# ESPRESSO — An Echelle SPectrograph for Rocky Exoplanets Search and Stable Spectroscopic Observations

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**ESPRESSO is the next generation European exoplanet hunter, combining the efficiency of a modern echelle spectrograph with extreme radial velocity and spectroscopic precision. ESPRESSO will be installed in the Combined Coudé Laboratory of the VLT and linked to the four Unit Telescopes (UT) through optical coudé trains, operated either with a single UT or with up to four UTs for 1.5 magnitude gain. The instrumental radial velocity precision will reach the 10 cm s$^{-1}$ level and ESPRESSO will achieve a gain of two magnitudes with respect to its predecessor HARPS. This is the first VLT instrument using the incoherent combination of light from four telescopes and, together with the extreme precision requirements, calls for many innovative design solutions while ensuring the technical heritage of HARPS.**

The main scientific drivers for ESPRESSO are the search and characterisation of rocky exoplanets in the habitable zone of quiet, nearby G to M dwarf stars and the analysis of the variability of fundamental physical constants. As an ultra-stable high-resolution spectrograph however, ESPRESSO will allow new frontiers to be explored in most domains of astrophysics. The project passed its final design review in May 2013 and has entered the manufacturing phase. ESPRESSO will be installed at the Paranal Observatory in 2016 and is planned to begin operations by the end of that year.

## Introduction

High-resolution spectroscopy has always been at the heart of astrophysics. It provides the data that bring physical insight into the behaviour of stars, galaxies, interstellar and intergalactic media. Correspondingly, high-resolution spectrographs have always been in high demand at major observatories, see, e.g., UVES at the VLT or HIRES at the Keck Telescope. As telescope apertures become larger, the capabilities of high-resolution spectrographs extend to fainter and fainter objects. Besides this increase in photon-collecting power, another aspect has emerged in recent years: the power of high-precision spectroscopy. In many applications there is the need for highly repeatable observations over long timescales where instrumental effects must be completely removed, or at least minimised. For instance, this is the case for radial velocity (RV) measurements, or, more generally, for the determination of the positions and shapes of spectral lines. In this respect, the HARPS spectrograph at the ESO 3.6-metre telescope (Mayor et al., 2003) has been a pioneering instrument. It has been widely recognised in the European astronomical community that a similar instrument on the VLT would be necessary.

The need for a ground-based follow-up facility capable of high RV precision was stressed in the ESO–ESA working group report on extrasolar planets (Perryman et al., 2005). The research area "*terrestrial planets in the habitable zone*" is one of the main scientific topics for the next few decades in astronomy, and one of the main science drivers for the new generation of extremely large telescopes (ELTs). The ESO–ESA working group report states: "High-precision radial velocity instrumentation for the follow-up of astrometric and transit detections, to ensure the detection of a planet by a second independent method, and to determine its true mass. For Jupiter-mass planets, existing instrumentation may be technically adequate, but observing time inadequate; for Earth-mass candidates, special purpose instrumentation (like HARPS) on a large telescope would be required." (Perryman et al., 2005, p. 63). The same concept is reiterated in the first recommendation: "Support experiments to improve RV mass detection limits, e.g., based on experience from HARPS, down to those imposed by stellar surface phenomena" (Perryman et al., 2005, p. 72).

*Do the fundamental constants vary?* This is one of the six big open questions in cosmology as listed in the ESA–ESO working group report for fundamental cosmology (Peacock et al., 2006). In the executive summary, the document states: "Quasar spectroscopy also offers the possibility of better constraints on any time variation of dimensionless atomic parameters such as the fine structure constant $\alpha$ and the proton-to-electron mass ratio. Presently there exist controversial claims of evidence for variations in $\alpha$, which potentially relate to the dynamics of dark energy. It is essential to validate these claims with a wider range of targets and atomic tracers." This goal can only be reached with improved spectroscopic capabilities.

In this context the ESO Scientific Technical Committee (STC) recommended, at its 67th meeting in October 2007, the development of additional second generation VLT instruments, and its detailed proposal was endorsed by the ESO Council at its 111th meeting in December 2007. Among the recommended instruments, a high-resolution, ultra-stable spectrograph for the VLT combined coudé focus arose as a cornerstone to complete the current second generation VLT instrument suite. In March 2007, following these recommendations, ESO issued a call for proposals, open to Member State institutes or consortia, to carry out the Phase A study for such an instrument. The submitted proposal was accepted by ESO and the ESPRESSO consortium was selected to carry out the project for the construction of this spectrograph. The main scientific drivers for this project were defined by ESO as follows:
1. Measure high-precision RV to search for rocky planets.
2. Measure the variation of physical constants.
3. Analyse the chemical composition of stars in nearby galaxies.

The official project kick-off was held in February 2011. The design phase lasted about 2.5 years and ended with the final design review (FDR) in May 2013. The procurement of components and manufacturing of subsystems will last about 18 months. Early in 2015 the subsystems will be ready for integration in Europe. Acceptance Europe of the instrument will be held in late 2015. The transfer of the instrument to Paranal, installation and onsite commissioning is foreseen to take place in 2016. Acceptance Paranal is planned to take place at the end of 2016.

## A new generation instrument for the VLT

### Design concepts

ESPRESSO is a fibre-fed, cross-dispersed, high-resolution, echelle spectrograph. The telescope light is fed to the instrument via a coudé train optical system and within optical fibres. ESPRESSO is located in the Combined Coudé Laboratory (incoherent focus) where a front-end unit can combine the light from up to four Unit Telescopes of the VLT. The target and sky light enter the instrument simultaneously through two separate fibres, which together form the pseudo slit of the spectrograph.

Several optical tricks have been used to obtain high spectral resolution *and* efficiency despite the large size of the telescope and the 1-arcscecond sky aperture of the instrument. At the spectrograph entrance, the anamorphic pupil slicing unit (APSU) shapes the beam in order to compress it in cross dispersion and split it into two smaller beams, while superimposing them on the echelle grating to minimise its size. The rectangular white pupil is then re-imaged and compressed. Given the wide spectral range, a dichroic beam-splitter separates the beam into a blue and a red arm, which in turn allows each arm to be optimised for image quality and optical efficiency. The cross-disperser has the function of separating the dispersed spectrum into all its spectral orders. In addition, an anamorphism is re-introduced to make the pupil square and to compress the order height such that the inter-order space and the signal-to-noise ratio (SNR) per pixel are both maximised. Both functions are accomplished using Volume Phase Holographic Gratings (VPHGs) mounted on prisms. Finally, two optimised camera lens systems image the full spectrum from 380 nm to 780 nm on two large 92 mm × 92 mm CCDs with 10 µm pixels. A sketch of the optical layout is shown in Figure 1. The spectral format covered by the blue and the red chips is shown in Figure 2a and 2b and the shape of the pseudo slit is shown in Figure 2c.

The spectrograph is also equipped with an advanced exposure meter that measures the flux entering the spectro-

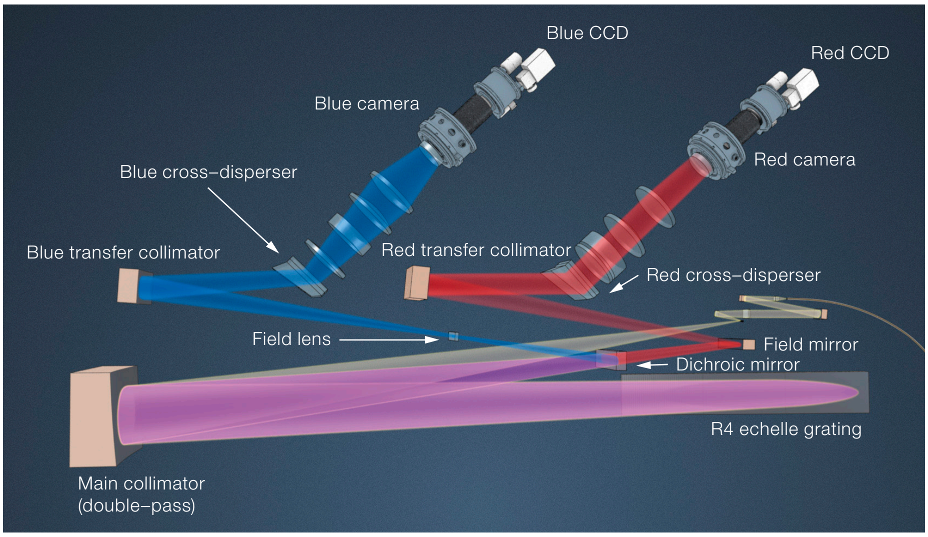



Figure 1. Layout of the ESPRESSO spectrograph and its optical elements.

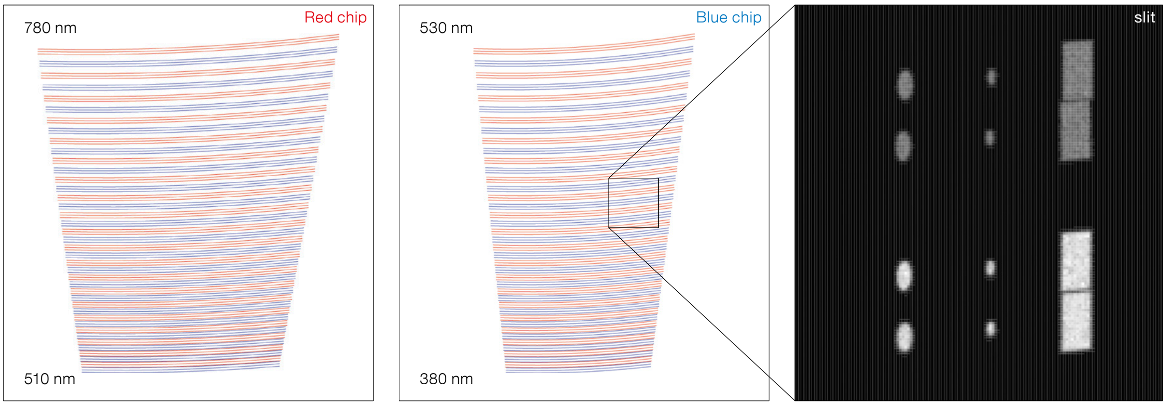



Figure 2. Shown left to right: Format of the red spectrum; format of the blue spectrum; zoom of the pseudo slit. This latter shows the image of the target (bottom) and sky fibre (top). Each fibre is re-imaged into two slices. The three sets of fibres, corresponding (from left to right) to the standard resolution 1-UT mode, ultra-high resolution 1-UT mode, and mid-resolution 4-UT mode, are shown simultaneously.

graph as a function of time. This function is necessary to compute the weighted mean time of exposure at which the precise relative Earth motion must be computed and applied to correct the RV measurement. The innovative design (based on a simple diffraction grating) allows a flux measurement and an RV correction at different spectral channels, in order to cope with possible chromatic effects that could occur during the scientific exposures. The use of various channels also provides a redundant and thus more reliable evaluation of the mean time of exposure.

## Dealing with a large étendue

In order to minimise the size of the optics, particularly of the collimator and echelle grating, ESPRESSO implements an anamorphic optical element, the APSU, which compresses the size of the pupil in the direction of the cross dispersion. The pupil is then sliced in two by a pupil slicer and the slices are overlapped on the echelle grating, leading to a doubled spectrum on the detector. The shape and size of both the pupil and the fibre image is shown in Figure 3 for various locations along the optical beam of the spectrograph.

Without using this method, the collimator beam size would have been 40 cm in diameter and the size of the echelle grating would have reached 240 × 40 cm. The actual ESPRESSO design foresees the use of an echelle grating of "only" 120 × 20 cm and of much smaller optics (collimators, cross dispersers, etc.). This solution significantly reduces the overall costs. The drawback is that each spectral element will be covered by more detector pixels, given the two image slices and their elongated shape on the CCD. In order to avoid increased detector noise, heavy binning will be performed for faint object observations, especially in the 4-UT mode.

## The opto-mechanics

ESPRESSO is designed to be an ultra-stable spectrograph capable of reaching RV precision of the order of 10 cm $s^{-1}$, i.e. one order of magnitude better than its predecessor HARPS. ESPRESSO is therefore designed with a totally fixed configuration, and for the highest thermo-mechanical stability. The spectrograph optics is mounted on a tri-dimensional optical bench specifically designed to keep the optical system within the thermo-mechanical tolerances required for high-

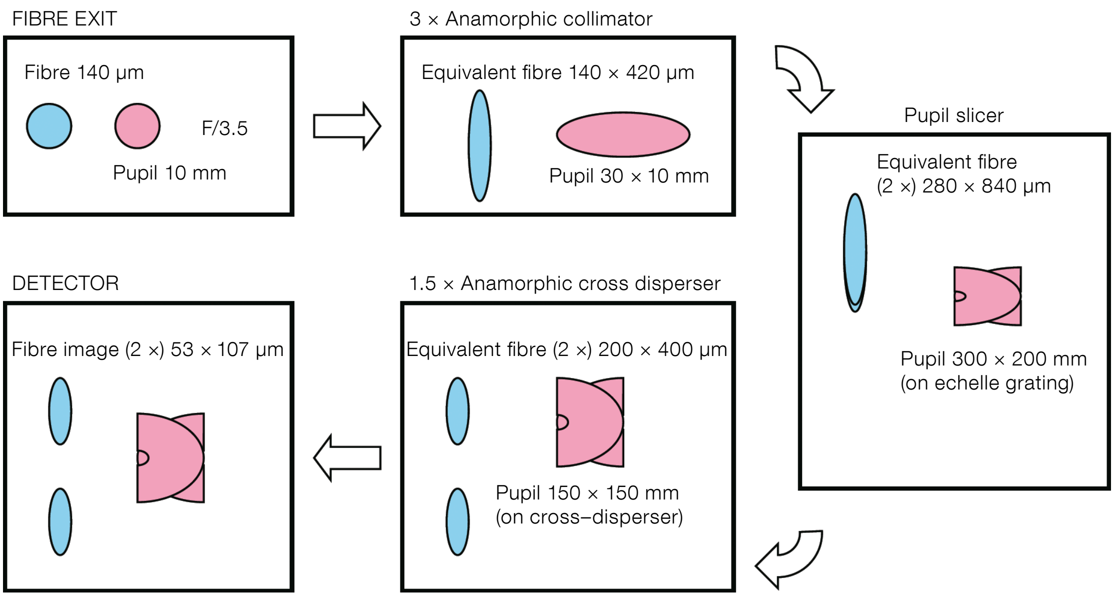



Figure 3. Conceptual description of pupil and fibre image at relevant locations of the ESPRESSO spectrograph.

precision RV measurements. The bench is mounted in a vacuum vessel in which a $10^{-5}$ mbar class vacuum is maintained during the entire duty cycle of the instrument. An overview of the opto-mechanics is shown in Figure 4.

The temperature at the level of the optical system is required to be stable at the mK level in order to avoid both short-term drift and long-term mechanical instabilities. Such an ambitious requirement is obtained by locating the spectrograph in a multi-shell active thermal enclosure system (Figure 5). Each shell will improve the temperature stability by a factor of ten, thus going from typically Kelvin-level variations in the Combined Coudé Laboratory (CCL) down to mK stability inside the vacuum vessel and on the optical bench.

## New large-area CCDs

ESPRESSO also presents innovative solutions in the area of the CCDs, their packages and cryostats. One of the world's largest monolithic state-of-the-art CCDs was selected to properly utilise the optical field of ESPRESSO and to further improve the stability compared to a mosaic solution, as employed in HARPS. The sensitive area of the e2v chip is 92 mm by 92 mm, covering about 9k by 9k pixels of 10 μm size. Fast readout of such a large chip is achieved by using its16 output ports at high speed. Other requirements on the CCDs are very demanding, e.g., in terms of charge transfer efficiency (CTE) and all the other parameters affecting the definition of the pixel position, immediately reflected in the radial velocity precision and accuracy.

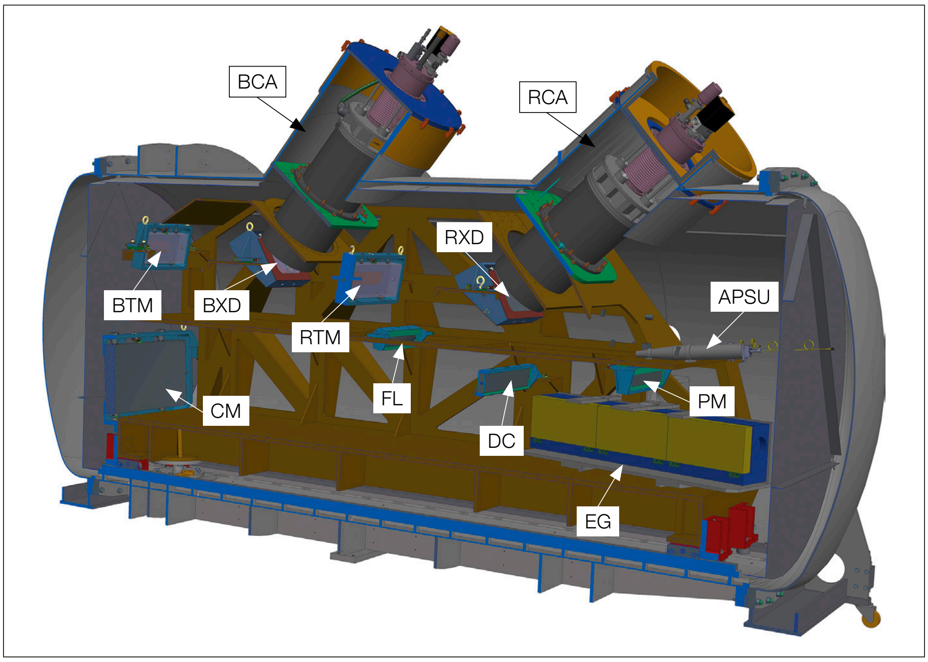



Figure 4. Opto-mechanical drawing of the ESPRESSO spectrograph is shown. Key to components: APSU: Anamorphic Pupil Slicer Unit; BCA: Blue Camera; BTM: Blue Transfer Mirror; BXD: Blue Cross Disperser; CM: Main Collimator; DC: Dichroic; EG: Echelle Grating; FL: Field Lens; PM: Field Mirror; RCA: Red Camera; RTM: Red Transfer Mirror; RXD: Red Cross Disperser.

The CCDs are currently being procured by ESO from the e2v supplier. An engineering sample has already been received (see Figure 6). First warm technical light with the ESO custom-made components (NGC controller, cabling, cryostat electronics, firmware and mock-up mechanics) took place in July 2013.

The precision of 10 cm $s^{-1}$ root mean squared (RMS) aimed at by ESPRESSO requires measuring spectral line position changes of 2 nm (physical) in the CCD plane, equivalent to only four times the silicon lattice constant! For better stability and thermal expansion matching, the CCD package is made of silicon carbide. The combination of the CCDs, the surrounding mechanics and precision temperature control inside the cryostat head

Figure 5. The appearance of ESPRESSO inside the Coudé Combined Laboratory with its vacuum vessel and multi-shell thermal control system shown.

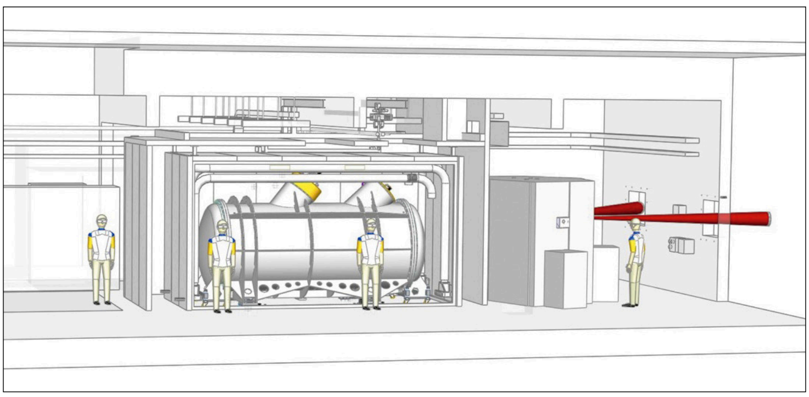
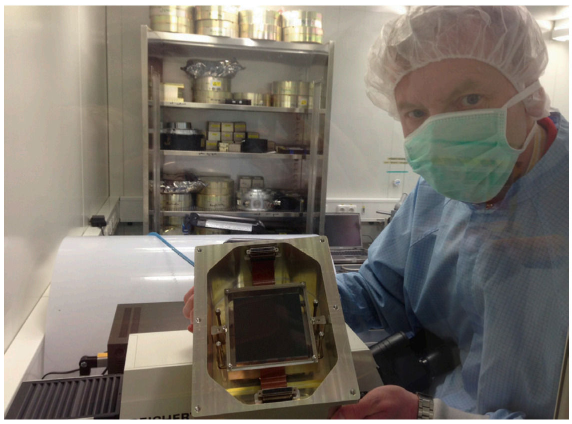


Figure 6. The first ESPRESSO e2v CCD is shown in its opened shipping container, being handled inside the ESO cleanroom.



and its cooling system, as well as the thermal stability and the homogeneous dissipation of the heat locally produced in the CCDs during operation, are of critical importance. ESO has therefore built a new "superstable" cryostat that has already demonstrated excellent short-term stability. A breadboard of the concept is currently being tested and the results will drive the design of the final ESPRESSO detector system.

## Ultimate wavelength calibration and drift measurement

In order to track possible residual instrumental drifts, ESPRESSO will implement the simultaneous reference technique in a manner similar to HARPS (see, e.g., Baranne et al., 1996) where the spectrum of a spectral reference is recorded simultaneously on the scientific detector. All types of spectrographs need to be wavelength-calibrated in order to assign to each detector pixel the correct wavelength with a repeatability of the order of $\Delta\lambda/\lambda = 10^{-10}$. A necessary condition for this step is the availability of a suitable spectral wavelength reference. None of the currently used spectral sources (thorium argon spectral lamps, iodine cells, etc.) would provide a spectrum sufficiently wide, rich, stable and uniform for this purpose.

Therefore, the baseline source for the calibration and simultaneous reference adopted for ESPRESSO is a laser frequency comb (LFC). The LFC presents all the characteristics that are indispensable for precise wavelength calibration and provides a link to the frequency standard. The procurement of an LFC suited for ESPRESSO is ongoing and appears to be very promising. In parallel, ESO has been developing such a source for HARPS, in collaboration with other institutes and industrial partners (Lo Curto et al., 2012). As a back-up solution and in order to minimise risks, a stabilised Fabry Perot is also currently under development within the consortium.

## 1-UT or 4-UT? The astronomer's choice between an 8- or 16-metre equivalent telescope

ESPRESSO is an instrument designed for the incoherent combined focus of the VLT. Although foreseen in the original plan, such a focus has never been implemented at the VLT. But the use of a combined focus has been provided for, in terms of space left in the UT structures and ducts in the rock of the mountain. As part of the project agreement, the ESPRESSO consortium has been asked to furnish such a focus by providing the necessary hardware and software as part of the deliverables. The implementation of the coudé train requires substantial changes to the Paranal Observatory infrastructure which can only be achieved by developing the existing interfaces.

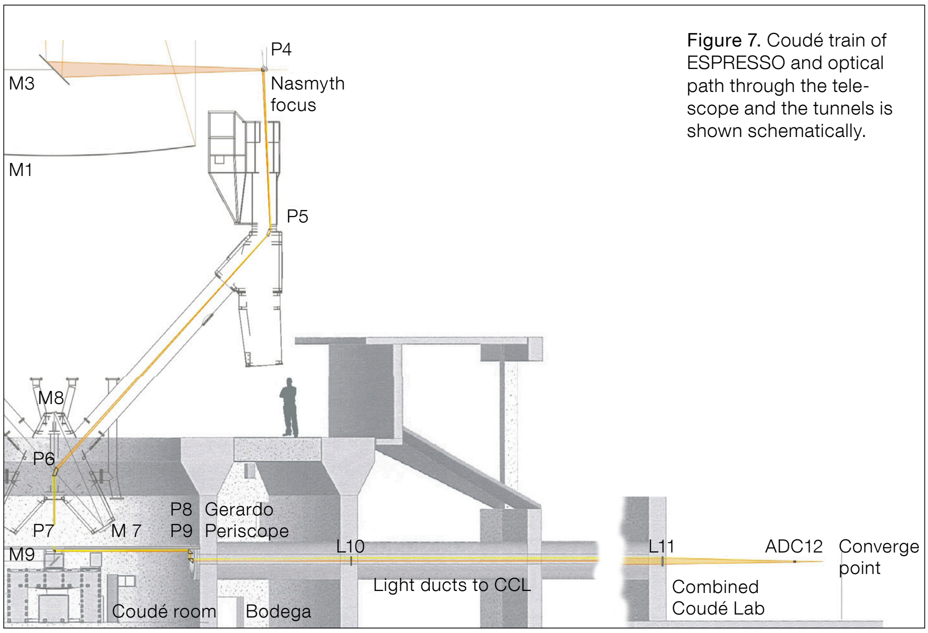



Figure 7. Coudé train of ESPRESSO and optical path through the telescope and the tunnels is shown schematically.

ESPRESSO will be located in the VLT CCL and, unlike any other instruments built so far, will be able to receive light from any of the four UTs. The light of the single UT scheduled to work with ESPRESSO is then fed into the spectrograph (1-UT mode). Alternatively, the combined light of *all* the UTs can be fed into ESPRESSO simultaneously (4-UT mode).

A trade-off analysis considering the use of mirrors, prisms, lenses and/or fibres, and possible combinations of them, suggested a full optical solution, i.e. using only conventional optics (no use of fibres) for transporting the light from the telescope into the CCL. In the chosen design, the coudé train intercepts the light with a prism at the level of the Nasmyth B platform and routes the beam through the UT mechanical structure down to the UT coudé room, and further to the CCL along the existing incoherent light ducts (see Figure 7). The selected concept to convey the light of the telescope from the Nasmyth focus (B) to the entrance of the tunnel in the coudé room (CR) below each UT unit is based on a set of six prisms (with some power). The light is directed from the UT's coudé room towards the CCL using two large lenses. The beams from the four UTs converge into the CCL, where mode selection and beam conditioning is achieved by the fore-optics of the front-end subsystem.

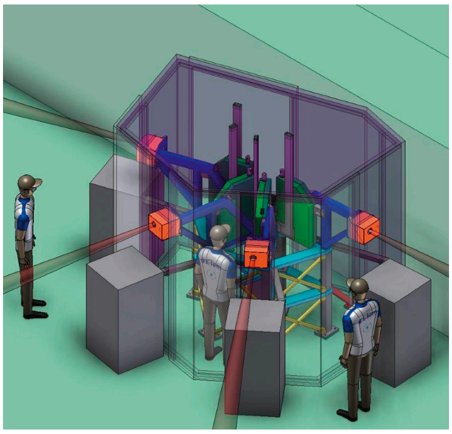


Figure 8. Top view of the ESPRESSO front end and the arrival of the four UT beams at the CCL is shown.

The front end transports the beam received from the coudé, once corrected for atmospheric dispersion by the atmospheric dispersion corrector (ADC), to the common focal plane on which the heads for the fibre-to-spectrograph connection are located. While performing such a beam conditioning, the front end applies pupil and field stabilisation. These two functions are achieved via two independent control loops each composed of a technical camera and a tip-tilt stage. Another dedicated stage delivers a focusing function. In addition, the front end provides the means to inject calibration light (white and spectral sources) into the spectrograph fibre if and when needed. A top view of the front-end arrangement is shown in Figure 8.

The fibre-link subsystem relays the light from the front end to the spectrograph and forms the spectrograph pseudo slit inside the vacuum vessel. The 1-UT mode uses a bundle of two octagonal fibres each, one for the object and one for the sky or simultaneous reference. In the high-resolution (singleHR) mode, the fibre has a core of 140 μm, equivalent to 1 arcsecond on the sky; in the ultra-high resolution (singleUHR) mode the fibre core is 70 μm and the covered field of view is 0.5 arcseconds. The fibre entrances are organised in heads that are brought to the focal plane of the front end when that specific bundle is used for observations, i.e., when that specific mode is selected.

In the 4-UT (multiMR) mode, four object fibres and four sky/reference fibres converge together from the four telescopes. The four object fibres will finally feed a single square 280 μm object fibre, while the four sky/reference fibres will feed a single square 280 μm sky/reference fibre. Also in the 4-UT mode the spectrograph will "see" a pseudo-slit of four fibre images, although they will be square and twice as wide as the 1-UT fibres.

Another essential task performed by the fibre-link subsystem is light scrambling. The use of a double-scrambling optical system will ensure both scrambling of the near field and far field of the light beam. A high scrambling gain, which is crucial to obtain the required RV precision in the 1-UT modes, is achieved by the use of octagonal fibres (Chazelas et al., 2011).

## Modes and performance

The extreme precision required by the scientific goals of ESPRESSO will be obtained by adopting and improving well-known HARPS concepts. The light of one or several UTs is fed by means of the front-end unit into optical fibres that scramble the light and provide excellent illumination stability to the spectrograph. In order to improve light scrambling, non-circular fibre shapes will be used. The target fibre can be fed either with the light from the astronomical object or the calibration source. The reference fibre will receive either sky light (faint source mode) or calibration light (bright source mode). In the latter case — the famous simultaneous reference technique adopted in HARPS — it will be possible to track instrumental drifts down to the cm $s^{-1}$ level. It is assumed that in this mode the measurement is photon-noise limited and that detector readout noise is negligible. In the faint-source mode detector noise and sky background may become significant. In this case, the second fibre will allow the sky background to be measured, while a slower readout and high binning factor will reduce the detector noise.

In summary (see Table 1), ESPRESSO will have three instrumental modes: singleHR, singleUHR and multiMR. Each mode will be available with two different detector readout modes optimised for low- and high-SNR measurements, respectively. In high-SNR (high-precision) measurements the second fibre will be fed with the simultaneous reference, while in the case of faint objects it may be preferable to feed the second fibre with sky light.

The observational efficiency of ESPRESSO is shown in Figure 9. In the singleHR mode a SNR of 10 per extracted pixel is obtained in 20 minutes on a $V = 16.3$ mag star, or a SNR of 540 on a $V = 8.6$ mag star. We have estimated that at the $R = 134\,000$ resolution, this SNR value will lead to 10 cm $s^{-1}$ RV precision for a non-rotating K5 star. For an F8 star, the same precision would be achieved for $V = 8$ mag. In the multiMR mode, a SNR of 10 on a $V = 19.4$ mag star is achieved with a single 20 minute exposure. A slight gain could be achieved with higher binning (2 × 8).

## ESPRESSO's data flow

Following the very positive experience gained with HARPS, ESPRESSO has always been conceived as a "science-generating machine" rather than a "simple" standalone instrument. The final goal is to provide the user with scientific data that are as complete and precise as possible within a short time (minutes) of the end of an observation, thus increasing the overall efficiency and the scientific output of ESPRESSO. For this purpose an integrated view of the software cycle, from the preparation of the observations through instrument operation and control, to data reduction and analysis, has been adopted since early phases of the project. Coupled with a careful design, this approach will ensure optimal compatibility, ease of operations and maintenance within the existing ESO Paranal data-flow environment both in service and visitor modes.

The ESPRESSO data flow contains the following main subsystems:
- EOPS (ESPRESSO Observation Preparation Software): A dedicated visitor tool (able to communicate directly with the vOT — Visitor Observing Tool) to help the observer to prepare and

Table 1. Summary of ESPRESSO's instrument modes and corresponding performance.

| Parameter/Mode | singleHR (1 UT) | multiMR (up to 4 UTs) | singleUHR (1 UT) |
|---|---|---|---|
| Wavelength range | 380–780 nm | 380–780 nm | 380–780 nm |
| Resolving power | 134 000 | 59 000 | 225 000 |
| Aperture on sky | 1.0 arcsec | 4 × 1.0 arcsec | 0.5 arcsec |
| Spectral sampling (average) | 4.5 pixels | 5.5 pixels (binned × 2) | 2.5 pixels |
| Spatial sampling per slice | 9.0 (4.5) pixels | 5.5 pixels (binned × 4) | 5.0 pixels |
| Simultaneous reference | Yes (no sky) | Yes (no sky) | Yes (no sky) |
| Sky subtraction | Yes (no simul. ref.) | Yes (no simul. ref.) | Yes (no simul. ref.) |
| Total efficiency | 11 % | 11 % | 5 % |
| Instrumental RV precision | < 10 cm $s^{-1}$ | ~ 1 m $s^{-1}$ | < 10 cm $s^{-1}$ |

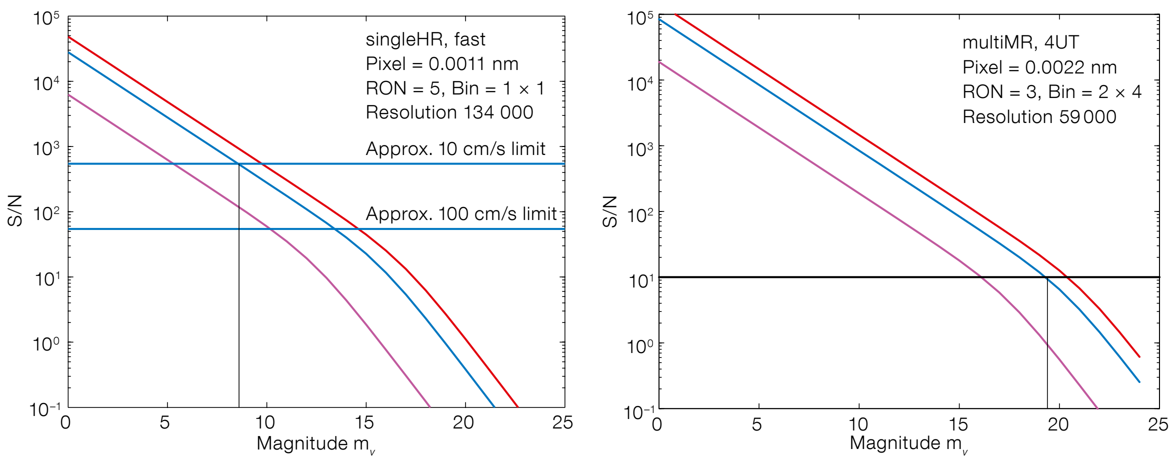



Figure 9. Achievable signal-to-noise ratio (SNR) plotted as a function of stellar visible magnitude for the singleHR (left) and the multiMR (right) modes. Red, blue and magenta curves indicate exposure times of 3600 s, 1200 s and 60 s, respectively.

schedule ESPRESSO observations at the telescope according to the needs of planet-search surveys. The tool will allow users to choose the targets best suited for a given night and to adjust the observation parameters in order to obtain the best possible quality of data.

– DRS (Data Reduction Software): ESPRESSO will have a fully automatic data reduction pipeline with the specific aim of delivering high-quality reduced data to the user. These data will be “science ready” a short time after an observation has been performed. The computation of the RV at a precision better than 10 cm $s^{-1}$ will be an integral part of the DRS. Coupled with the need to optimally remove the instrument signature, to take account of the complex spectral and multi-HDU (header data unit) FITS format, to handle the simultaneous reference technique and the multi-UT mode, this will make the DRS a truly challenging component of the data flow chain.

– DAS (Data Analysis Software): Dedicated data analysis software will allow the best scientific results to be obtained from the observations directly at the telescope. A robust package of recipes tailored to ESPRESSO, taking full advantage of the existing ESO tools (based on the Common Pipeline Library [CPL] and fully compatible with Reflex), will address the most important science cases for ESPRESSO by analysing (as automatically as possible) stars and quasar spectra. (Among others, tasks that can be performed will include Voigt-profile line fitting, estimation of stellar atmospheric parameters, quasar continuum fitting and identification of absorption systems).

– Templates and control: Compared to other standalone instruments, the main reason for the complexity of the ESPRESSO acquisition and observation templates will be the possible usage of any combination of UTs, besides the proper handling of the simultaneous reference technique. Coupled with the fact that, at the instrument control level, PLCs (Programmable Logical Controllers) and new COTS (Component Off-The Shelf) Technical CCDs will be adopted instead of the (old) Versa Model Eurocard (VME) technology, ESPRESSO will contribute to opening a new path for the control systems of future ESO instrumentation. A general overview of the ESPRESSO control system is shown in Figure 10.

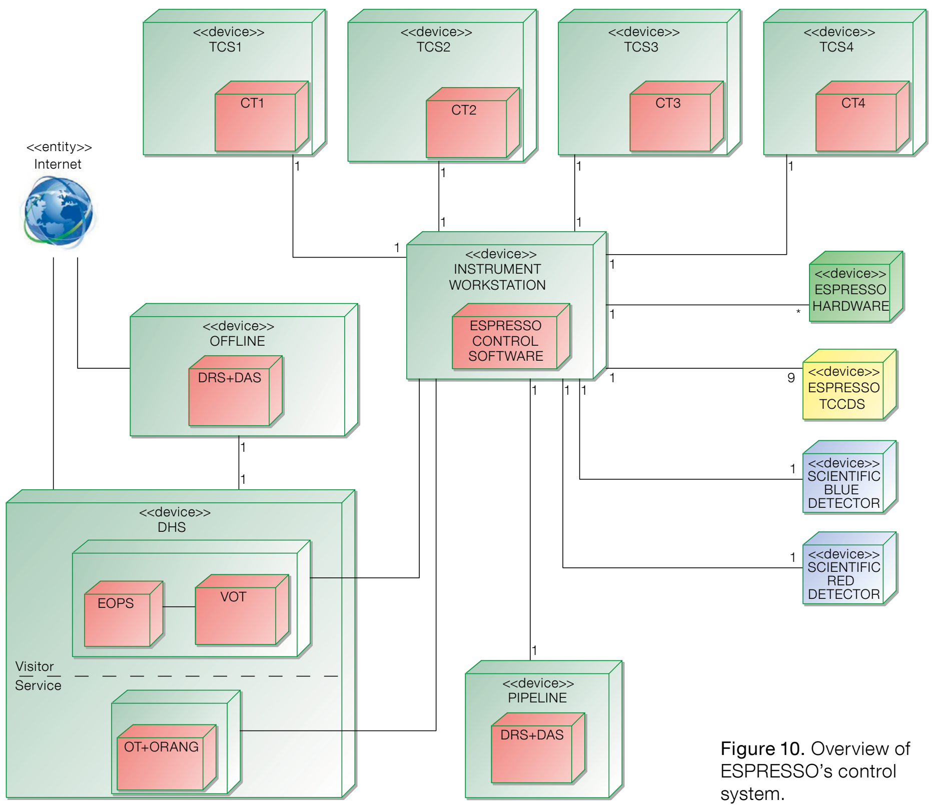



Figure 10. Overview of ESPRESSO’s control system.

### End-to-end operation

The implementation of the feed from the 4 UTs indirectly provides another major advantage for the singleHR mode: operational flexibility. In this mode, ESPRESSO can be fed by any of the four UTs, a possibility which significantly improves the scheduling flexibility for ESPRESSO programmes and optimises the use of VLT time in general. Scheduling flexibility is a fundamental advantage for survey programmes like RV searches for extrasolar planets or time-critical programmes like studies of transiting planets. The single-HR mode itself will thus greatly benefit from the implementation of the multiMR mode.

The overall efficiency and the scientific output of long-lead programmes can be considerably increased if an integrated view of the operations is adopted. Full integration of the data-flow system as described above is fundamental to allowing ESPRESSO to deliver full-quality scientific data less than a minute after the end of an observation.

## Science with ESPRESSO

### Searching for rocky planets in the habitable zone

Terrestrial planets in the habitable zones of their parent stars are one of the main scientific topics for the next few decades in astronomy, and one of the main science drivers for the new generation of extremely large telescopes. ESPRESSO, which is capable of achieving a precision of 10 cm $s^{-1}$ in terms of RV, will be able to register the signals of Earth-like planets and massive Earths in the habitable zones (i.e., in orbits where water is retained in liquid form on the planet's surface) around nearby solar-type stars and stars smaller than the Sun.

Since 1995, research teams, using the RV technique, have discovered about 600 extrasolar planets, some with only a few times the mass of the Earth. Today, dozens of detected RV extrasolar planets have masses estimated at below ten Earth masses ($M_\oplus$), and most of them were identified using the HARPS spectrograph (e.g., Mayor et al., 2011). The rate of these discoveries is increasing steadily. The HARPS high-precision RV programme has shown that half of the solar-like stars in the sky harbour Neptune-mass planets and super-Earths, a finding also supported by the recent discoveries of the Kepler satellite (e.g., Howard et al., 2012). These exciting discoveries were made possible thanks to the sub-m $s^{-1}$ precision reached by HARPS (Figure 11). Given the faint magnitude of the target star and/or the tiny RV signal induced by the planet, most of the observed objects would have remained out of reach of the existing facilities that were limited to 3 m $s^{-1}$. The most recent planet formation models support the current view that this emerging population is only the tip of the iceberg.

Considering the observational bias towards large masses, on the one hand, and the model predictions, on the other, a huge number of still-undiscovered low-mass planets is expected, even in already observed stellar samples. ESPRESSO is designed to explore this new mass domain and chart unknown territory (see Figure 12). This goal can only be obtained by combining high efficiency with high instrumental precision. ESPRESSO will be optimised to obtain its best RVs on quiet solar-type stars. A careful selection of these stars will allow the observations to focus on the best-suited candidates: non-active, non-rotating, quiet G to M dwarfs. The high efficiency of the instrument and an optimised observational strategy will permit demanding planetary systems and very low-mass planets to be characterised despite stellar noise. An impressive demonstration that this approach is realistic has been delivered recently with HARPS through the detection of a 1 $M_\oplus$ planet around the neighbouring star α Cen B (Dumusque et al., 2012).

With a precision of 10 cm $s^{-1}$ (about a factor of ten better than HARPS), it will be possible to detect rocky planets down to Earth mass in the habitable zone of solar-type stars (for comparison the Earth imposes a velocity amplitude of 9 cm $s^{-1}$ on the Sun). By extending the sample towards the lighter M stars, the task becomes even easier since the RV signal increases with decreasing stellar mass. Given its efficiency, spectral resolution and spectral domain, ESPRESSO will operate at the peak of its efficiency for a spectral type up to M4. An example of such capabilities is given by the discovery of HD 85512 b, a 3.6 $M_\oplus$ planet just at the edge of the habitable zone of a K5 dwarf (Pepe et al., 2011), see Figure 13. The discovery and the characterisation of this new population of very light planets will open the door to a better understanding of planet formation and deliver new candidates for follow-up studies by transit, astrometry, Rossiter–McLaughlin effect, etc.

Another important task for ESPRESSO will be the follow-up of transiting planets. It should be recalled that many KEPLER transit candidates are very faint and can hardly be confirmed by existing RV instruments. ESPRESSO will play a significant role in this respect. Most important yet, is the fact that other satellites like GAIA, TESS and hopefully PLATO will provide many new transit candidates, possibly

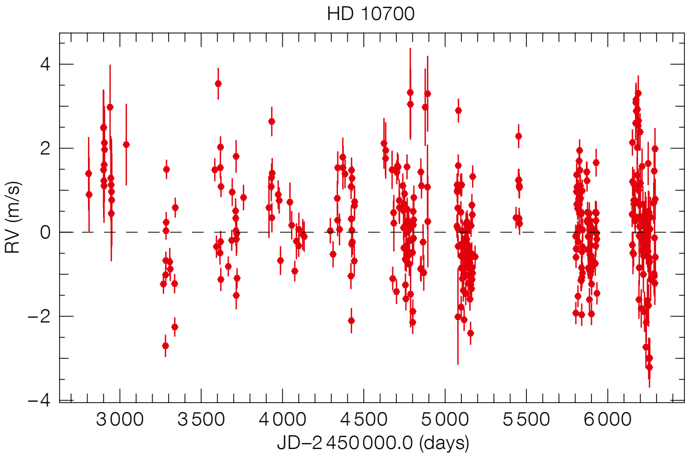



Figure 11. Ten years of RVs for Tau Ceti are plotted as measured by HARPS. The overall dispersion is 1 m $s^{-1}$. Time-binning of the data reduces the dispersion as expected with the square root of the number of observations down to 20 cm $s^{-1}$. Most important yet, is the absence of any long-term trend, thus proving the exquisite precision of HARPS.

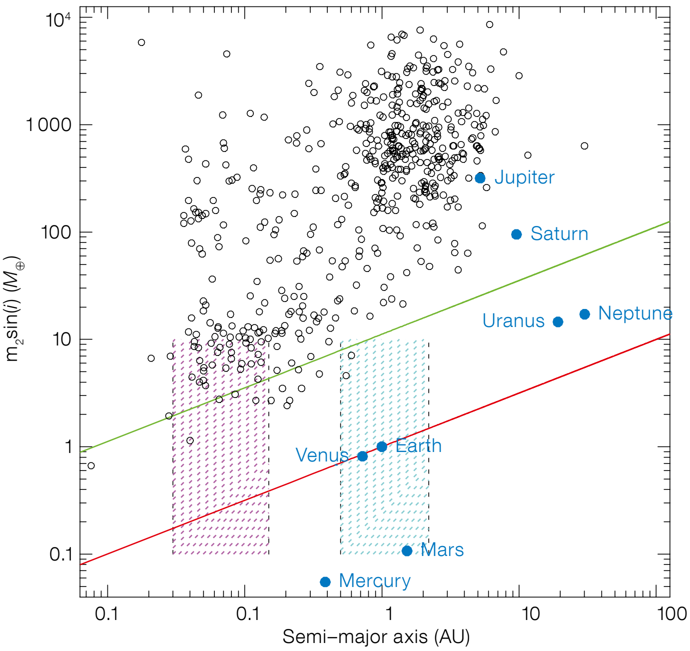



Figure 12. Detectability of planets orbiting a 0.8 $M_\odot$ star (red solid line) and a 1.0 $M_\odot$ star (green solid line) in the mass *vs.* semi-major axis plane expected for ESPRESSO. The detectability curves have been calculated assuming a velocity amplitude of 10 cm $s^{-1}$ (for the 1.0 $M_\odot$ star) and 1 m $s^{-1}$ (for the 0.8 $M_\odot$ star), zero eccentricity, and sin $i$ = 1. Known RV planets of solar-type stars are plotted as open circles, and the planets of the Solar System (solid circles) are labelled. The "habitable zones" of 0.8–1.2 $M_\odot$ and 0.2–0.3 $M_\odot$ stars are indicated within the blue and pink dotted areas, respectively. These are regions where rocky planets with a masses in the interval 0.1–10 $M_\oplus$ can retain liquid water on their surface.

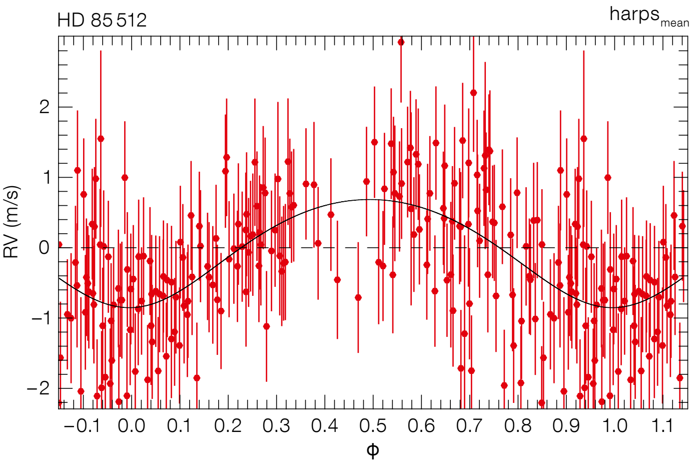



Figure 13. Phase-folded RV variation induced by the planet with a period of 58 days around the K5 dwarf HD 85512.

hosted by bright stars. ESPRESSO will be the ideal (and perhaps unique) machine to make a spectroscopic follow-up of Earth-sized planets discovered by the transit technique. Fast-cadence spectra of the most promising candidates will provide estimates of the maximum frequency of solar-like oscillations. The resulting seismic constraints on the gravity of the host stars and precise spectroscopic analysis will allow improvement in the determination of the mass and radius of the star and, therefore, of the planet (Chaplin & Miglio, 2013).

Besides being an exquisite RV machine, ESPRESSO will provide extraordinary and stable spectroscopic observations, opening up new possibilities for transit spectroscopy and the analysis of the light reflected and emited by the exoplanet. Several groups are currently investigating the extent to which this will be feasible in the visible and infrared spectral domains (see e.g., Snellen, [2013 a; b] and Martins et al. 2013). ESPRESSO should also certainly be considered as an important intermediate step towards the high-precision spectrographs on extremely large telescopes, such as HIRES for the European Extremely Large Telescope (E-ELT).

## Do the physical constants vary?

The Standard Model of particle physics depends on many (~ 27) independent numerical parameters that determine the strengths of the different forces and the relative masses of all known fundamental particles. There is no theoretical explanation for their actual value, but they nevertheless determine the properties of atoms, molecules, cells, stars and the whole Universe. They are commonly referred to as the fundamental constants of Nature, although most of the modern extensions of the Standard Model predict a variation of these constants at some level (see Uzan, 2011). For instance, in any theory involving more than four spacetime dimensions, the constants we observe are merely four-dimensional shadows of the truly fundamental high dimensional constants. The four dimensional constants will then be seen to vary as the extra dimensions change slowly in size during their cosmological evolution. An attractive implication of quintessence models for dark energy is that the rolling scalar field produces a negative pressure and therefore the acceleration of the Universe may couple with other fields and be revealed by a change in the fundamental constants (Amendola et al., 2013).

Earth-based laboratories have so far revealed no variation in the values of the fundamental constants. For example, the constancy of the fine structure constant $\alpha$ is ensured to within a few parts in $10^{17}$ over a ~ 1 yr period (Rosenband et al., 2008). Hence its status as truly "constant" is amply justified. Astronomy has a great potential to probe the variability at very large distances and in the early Universe. In fact, the transition frequencies of the narrow metal absorption lines observed in the spectra of distant quasars are sensitive to $\alpha$ (e.g., Bahcall et al., 1967) and those of the rare molecular hydrogen clouds are sensitive to $\mu$, the proton-to-electron mass ratio (e.g., Thompson, 1975).

With the advent of 10-metre-class telescopes, observations of spectral lines in distant quasi-stellar objects (QSOs) gave the first hints that the fine structure constant might change its value over time, being lower in the past by about 6 parts per million (ppm; see Webb et al., 1999; Murphy et al., 2004). The analysis of 153 absorbing systems from observations with VLT UVES (Figure 14) has revealed 4σ evidence for a dipole-like variation in α across the sky at the 10 ppm level (Webb et al., 2011; King, 2012). Several other constraints from higher-quality spectra of individual absorbers also exist, but none directly support or strongly conflict with the evidence for a dipole in α; possible systematic effects producing opposite values in the two hemispheres are not easy to identify.

In order to probe μ, $H_2$ absorbers need to be at $z > 2$–2.5 to place the Lyman and Werner $H_2$ transitions redward of the atmospheric cut-off. Only five systems have been studied so far, with no current indication of variability at the level of ~ 10 ppm (e.g., Rahmani et al., 2013). At lower redshifts, precise constraints on variation of μ are available from radio and millimetre-wave spectra of cool clouds containing complex molecules such as ammonia and methanol (see, e.g., Flambaum & Kozlov, 2007; Levskakov et al., 2013).

Extraordinary claims require extraordinary evidence and a confirmation of variability of α or μ with high statistical significance is of crucial importance. Only a high-resolution spectrograph that combines a large collecting area with extreme wavelength precision can provide definitive clarification. A relative variation in α or μ of 1 ppm leads to velocity shifts of about 20 m $s^{-1}$ between typical combinations of transitions. ESPRESSO is expected to provide an increase in the accuracy of the measurement of these two constants by at least one order of magnitude compared to VLT with UVES or Keck and HIRES. More stringent bounds are also important and the ones provided already constrain the space of the parameters of various theoretical models that predict their variability.

### A scientific Pandora's box

ESPRESSO combines unprecedented RV and spectroscopic precision with the largest photon-collecting area available today at ESO and unique resolving power (*R* ~ 200 000). ESPRESSO will certainly

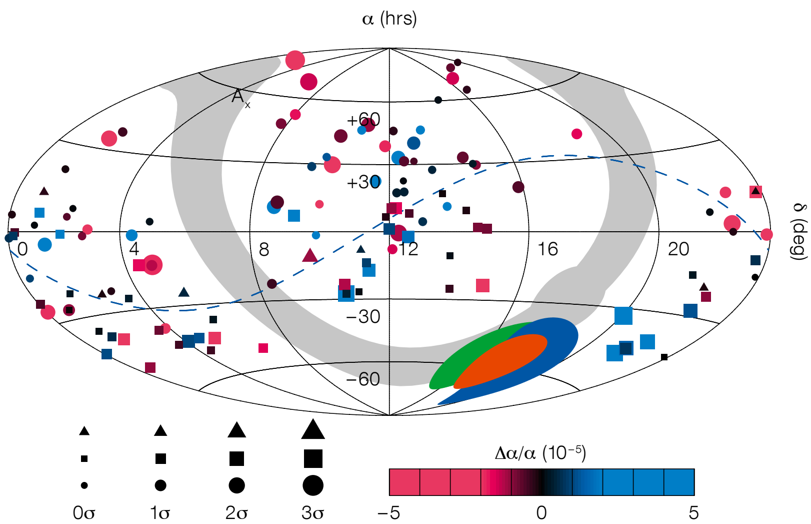



Figure 14. All-sky spatial dipole obtained from the combined VLT (squares) and Keck (circles) measurements of α (from Webb et al., 2011). Triangles are measurements in common to the two telescopes and the blue dashed line shows the equatorial region of the dipole.

provide breakthroughs in many areas of astronomical research, many of which we cannot anticipate. Below we provide just a few examples.

### Chemical composition of stars in local galaxies

One important piece of information in the understanding of galaxy formation is the chemical composition for local galaxies. In spite of the many successes in this field, the majority of local galaxies still lack detailed abundance information. There are about a dozen nearby galaxies observable from Paranal which, except for Sagittarius, have some chemical information, albeit generally for only a few stars and for a limited set of elements; for the faintest galaxies these results are based on low to medium resolution spectra. The Local Group galaxies all possess giant stars of magnitude $V = 20$, or fainter. Although some work has been done with UVES at the VLT, it is really difficult, if not impossible, to obtain accurate chemical abundances at these magnitudes. For galaxies that possess a young population, like Phoenix or Wolf–Lundmark–Melotte (WLM), one can rely on bright O and B supergiants. However, if one considers old metal-poor systems, like Bootes or Hercules, one has to rely on red giants. Although it is clear that most of the chemical information for local galaxies will have to come largely from the ELTs, ESPRESSO will provide the opportunity for a first, but important, glimpse into this area.

### Metal-poor stars

The most metal-poor stars in the Galaxy are probably the most ancient fossil records of the chemical composition and thus can provide clues on the pre-Galactic phases and on the stars that synthesised the first metals. Masses and yields of Population III stars can be inferred from the observed element ratios in the most metal-poor stars (Heger & Woosley, 2010). One crucial question to be answered is the presence of Population III low-mass stars. For a long time, Population III stars were thought to be very massive, but the recent discovery of a very metal-poor star with [Fe/H] ~ −5.0 and "normal" C and N has presented an entirely new picture (Caffau et al., 2011). Several surveys searching for metal-poor stars are currently ongoing or are being planned, and thousands of extremely metal-poor stars with [Fe/H] < −3.0, of which several down to [Fe/H] ~ −5.0, and hopefully lower, are expected to be found. These stars will be within the reach of ESPRESSO, which will be able, in both the 1-UT and 4-UT modes, to provide spectra for exquisite chemical analysis.

### Stellar oscillations, asteroseismology and variability

Stars located in the upper main sequence show non-radial pulsations that cause strong line profile variations. Asteroseismic study (i.e., mode identification) of these pulsating stars (γ Dor, δ Sct, β Cep, slowly pulsating B stars, etc.) provides constraints on the structure of massive stars (e.g., internal convection, overshooting, core size, extension of acoustic and gravity cavities, mass-loss phenomena and interplay between rotation and pulsation). ESPRESSO will allow the short exposures required to identify the high-frequency modes, currently achievable on a wide variety of stars only with photometry from space.

### Galactic winds and tomography of the intergalactic medium

Spectroscopy of close, multiple, high-redshift quasars allows, in principle, recovery of the three-dimensional distribution of matter from the analysis of the H I Ly-α absorption lines. If the multiple lines of sight cross a region where there are known high-redshift galaxies, it is also possible to investigate the properties of outflows and inflows, studying the spectral absorption lines at the redshift of the galaxies and how they evolve with distance from the galaxies themselves. The main limitation to the full exploitation of this tomography of the intergalactic medium is the dearth of quasar pairs at the desired separation, and bright enough to be observed with the present high-resolution spectrographs at 10-metre-class telescopes. ESPRESSO, used in the 4-UT mode, would result in a gain of ~ 1.5 mag over UVES, translating into almost a factor 20 more observable quasar pairs with separation less than 3 arcminutes and emission redshift in the range $2 < z < 3$.

### The expanding Universe

Sandage (1962) first argued that in any cosmological model the redshifts of cosmologically distant objects drift slowly with time. If observed, their redshift drift rate, $dz/dt$, would constitute evidence of the deceleration or acceleration of the Hubble flow between redshift $z$ and today. Indeed, this observation would offer a direct, non-geometric, entirely model-independent measurement of the Universe's expansion history (Liske et al., 2008). The VLT, even in the 4-UT mode, probably does not have the capability to measure the tiny signal, which is at the level of a few cm $s^{-1}$ $yr^{-1}$. However, it might provide the first accurate historical reference measurements and will, in any case, represent an important step forward, setting the scene for the next generation of high resolution spectrographs on ELTs.

## Use of Guaranteed Time Observation allocation

In recognition of the capital and human investment, the consortium will be awarded Guaranteed Time Observations (GTO). Eighty percent of these observing nights will be invested in the search for and characterisation of rocky planets in the habitable zone of G, K and M stars in the 1-UT mode. Ten percent of the time will be dedicated to the determination of the possible variability of the fundamental constants. Depending on the magnitude of the targets, this programme will be carried out partially in the 1-UT and 4-UT modes. The remaining 10 % of GTO time will be reserved for outstanding science cases and allocated as a function of topical questions arising at the moment of the observations.

## The ESPRESSO consortium

The ESPRESSO consortium is composed of:
– Observatoire Astronomique de l'Université de Genève, Switzerland (Project lead)
– Centro de Astrofísica da Universidade do Porto (Portugal)
– Faculdade de Ciências da Universidade de Lisboa (Portugal)
– INAF–Osservatorio Astronomico di Brera (Italy)
– INAF–Osservatorio Astronomico di Trieste (Italy)
– Instituto de Astrofísica de Canarias (Spain)
– Physikalisches Institut der Universität Bern (Switzerland)

ESO participates in the ESPRESSO project as an associated partner and is contributing the echelle grating, the camera lenses, the detector system and the cryogenic and vacuum control system.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