From ESPRESSO to CODEX

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Abstract CODEX and ESPRESSO are concepts for ultra-stable, high-resolution spectrographs at the E-ELT and VLT, respectively. Both instruments are well motivated by distinct sets of science drivers. However, ESPRESSO will also be a stepping stone towards CODEX both in a scientific as well as in a technical sense. Here we discuss this role of ESPRESSO with respect to one of the most exciting CODEX science cases, i.e. the dynamical determination of the cosmic expansion history.

1 Introduction

CODEX (= COsmic Dynamics EXperiment) is a concept for an extremely stable, high-resolution optical spectrograph for the European Extremely Large Telescope (E-ELT). The science case for CODEX encompasses a large range of topics, including the search for exo-planets down to Earth-like masses, primordial nucleosynthesis and the possible variation of fundamental constants. However, its prime science driver is the exploration of the universal expansion history by detecting and measuring the cosmological redshift drift using QSO absorption lines. This is also one of the 9 'prominent' science cases chosen by the E-ELT Science Working Group to be among the highlights of the entire E-ELT science case. A description of the CODEX project as a whole was given by [3].

The recognition that an ultra-stable, high-efficiency, high-resolution optical spectrograph would not only be an extremely valuable instrument for the E-ELT but also for the VLT led to the development of the ESPRESSO concept (= Echelle Spectrograph for PREcision Super Stable Observations, see L. Pasquini's contribution to these proceedings). Again, there are a large number of applications for such an instrument, as several other contributions to these proceedings have highlighted. Hence, there is also a very strong science case for ESPRESSO, including e.g. detailed studies of the intergalactic medium and of stellar abundances.

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However, apart from these scientific drivers, ESPRESSO will also fulfil another role: CODEX will represent a major development in high-resolution optical spectrographs compared to existing instruments such as UVES and HARPS. In order to achieve its science goals CODEX will have to deliver an exceptional radial velocity accuracy and stability, i.e. $2\,\mathrm{cm\,s^{-1}}$ over a timescale of ~ 20 yr. Although the basic design concepts are already in place, several of the sub-systems needed to achieve the CODEX requirements do not currently exist. However, they will be implemented in ESPRESSO for the first time. Hence, in many respects ESPRESSO will be a CODEX precursor instrument that will allow us to test and gain experience with the novel aspects of these instruments. Here we will discuss ESPRESSO in the context of its CODEX precursor role, both in a technical sense as well as with respect to the main CODEX science driver, which we briefly describe next.

2 Cosmic Dynamics

The discovery from type Ia SNe that the universal Hubble expansion appears to have begun accelerating at a relatively recent epoch, and its profound implications for fundamental physics have sparked an intense interest in the observational exploration of the Universe's expansion history. Several methods for measuring the Hubble parameter $H(z)$ already exist but all of them are either geometric in nature or use the dynamics of localised density perturbations. The simplest, cleanest and most direct method of determining the expansion history, however, is to observe the dynamics of the global Robertson-Walker metric itself. One way to achieve this is by measuring the so-called redshift drift, i.e. the tiny, systematic drift as a function of time in the redshifts of cosmologically distant sources (Fig. 1). This effect is directly caused by the de- or acceleration of the universal expansion and can hence be used to determine its history. A measurement of this effect would be able to provide evidence of the acceleration that is entirely independent of the SNIa results or any other cosmological observations, and that does not require any cosmological or astrophysical assumptions at all. It would also provide $H(z)$ measurements over a redshift range inaccessible by other methods. Recently, [1] found that a 42 m telescope would indeed have the photon collecting power to detect the redshift drift by monitoring the redshifts of QSO absorption lines over a timescale of ~ 20 years (Fig. 1), providing a strong motivation for a CODEX-like instrument at the E-ELT.

3 ESPRESSO as a CODEX Pathfinder

3.1 Technical Aspects

The UVES and HARPS experiences have allowed us to identify a number of properties that a spectrograph must feature in order to deliver exceptional radial velocity

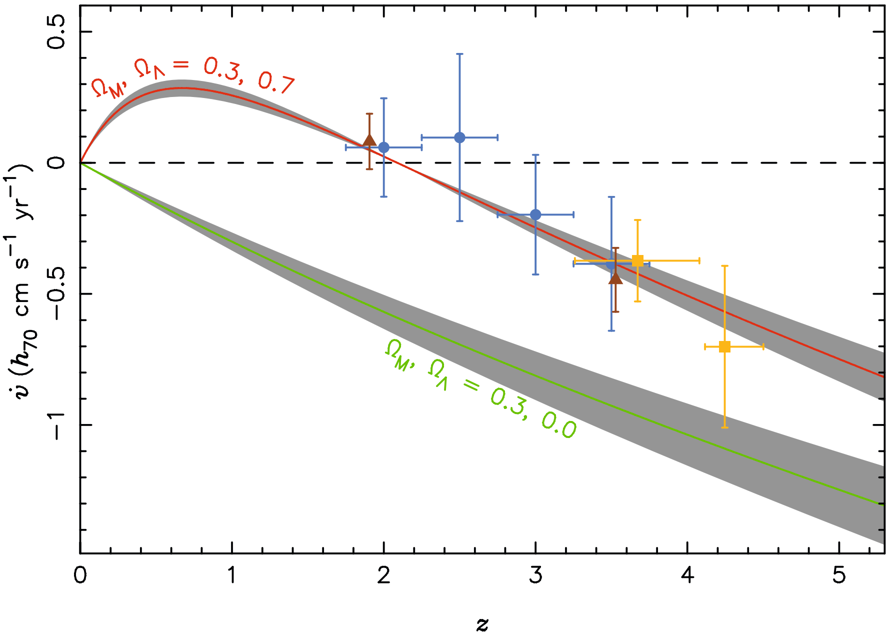

Fig. 1 The *solid lines* show the redshift drift as a function of redshift in velocity units for two different combinations of Ω_M and Ω_Λ as indicated, and a Hubble constant of $H_0 = 70$ km s^{-1} Mpc^{-1}. The *grey shaded areas* result from varying H_0 by ±8 km s^{-1} Mpc^{-1}. The three sets of 'data' points show Monte Carlo simulations of a redshift drift experiment with CODEX/E-ELT using a total of 4000 h observing time and a total experiment duration of 20 yr. Each of the sets of points corresponds to a different implementation of the drift experiment pursuing different observational goals. See [1] for more details. A colour version of this figure is available at dx.doi.org/10.1007/978-1-4020-9190-2_41

accuracy and long-term stability, including: simultaneous wavelength calibration, a fully passive instrument with zero human access, located inside a vacuum tank which is itself located inside a nested environment in an underground facility that allows progressively more precise temperature and pressure control, and the flux-weighted timing of observations with sub-second precision. Temperature control of the CCD will be particularly important, while high system throughput will also be of the essence. Some of these concepts are already established. However, two of the most critical aspects are also those requiring the most R&D: light scrambling and wavelength calibration.

At a resolution of 150 000 a typical pointing accuracy of ∼ 0.05 arcsec corresponds to an error of 100 m s^{-1} necessitating a scrambling gain of ∼ 5000 in order to reach 2 cm s^{-1} accuracy. Hence, in addition to any fibre we will require a dedicated scrambling device to ensure that a photon's position on the CCD only depends on its wavelength but not on its position on the entrance aperture.

Current wavelength calibration sources such as ThAr lamps and I_2 cells are suboptimal in several respects, their non-uniformity and lack of long-term stability being among the concerns. However, a new concept for wavelength calibration has recently emerged. A 'laser frequency comb' system provides a series of uniformly spaced, very narrow lines whose absolute positions are known a priori with a relative precision of $\sim 10^{-12}$ (see A. Manescau's contribution; [2]).

Neither of the two systems above currently exist, but they would be developed for ESPRESSO. Being able to test and validate them 'on the sky' would provide valuable experience and input for further improvements.

3.2 Scientific Aspects

The scientific goals of CODEX are sufficiently removed from current observational reality to require validation and demonstration of feasibility of all aspects of data handling and analysis. This includes data acquisition strategies (e.g. minimum and maximum viable exposure times), the tracking of CCD distortions, and the accuracy of flat-fielding, sky subtraction and scattered light corrections. The extraction of the cosmological signal from the data will also require testing. Issues include how to deal with QSO variability and the accuracy of the conversion to the cosmological reference frame. In addition ESPRESSO will allow us to determine the currently unknown intrinsic widths of the narrowest metal absorption lines in order to reassess their usefulness for the drift experiment, and to look for any sources of astrophysical noise so far overlooked.

Data on QSOs collected with ESPRESSO for other scientific purposes would allow us to address all of the above issues. We estimate that ~ 200 hours of observations of the brightest known QSOs would provide an end-to-end system verification, from data acquisition to signal extraction, at the level of ~ 30–$40\ \mathrm{cm\,s^{-1}}$.

4 CODEX + ESPRESSO = $\dot{z}$?

Since ESPRESSO will have characteristics similar to those of CODEX the question arises whether ESPRESSO can be used to make a start on the redshift drift experiment. The idea is that since ESPRESSO would be available several years before CODEX data appropriately collected with ESPRESSO could serve as a 'zeroth' epoch measurement, effectively extending the time baseline of the experiment for a few years, thereby improving the final result without delaying it. Figure 2 shows the comparison of the cosmological constraints in the Ω_Λ–Ω_M plane expected from a drift experiment using CODEX only (coloured ellipses) and CODEX + ESPRESSO (solid contour), where we have assumed that ESPRESSO would take up operation 8 years before CODEX. Evidently the extension of the time baseline by 8 years is not enough to offset the lack of the VLT's photon collecting power compared to the E-ELT: the improvement of the constraints is only quite modest, with the lower limit on Ω_Λ increasing by ~ 20 per cent.

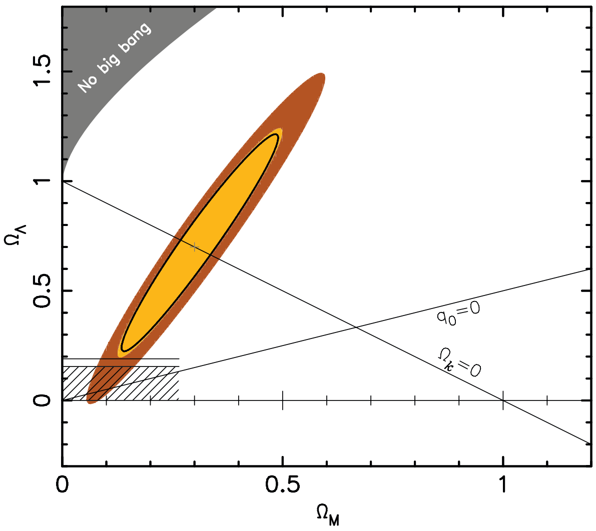

Fig. 2 Expected constraints in the Ω_Λ–Ω_M plane from the redshift drift experiment with CODEX/E-ELT described in detail in [1]. The *coloured ellipses* show the joint 68 and 90 per cent confidence regions that result from a total integration time of 4000 h and a total experiment duration of $\Delta t = 20$ yr. The *hashed region* indicates the 95 per cent lower limit on Ω_Λ. The *solid contour* shows the improvement of the 68 per cent confidence region that results from the additional investment of 4000 h of observing time using ESPRESSO on the VLT in its 'SuperHarps' mode (i.e. at $R \approx 150\,000$ and using one UT), assuming that these observations take place ~ 8 yr before the start of the CODEX observations. The 95 per cent lower limit on Ω_Λ of the combined experiment is shown has the *horizontal line* above the *shaded region*. Flat cosmologies and the boundary between current de- and acceleration are marked by *solid black lines*. The *dark shaded region* in the *upper left corner* designates the regime of 'bouncing universe' cosmologies which have no big bang in the past. A colour version of this figure is available at dx.doi.org/10.1007/978-1-4020-9190-2_41

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