of 6 in 4 transits of the planet, while O_2 absorption at 0.75 micron can be detected in only 25 transits of the planet, i.e. less than 30 hours of observations.
- HIRES will also be able to directly probe exoplanets, by spatially resolving them from their host star, focussing on their reflected star light and taking advantage of the angular resolution of the ELT with AO-assisted observations. For example, it will be possible to detect the Proxima-b planet in 4 nights of integration with a S/N of 8 with an AO system similar to that of MICADO; see Figure 2 (left) for a simulation of such detection for Proxima-b. Using extreme AO, the same result can be reached in 1 night.

Protoplanetary disks are a natural outcome of angular momentum conservation in star formation and are ubiquitous around young, forming stars. They represent the environment in which planets form, grow and migrate. Indeed, the gas and dust in the inner disk ($r < 10$ AU) constitute the likely material from which planets form.

- HIRES will be able to determine the properties of the gas in the inner star-disk region, where different competing mechanisms of disk gas dispersal are at play, namely magnetospheric accretion, jets, photo-evaporated and magnetically driven disk winds. This will constrain on one side on the mechanisms through which the forming star acquires mass and removes the angular momentum, and on the other side the initial condition for planets formation.

3.2 Stars and Stellar populations

The vast light-collecting power of the ELT will enable detailed high-resolution spectroscopy of individual stars, and in particular very faint red dwarfs and distant red giants in nearby galaxies (Figure 2, right). It will also expand our horizon by exploring the most primitive stars known and measuring their chemical composition. Last, but not least, the combination of very high spectral resolving power and diffraction-limited angular resolution makes the ELT a unique resource for deepening our understanding of the physics of stellar atmospheres.

- HIRES will be able to provide tight constraints for the atmospheric parameters of intrinsically faint and/or distant cool stars and substellar objects, in particular their chemical composition, or the presence of significant velocity fields, accretion from circumstellar material, or strong magnetic fields. These constraints will be extremely important to characterize the stellar hosts of exoplanets.

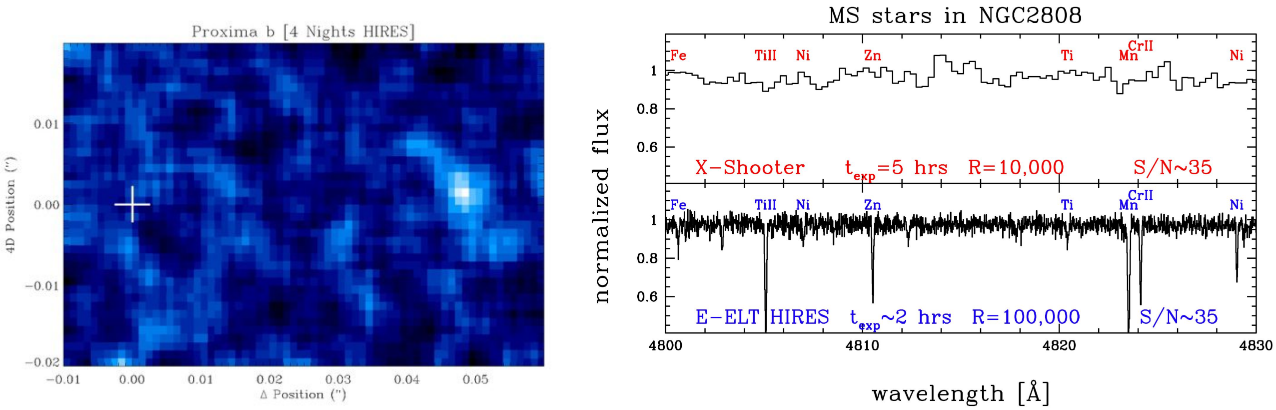

Figure 2. Left: Reflected light cross-correlation signal of the direct surroundings of Proxima Cen. Right: simulated spectrum of a main sequence star in the NGC 2808 globular cluster showing the power of HIRES for metallicity measurements of faint, dwarf stars. The quoted S/N refers to spectral channels.

- HIRES will be able to measure the heavy-elements abundances in the most primitive stars (low mass, low metallicity) in our galaxy and its satellites helping us to understand what is the lowest metallicity for which gas can collapse to form low-mass stars, and what are the nature and yields of the very first generation of stars and their supernovae. Only with HIRES will it be possible to follow up faint (V$\sim$20 mag) targets identified by ongoing and planned wide-angle spectroscopic surveys such as SDSS, LAMOST, MOONS, DESI, WEAVE and 4MOST.

- HIRES will open a new frontier in stellar astrophysics allowing us to resolve spectroscopically the effects of surface convection in line profiles and to accurately measure variations in chemical composition and isotopic ratios in stars of similar spectral types. It will improve the precision limits for chemistry from 0.1 to less than 0.01 dex. This will allow us to reveal secular changes in surface composition of stars due to diffusion, mixing, or the accretion of interstellar or protoplanetary material onto the star, as currently seen in studies of solar twins. It will further give us a sharper view of nucleosynthesis processes in stars and supernovae by allowing us to measure isotopic abundances of atomic species.

3.3 Galaxy Formation and evolution and the intergalactic medium

The detection of Pop III stars and the observational characterization of their properties is one of the main objectives of extragalactic astrophysics. Individual Pop III stars are expected to be too faint for direct detection, even with JWST. However, Pop III stars could be characterized by their nucleosynthetic yields which can be potentially observed in the abundance patterns of very metal-poor absorption systems in the spectra of bright high-redshift sources.

- Thanks to its resolution and wavelength extent in the NIR, HIRES will enable the detection of pristine gas directly in the reionization epoch (see Figure 3, left). Although the information on neutral hydrogen is not available, relative abundances of metals can still be used to constrain the abundance pattern and detect the signature of Pop III stars.

The direct detection and characterization of the beginning of the reionization epoch is a very important goal in the study of galaxy formation. This process is believed to have been dominated by ultraviolet photons from the first generations of galaxies, most of which are too faint to be observed directly even with the James Webb Space Telescope.

- By targeting bright quasars at high redshift as background continuum sources, HIRES will be able to study both transmission features in the Lyman-α forest and metal absorption lines along the line of sight to these

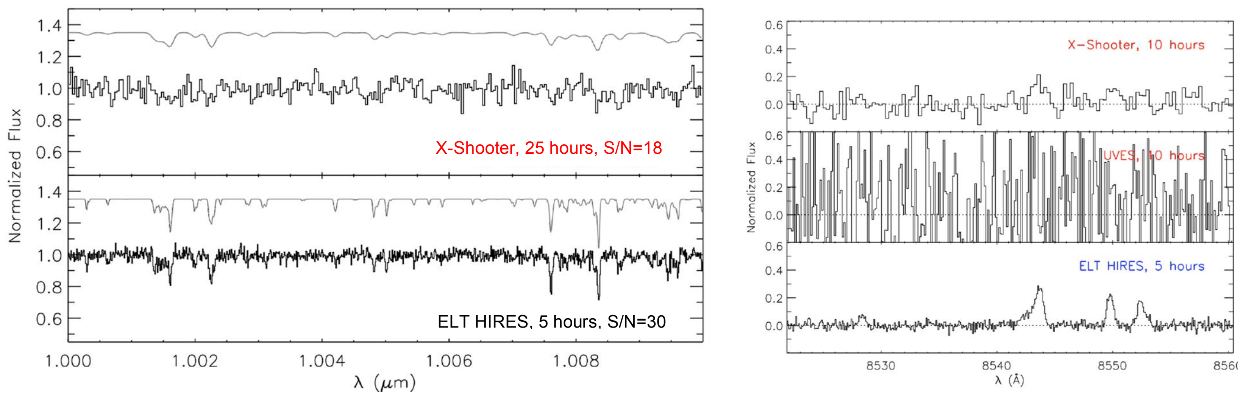

Figure 3. Left: Simulated observations using VLT+X-shooter (top) and ELT-HIRES (bottom) of absorption due to OI, SiII and CII generated from a simulation assuming an IGM neutral fraction of 10% and a metallicity of 10^{-3} $Z_{\odot}$. Signal-to-noise ratios per spectral channel have been calculated assuming a 25 (5) hour integration with Xshooter (HIRES) on a z=7 source J_{AB} = 20.2. Right: Due to its unprecedented sensitivity, HIRES will be able to study currently undetectable narrow transmission peaks in the otherwise saturated Lyman-α forest of z ≈ 6 quasars at $m_{AB} \leq 21$ mag. This will constrain the patchiness of the reionization process at scales an order of magnitude smaller than what SKA-1 can resolve.

reionization-epoch objects. This will allow HIRES to constrain the patchiness of the reionization process, the properties of the ultraviolet background radiation and the chemical enrichment of the intergalactic medium in this epoch.

- While the intergalactic medium is expected to be increasingly neutral at $z > 6$, HIRES will be able to detect small ionized regions as these will manifest themselves as narrow transmission peaks at wavelengths short ward of the redshifted Lyman-α line (see Figure 3, right). The Intergalactic Medium (IGM) at high redshift, as probed by Lyman-α absorption systems, contains most ($> 90\%$) of the baryons in the Universe. The interplay between galaxies and the IGM is central to an understanding of galaxy formation. Absorption line studies are therefore the method of choice to study the baryonic reservoir from which galaxies form. Recently, several studies have been carried out, in particular at low redshifts, linking the absorption lines observed in a quasar spectrum with the galaxies in the field at small impact parameters and effectively probing the so-called Circumgalactic Medium (CGM).
- HIRES will make a significant improvement in this field by making available several lines of sight to background sources piercing the CGM of the same galaxy at different impact parameters. HIRES will grant us the observability of both fainter quasars and galaxies at $z > 2$ increasing by 2-3 orders of magnitude the number of background sources in the field. The study of the HI and metal absorbers correlated with the galaxy along the different lines of sight will allow us to reconstruct the 3D distribution and physical properties of the gas in the high redshift CGM.

3.4 Cosmology and Fundamental Physics

The observational evidence for the acceleration of the expansion of the universe shows that our canonical theories of cosmology of fundamental physics are incomplete (and possibly incorrect), and that there is unknown physics yet to be discovered. The unique characteristics of the HIRES/ELT combination (notably collecting area, resolution, wavelength coverage and precise wavelength calibration) will allow to search for, identify and ultimately characterize this new physics through several different but fundamentally inter-related tests. Irrespective of whether one finds results consistent with the standard paradigm or detects deviations from it, any improvement in the sensitivity of these searches will automatically lead to improved constraints on fundamental cosmological paradigms and will rule out previously viable scenarios. HIRES will enable a unique set of tests of the canonical cosmological paradigm.

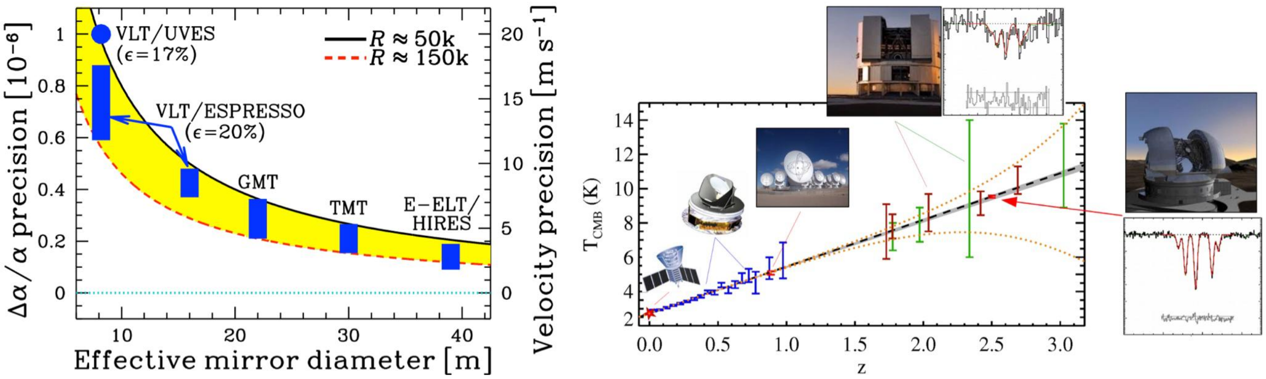

Figure 4. Left: Expected statistical precision on variations in the fine-structure constant, $\Delta\alpha/\alpha$, achievable with future high-resolution spectrographs as a function of telescope diameter. The equivalent velocity precision is also shown (assuming a typical variety of metal-ion transitions). The length of the bars indicates the range of precision expected for different spectral resolutions available on those facilities. Two modes of operation for VLT/ESPRESSO are shown, its single-telescope mode (8-m effective diameter), with a range of resolving powers, and its anticipated four-telescope mode (16-m effective diameter), with R up to ≈70,000. Right: Existing and simulated T_{CMB} measurements. The red star is the COBE measurement at z = 0. Blue points are the SZ-based measurements using Planck. The red point at z = 0.9 is an ALMA measurement using molecular radio lines. Green and brown error bars at $z > 1$ are from optical spectroscopy of atomic C and CO molecules, respectively. The dashed line is the standard $T_{CMB}(z)$ relation. The grey-shaded area shows the constraints provided by the $z < 1$ data on a specific parameterization. The same is shown by the dotted lines for a more general parametrisation. Constraining these more general models requires much better precision measurements at $z > 1$ which are only possible with HIRES: the current best measurements at $z > 1$ are typically based on S/N ∼ 20, R ∼50,000 CO lines, as shown in the upper inset, and provide at best ∼0.7 K precision. Pushing to S/N = 100 and R = 100,000 with HIRES would provide a factor of 10 higher precision, as illustrated by the simulated red point at z=2.5. HIRES will thus enable TCMB measurements at high redshift with a precision similar to that obtained from COBE, Planck and ALMA at $z < 1$.

- HIRES will be able to constrain the variation of fundamental physical constants like the fine-structure constant (α) and proton-electron mass ratio (μ) with the advantage, compared to laboratory measurements, of exploring variations over 12 Gyr time-scales and 15 Gpc spatial scales. A detection of varying fundamental constants would be revolutionary: it would automatically prove that the Einstein Equivalence Principle is violated (i.e. gravity is not purely geometry), and that there is a fifth force. Figure 4 shows the expected improvement of HIRES of the accuracy of the $\Delta\alpha/\alpha$ measurements compared to VLT (UVES, ESPRESSO), GMT and TMT.

- HIRES will enable a test of the CMB temperature-redshift relation, T(z) = T0 (1 + z), which is a robust prediction of standard cosmology but that must be directly verified by measurements. A departure from this relation can in turn reveal a violation of the hypothesis of local position invariance (and thus of the equivalence principle) or that the number of photons is not conserved. HIRES will be able to measure T(z) with unprecedented accuracy: in other words, a single HIRES measurement will already improve on the existing constraints from all current data combined (Figure 4, right).

- The redshifts of cosmologically distant objects drift slowly with time (the so-called Sandage effect). A redshift drift measurement is fundamentally different from all other cosmological observations and can provide a direct detection of cosmic reacceleration, thus undoubtedly confirming cosmic acceleration and the existence of dark energy. HIRES will be capable of detecting the redshift drift in the Lyα forests of the brightest currently known QSOs (∼6 cm/s/decade at z = 4 for a Planck-like standard cosmology). The ELT may thus become the first facility ever to watch the Universe change in "real time".

4. SCIENCE PRIORITIES AND TOP LEVEL REQUIREMENTS

Only an instrument well above the 18 MEUR cost cap would fulfil the requirements associated with the top priority science cases identified within each science area. Therefore, an overall science prioritization was performed by the core SAT to drive the corresponding process of instrument design and to establish a trade-off between cost and scientific priorities. The following criteria were identified:

1. Scientific impact: transformational versus incremental.
2. Feasibility.
3. Competitiveness.

Also, if the TLR's of the top priority science case were enabling other science cases, the latter were not considered any further in the subsequent prioritization, as considered accomplished together with the top priority science case. The top science priorities and associated requirements are listed below. However, also the lower priority science cases have been considered when defining the technical specifications in order to allow for additional extensions.

4.1 Priority 1: Exoplanet atmospheres in transmission.

The essential TLR associated with this science case are summarized here:

1. Spectral resolution: at least 100,000
2. Spectral sampling: at least 2.5 pixels per resolution element
3. Wavelength coverage: 0.50-1.80 μm
4. High flat-field accuracy and/or PSF/detector stability
5. Wavelength calibration accuracy: 1 m/s.

We emphasize that achieving the complete wavelength coverage outlined above is of utmost importance to carry out this science case successfully. The implementation of the above TLRs would automatically enable the following science cases: Reionization of the Universe, characterization of cool stars. In addition, the following science cases would also be doable, although not optimally as their TLRs would be closely, but not fully met: Detection and investigation of near pristine gas, 3D reconstruction of the CGM, Extragalactic transients.

4.2 Priority 2: Variation of the Fundamental Constants

The essential TLR of this science case would be an extension of the Priority 1 TLR and, specifically:

1. Wavelength range: 0.37-0.67 μm

This would be an extension towards the blue of the wavelength range required for the previous science case. We are aware that at $\lambda < 0.40\mu$m the throughput of the E-ELT is expected to be low as a consequence of the planned coating. However, even in the range 0.37-0.40μm the system is expected to be competitive with ESPRESSO. It is important to note that the same extension towards the blue would also automatically enable: Cosmic variation of the CMB temperature, Determination of the deuterium abundance, Investigation and characterization of primitive stars.

4.3 Priority 3: Detection of exoplanet atmospheres in reflection.

The essential TLRs for this science case are the same as for the transmission case (priority one) with the additional request of:

1. Adaptive Optics (SCAO)
2. Integral Field Unit

The implementation of these additional TLRs would automatically enable also the following cases: Planet formation in protoplanetary disks, Characterization of stellar atmospheres, Search of low mass Black Holes. In addition, the following science case would also be doable, although not optimally as its TLR would be closely, but not fully met (sect. 4.1): Characterization of the physics of protoplanetary disks.

4.4 Priority 4: Sandage test.

This is the science case with the most demanding requirements in terms of accuracy of the wavelength calibration and stability. More specifically the essential TLRs are:

1. Spectral resolution at least R=100,000
2. Wavelength range: 0.40-0.67 μm
3. Stability: 2 cm/s (if this is met then there are no constraints on wavelength accuracy as long as it is constant as a function of wavelength and time to within 2 cm/s)

The implementation of these TLR would automatically enable the: Mass determination of exoplanets (in particular of Earth-like objects) and, possibly, with an extension the wavelength range towards the red/infrared, would enable the: Radial velocity search and mass determinations for exoplanets around M-dwarf stars.

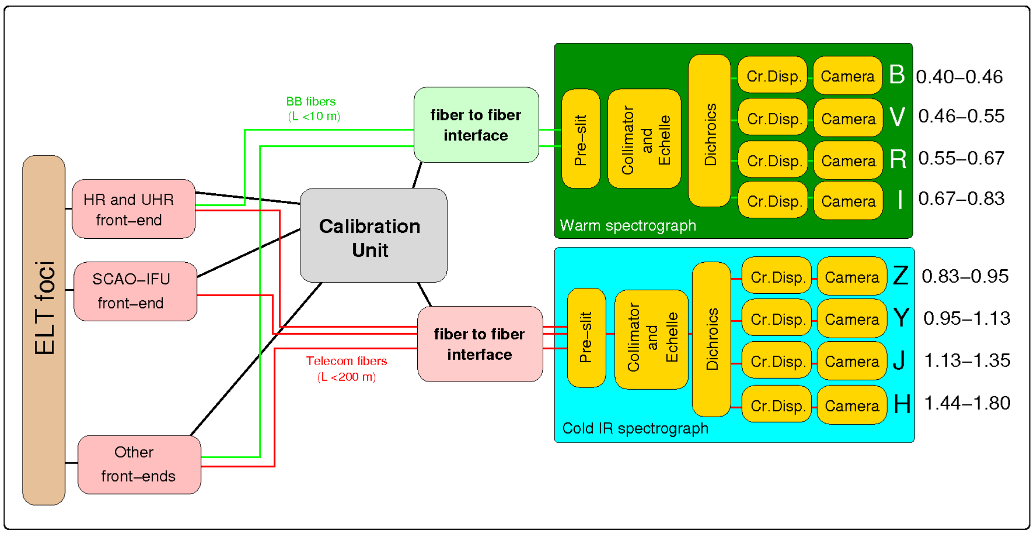

Figure 5. Schematic view of the functional architecture of the overall instrument with wavelength splitting in two spectrographs.

5. INSTRUMENT CONCEPT

The HIRES baseline design is that of a modular fiber-fed cross dispersed echelle spectrograph which has two ultra-stable spectral arms, VIS and NIR, providing a simultaneous spectral range of 0.4-1.8 μm at a resolution of 100,000 with several, interchangeable, observing modes ensuring maximization of either accuracy, throughput, spatially resolved or polarimetric information. With the addition of a SCAO module, the prosed baseline design is capable of fulfilling the requirements of the 4 top science cases. In the case of priority 2 (fundamental constant of physics) the required wavelength range is partially fulfilled as the blue limit of the spectrograph is 0.4 instead of 0.37 μm.

The baseline design is summarized below but several alternatives have been evaluated during the Phase A study. Also, several add-ons made possible by the modular nature of the instrument have been considered, and could be studied in detail during Phase B. The overall concept is summarized in Figure 5: the light from the telescope is split, via dichroics, into 2 wavelength channels. Each wavelength channel interfaces with several fiber bundles that feed the corresponding spectrograph module (VIS and NIR). Each fiber-bundle corresponds to an observing mode. All spectrometer modules have a fixed configuration, i.e. no moving parts. They include a series of parallel entrance slits consisting of linear micro-lens arrays each glued to the fiber bundles. Several analyses have been performed in order to define the best trade-off for the wavelength splitting and a huge effort has been made to push the VIS spectrograph as much as possible towards the blue wavelength range. The split in wavelengths between the modules is influenced, among other parameters by the optical throughput of the different types of fibers available on the market; therefore, the different modules can be positioned at different distances from the focal plane of the telescope. The final configuration foresees that the VIS module is placed on the Nasmyth platform while the IR model will sit in the Coudé Room (Figure 6).

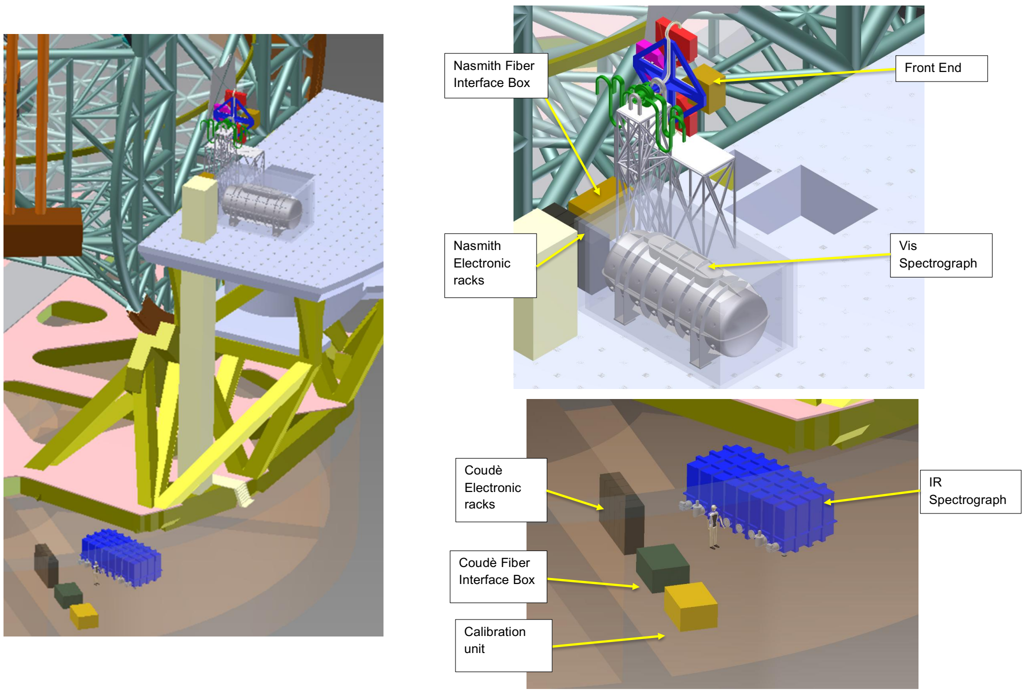

Figure 6. Overall and detailed views of HIRES Nasmyth and HIRES Coudé parts.

5.1 Main subsystems

The main subsystem of HIRES are as follows:

- Front End (FE) which collects the light coming from the ELT focus, split in different bandwidth, stabilizes the light beams and feeds the fiber bundles of the selected observing mode.
- Fiber Link (FL) which couples the light coming from the Front End fiber bundles into the fiber bundles that feed the spectrographs. The FL also couples the calibration light into the respective fiber bundles for the observing mode requiring simultaneous calibration.

Spectrographs. The baseline solution foresees two spectrographs, a visible (BVRI) and an infrared one (ZYJH). A more complete solution foresees two more spectrographs (U and K). The BVRI (and U) spectrographs are located on the Nasmyth platform B, close to the Front End. The cooled spectrographs, ZYJH (and, possibly, K depending on the fibers available) are located in the Coudé room. At the entrance of each spectrograph there is the input split which is facilitated by the spectrograph fibers and the corresponding micro-lenses. Each observing mode has an associated bundle of fibers in the input slit.

- Infrared Spectrograph (IR) The IR module has 4 cameras, Z, Y, J and H, with one scientific detector each. The optical layout is described in more detail in papers presented at this conference.[6]
- Visible Spectrograph (VIS) The VIS module has 4 cameras, B, V, R and I, with one scientific detector each. The optical layout is described in more detail in papers presented at this conference.[6]

obs mode	B1	B2	B3	B4
spectral resolution	100,000	100,000	150,000	150,000
# of apertures on sky	1 (obj)	2 (obj+sky)	1 (obj)	2 (obj+sky)
# of fibers per aperture	64	30	96	46
aperture diameter on sky 1.36”	0.93”	1.11”	0.77”	
simultaneous calib	no	no	no	no

Table 2. Summary of throughput maximization modes

- Calibration Unit (CU) The Calibration Unit is connected via fibers to the Front End through the Fiber Links. The CU is located in the Coud room and provides: Intensity calibration sources (for flat field; Laser Driven Light Source, Halogen lamps, Light Emitting Diodes, Light bulbs) and spectral sources for simultaneous calibration (AstroComb(s), Fabry-Perot, Single Wavelength Laser, Hollow-Cathode Lamps).
- Polarimetry (POL) The polarimeter is a dual channel, full Stokes vector instrument located in the Intermediate Focus of the telescope. It is retractable and both polarimetric beams are reimaged to the HIRES Nasmyth focus by a dual telescope collimator. Fibers are used to provide calibration light to the instrument. More details can be found in papers presented at this conference.[7,8]

5.2 Observing modes

The modularity of the array slit allows the implementation of several observing modes that can be also modified or added even after the initial implementation of the spectrograph. Following the science prioritization, three sets of observing modes were selected that enable the top priority science cases as well as the large majority of the other ones. These observing modes were then used to define the FL subsystem: throughput maximization, accuracy maximization, spatial resolution maximization. Throughput maximization modes are shown, as an example, in Table 2. The number of apertures on the sky corresponds to the number of fibre bundles, and each aperture/bundle is composed by a given number of fibres. The fibres of all bundles are then aligned along the entrance slits. Simultaneous observations of up to 2 objects (or 1 objects and 1 sky), as well as an IFU[9] with up to 0.9”x0.9” field of view and a SCAO[10] module are possible. Observing modes like Multi-Object Spectroscopy and Spectropolarimetry[7,8] are also possible.

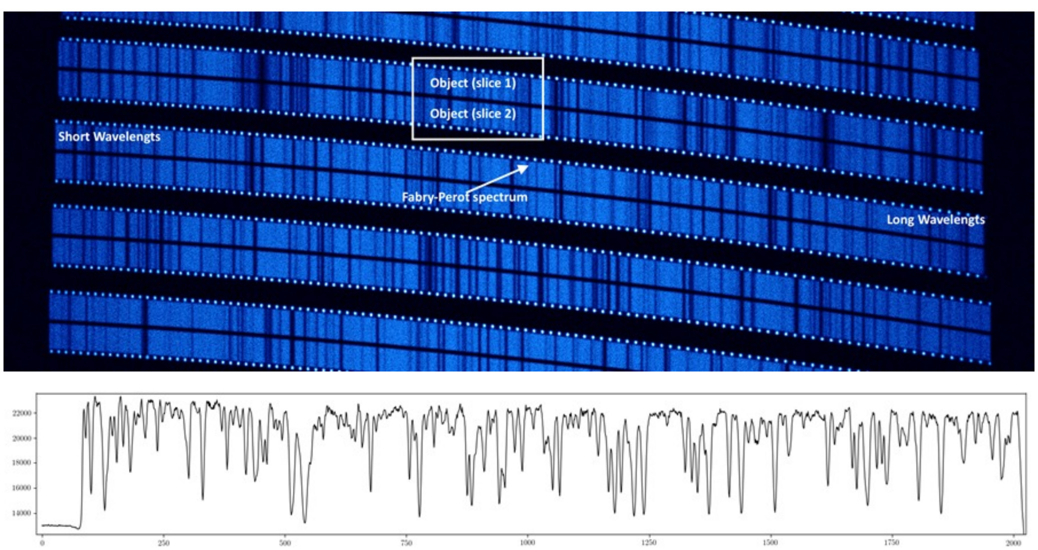

Figure 7. Top: Simulated science spectrum with E2E simulator. Bottom: Extracted science spectrum.

5.3 Software architecture

The entire HIRES software (control and scientific) has been developed with the final goal of providing the astronomer with high level products (e.g. RV measurements or other astronomical observables) as complete and precise as possible in a short time (within minutes) after the end of an observation. This will maximize the overall efficiency and the scientific output making HIRES truly a "science-grade products generating machine" following the philosophy adopted already for ESPRESSO. A fully integrated Data Analysis Package will allow to extract all the relevant astronomical parameters as soon as the reduced data are produced. Already in this phase we have a working HIRES-specific ETC (Exposure Time Calculator, see 5.4) and an initial version of a HIRES-specific end-to-end (E2E) simulator[11] has also been implemented (see Figure 7). Based on E2E results and according to scientific needs extrapolated from the science and operational concept document the main features of both DRS (Data Reduction Software) and DAS (Data Analysis Software) have been identified already in this project phase. The HIRES DRS is a data reduction library for both visible and near-infrared parts of the spectrograph. The concept of the DAS is modelled around the ESPRESSO DAS as a set of self-standing modules ("recipes") performing interdependent operations. For both, a fully integrated approach based on ESO standard tools like esorex, reflex and workflow have been considered. The HIRES control software on the other side is responsible to control all the vital functions of the instrument like motors, sensors, lamps and to manage the execution of the scientific exposures according to the given observation mode. It will also implement all the needed interfaces towards external subsystems (telescope, scheduler, archive). During this phase study a detailed requirement analysis have been conducted in order to identify main HIRES requirements. This led to an initial software architecture design where ideas and paradigms developed for the VLT have been largely considered.

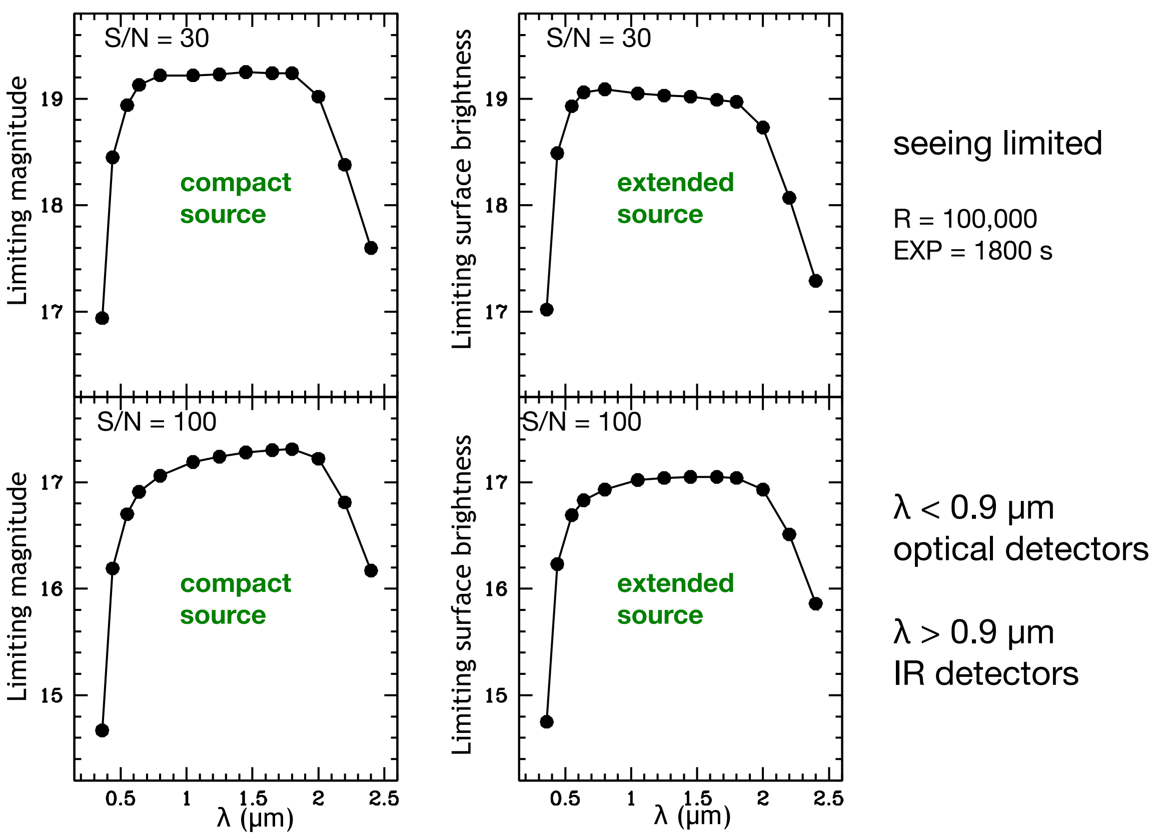

Figure 8. Expected HIRES performances.

5.4 Expected performances

The live ETC maintained by INAF-Arcetri is already available to the HIRES Consortium, and it can be run at the `http://www.arcetri.inaf.it/~hires/etc.html` web link. This ETC can compute the limiting magnitude achievable at a given wavelength, in a given exposure time and at a given signal to noise ratio or it can compute the signal to noise ratio achievable at a given wavelength, in a given exposure time and at a given magnitude. HIRES expected performances computed with the ETC are summarized in Figure 8.

6. POSSIBLE PROJECT SCHEDULE AND COSTS

The construction of the HIRES baseline design (with the VIS and NIR modules) will require an estimated 26 MEUR in hardware and 500 FTEs. Contingencies have been included at subsystem level using different margins according to the considered components (usually 5-10%). Then a 5% contingency at system level has been applied. We have considered these low contingencies because the proposed baseline design is based on proven technical solutions and can benefit on heritage from ESPRESSO and other previous high resolutions spectrographs. We also estimated that HIRES with only the VIS module would cost about 14 MEUR in hardware, while HIRES with only the NIR module would cost 17 MEUR. We also estimated a construction period of 8 years therefore, if Phase B starts at the beginning of 2019, HIRES could be finally delivered to ESO at the end of 2027.

7. CONCLUSIONS

We summarize here the results obtained from the current Phase A study for a High-Resolution Spectrograph for the ELT.

- The study has been conducted by an international consortium including the majority of the institutes in ESO member states expert in high resolution spectroscopy. The consortium is composed of 30 institutes from 12 countries, and a grand total of about 200 people have contributed to the study.
- The study has started on March 22, 2016 and has been completed in one and a half years, with the datapack delivery to ESO on October 6, 2017.
- The science priorities which have been identified for prioritizing the Top Level Requirements of the instrument are:

  1. the detection of the signatures of life through the study of exoplanet atmospheres in transmission
  2. the variation of the fundamental constants of Physics
  3. the detection of the signatures of life through the study of exoplanet atmospheres in reflection
  4. the direct detection of the Cosmic acceleration through the measurement of the Sandage effect

  Many other ground-breaking science cases are made possible with the TLRs inferred from 1 to 4.
- The HIRES baseline design is that of a modular fiber-fed cross dispersed echelle spectrograph which has two ultra-stable spectral arms, VIS and NIR, providing a simultaneous spectral range of 0.4-1.8 μm at a resolution of 100,000 with several, interchangeable, observing modes ensuring maximization of either accuracy, throughput or spatially resolved information.
- The proposed baseline design is capable of fulfilling the requirements of the 4 top science cases (partial fulfilment in case of priority 2 due to the blue limit at 0.4μm) with the addition of the SCAO module.
- The modularity of the instrument ensures that several extensions can be added without affecting the instrument design or stability. The fiber-feeding ensures ultra-stable VIS and NIR spectrographs with no internal moving parts while, at the same time, allowing for many different observing modes.
- The total estimated cost of the baseline design is about 26 MEUR, including contingencies, with an estimated 500 FTEs required to complete the project.
- A schedule proposed with a Phase B in kick-off at the beginning of 2019 would allow to start operating the instrument at the ELT in 2027, i.e. roughly two years after ELT first light.

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REFERENCES

[1] Ramsay, S., D'Odorico, S., Casali, M., and et al., "An overview of the E-ELT instrumentation programme," in [*Ground-based and Airborne Instrumentation for Astronomy III*], *Proc. SPIE* **7735**, 773524 (July 2010).

[2] Pasquini, L., Cristiani, S., García López, R., and et al., "Codex," in [*Ground-based and Airborne Instrumentation for Astronomy III*], *Proc. SPIE* **7735**, 77352F (July 2010).

[3] Origlia, L., Oliva, E., Maiolino, R., and et al., "SIMPLE: a high-resolution near-infrared spectrometer for the E-ELT," in [*Ground-based and Airborne Instrumentation for Astronomy III*], *Proc. SPIE* **7735**, 77352B (July 2010).

[4] Maiolino, R., Haehnelt, M., Murphy, M. T., and et al., "A Community Science Case for E-ELT HIRES," *ArXiv e-prints (1310.3163)* (Oct. 2013).

[5] Riva, M. and HIRES Technical team, "Hires Blue Book," (Jan. 2015).

[6] Oliva, E., Tozzi, A., Ferruzzi, D., and et al., "ELT-HIRES the high resolution instrument for the ELT: optical design and instrument architecture," *SPIE 10702-317, this conference* (2018).

[7] Di Varano, I., Woche, M., Strassmeier, K., and et al., "ELT-HIRES the High Resolution Spectrograph for the ELT: phase-A design of its polarimetric unit," *SPIE 10706-67, this conference* (2018).

[8] Woche, M., Di Varano, I., Strassmeier, K., and Weber, M., "ELT-HIRES the high resolution spectrograph for the ELT: optical design studies for the polarimetric unit," *SPIE 10706-193, this conference* (2018).

[9] Tozzi, A., Oliva, E., Sanna, D., and et al., "ELT-HIRES, the high resolution spectrograph for the ELT: the IFU- SCAO module," *SPIE 10702-319, this conference* (2018).

[10] Xompero, M. and et al., "ELT-HIRES the high resolution spectrograph for the ELT: implementing exoplanet atmosphere reflection detection with a SCAO module," *SPIE 10702-215, this conference* (2018).

[11] Genoni, M., Landoni, M., Riva, M., and et al., "ELT -HIRES the High Resolution Spectrograph for the ELT: End to End simulator. Design approach and results.," *SPIE 10705-43, this conference* (2018).