

# CODEX

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**Abstract:** The advent of Extremely Large Telescope will provide, for the first time, the possibility of measuring directly the acceleration of the Universe, and therefore, its dynamics. We present the concept of CODEX, an instrument for OWL, which will be able to perform this unique, fundamental test of General Relativity, measuring if the acceleration of the Universe is that expected by the current cosmological models. CODEX will be able to investigate the nature of the elusive dark energy in the range of redshifts  $z \sim 2-5$ , complementing other (geometrical) measurements, such as the SNa<sub>e</sub> magnitude decline or the CMB spectrum. In addition, being CODEX a high resolution, super stable spectrograph fed by the most powerful telescope ever conceived, it will provide unique opportunities of advance in many other branches of astrophysics

**Keywords:** list of words to be included in searchable index

## 1. BACKRGOUND

In September 2004, under the assignment by the ESO Council, the conceptual study for instruments for OWL, the ESO flavour of Extremely Large Telescope, was started. A group of Institutes (IoA Cambridge, INAF- Trieste and Observatoire de Geneve) joined ESO to study the case of a high resolution spectrograph which has the primary goal of measuring for the first time the expansion of the Universe. This collaboration lead to the birth of the CODEX concept; after one year the case has been fully developed, and the conceptual study has been summarized in a document (OWL-CSR-ESO-00000-0160) which has been added as an appendix to the OWL blue book and is available to the community. In this contribution we summarize some of the main results of the concept study and share with the community the exciting perspectives that CODEX@OWL will bring.

## 2. THE EXPANSION OF THE UNIVERSE

The discovery of the expansion of the Universe, established in the late 1920s by Edwin Hubble brought to an end the belief held by most Physicists of the time that the Universe is static and not evolving, leading to the now widely accepted Hot Big Bang Theory, which predicts that the Universe was very dense and hot at early times. With the detection of the relic Cosmic Microwave Background and the experimental verification of the prediction for the synthesis of light elements the Hot Big Bang is now an essential aspect of the cosmological standard model.

Around 1916 Einstein had introduced General Relativity (GR), which led to the description of the Universe as a homogeneous and isotropic four-dimensional space-time, the so-called Friedman-Robertson-Walker (FRW) Universe. If we consider in an expanding FRW Universe the light of a source which is emitted at time  $t_e$  and received at time  $t_0$ , the change of redshift  $z$  of the source with time can be expressed as:

$$\frac{dz}{dt} = (1+z)H_o - H(t_e)$$

The time derivative of the redshift of light emitted by a source at fixed coordinate distance is thus related in a simple manner to the evolution of the Hubble parameter  $H(t_e)$  between the epoch of emission and reception. The Hubble parameter is related to the energy content of the Universe as

$$H = H_o \left[ \Omega_{mat} \left( \frac{a_o}{a} \right)^3 + \Omega_R \left( \frac{a_o}{a} \right)^4 + \Omega_{de} \left( \frac{a_o}{a} \right)^{3(1+w)} + (1 - \Omega_{tot}) \left( \frac{a_o}{a} \right)^2 \right]^{1/2}$$

where  $\Omega_{tot} = \Omega_{mat} + \Omega_R + \Omega_{de}$  and  $\Omega_{mat}$ ,  $\Omega_R$ ,  $\Omega_{de}$  are the energy density of matter, radiation, and dark energy expressed in terms of the critical density, respectively. The dark energy density is characterized by an equation of state of the form  $p_{de} = w\rho_{de}c^2$ , and  $w=-1$  corresponds to the case of a cosmological constant. Note that we do not know much about the dark energy term, and its redshift dependence could well be more complicated than parameterized here by a simple equation of state. At the redshifts here considered ( $z \sim 2-5$ ) the radiation energy density is small  $\Omega_R \ll \Omega_{tot}$  and can be neglected.

Observations of the CMB, supernovae, Lyman- $\alpha$  forest and the clustering of galaxies are consistent with a FRW Universe with no curvature and a cosmological constant which corresponds to an energy density about twice that of the matter in the Universe at present. It is thus important to establish whether the dark energy actually has the dynamical effects expected if its evolution is described by GR in four dimensions. We shall recall that all observational constraints are basically geometric in nature as they mainly constrain the angular diameter distance to the last scattering surface (CMB) and the luminosity distance at moderate redshifts (supernovae). The constraints on actual dynamical effects of the cosmological constant as probed by the clustering of the matter distribution are coupled in a complicated way to geometrical constraints and are actually rather weak.

**The experiment proposed is conceptually very simple: by taking observations of high redshift objects with a time interval of several years, we shall be able to detect and use the wavelength shifts of spectral features of light emitted at high redshift to probe the evolution of the expansion of the Universe directly.**

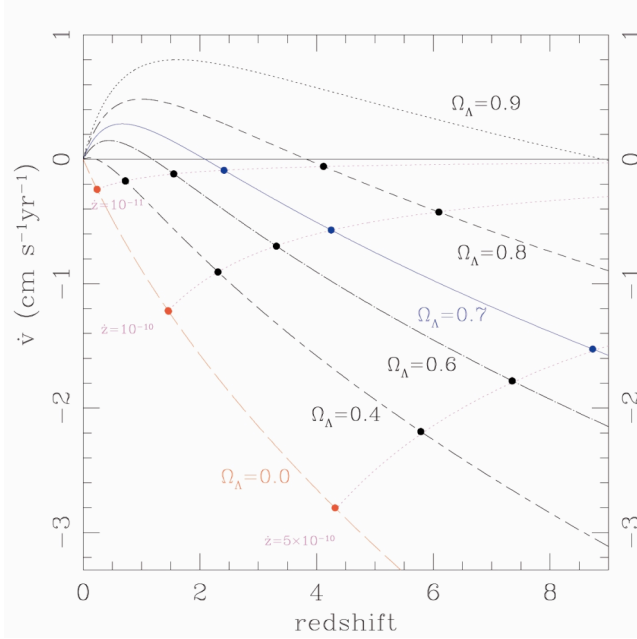
**If GR is the correct theory of physics on large scales, then there is a differential equation that relates the Hubble expansion function, inferred from measurements of angular diameter distance and luminosity, to the variation of the redshift as a function of time. Deviations from this consistency relationship could be the signature of the breakdown of GR on cosmological scales**

Fig. 1 shows the expected change of redshift for a range of FRW models with no curvature as a function of redshift. The wavelength shift has a very characteristic redshift dependence and corresponds to a Doppler shift of about 1-10 cm/s over a period of 10 yrs. This amount is extremely small, and brought Sandage (1962) to conclude that such a measurement was beyond our capabilities. Why do we think that this experiment is possible now? For three reasons:

- 1) In the last two decades our capability of measuring accurately wavelength shifts of astronomical sources has dramatically improved. Even if the expected cosmic shift requires about a factor 10-100 times improved performances compared to that currently achievable with an instrument like HARPS at the ESO 3.6m (Mayor et al. 2002), in asteroseismology a comparable sensitivity is already obtained for bright sources and short periods.
- 2) The use of 8m class telescopes and detailed numerical simulations has allowed the identification of a suitable class of objects: Ly $\alpha$  clouds systems. On the opposite of other possible tracers (masers,

molecular absorptions), Ly $\alpha$  forest lines are extremely numerous and trace beautifully the cosmic expansion, with negligible peculiar motions (see e.g. Rauch 1998 for a review). Those motions result in fact to be at least 10 times smaller than the Hubble flow.

3) These measurements require many photons and are conceivable only with ELTs.



**Fig. 1:** Evolution of  $\dot{v}$  as a function of redshift. The cosmological parameters have been fixed to  $\Omega_{tot}=1$ ,  $H_0=70$  and different values of  $\Omega_\Lambda$  have been considered. The  $\Omega_\Lambda=0.7$ ,  $\Omega_M=0.3$  cosmology is shown with a blue solid line, and the Einstein - de Sitter model is plotted with a red long-dashed line. The filled circles connected by dotted lines show loci of constant  $z$ , in units of  $\text{yr}^{-1}$ .

### 3. THE SIMULATIONS

In order to quantitatively assess the feasibility of the measurements, many Montecarlo simulations have been carried out independently by several groups. The high resolution spectra of QSO were simulated, the noise added and the process repeated for the second considered epoch. The pairs of spectra so produced were compared and the ‘measurement’ performed. Fig. 2 shows the difference expected among pair of spectra, where the second epoch spectrum has been redshifted according to different cosmological models. The results of the simulations agree with the fact that, if the lines are resolved, the final accuracy of the experiment can be expressed as a function of S/N ratio and redshift as :

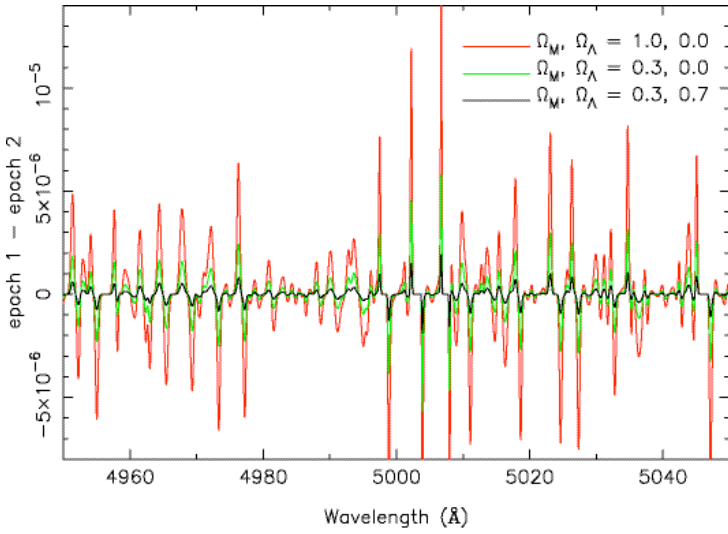
$$\sigma_v = 1.4 \left( \frac{S/N}{2350} \right)^{-1} \left( \frac{N_{QSO}}{30} \right)^{-1/2} \left( \frac{1+Z_{QSO}}{5} \right)^{-1.8} \text{ cm/s}$$

(where S/N refers to a pixel of 0.0125  $\text{\AA}$ ). This scaling law holds up to redshift  $z \sim 4$ ; at higher  $z$  it ‘saturates’ and no further gain is obtained. We notice that, with a typical width of 30 km/sec, Ly $\alpha$  clouds would be fully resolved with a resolution of  $R \sim 30000$ , however, due to the fact that much narrower metallic systems are also relevant for the measurement and that we need to improve the wavelength calibration, a much higher resolving power ( $R \sim 150000$ ) is required.

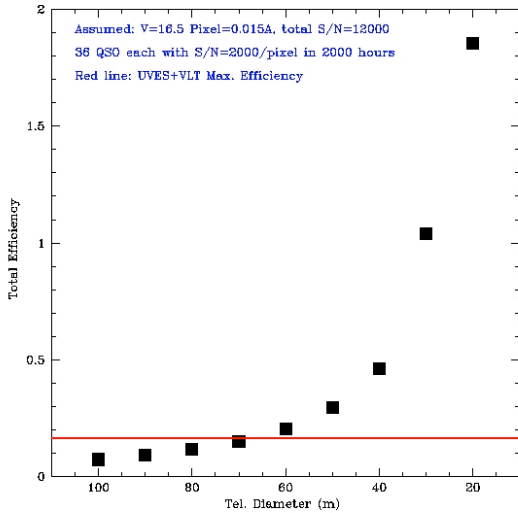
The above scaling law implies that observing at each epoch for instance 40 QSOs with a S/N ratio 2000 each, an accuracy of 1.5 cm/sec can be obtained. Fig. 3 shows that for a QSO of magnitude 16.5 and 2000 hours of observations, such a S/N ratio can be obtained with a variety of telescope diameters, provided that the whole system has an efficiency comparable to that of UVES at the VLT.

A sufficient number of bright QSOs is available already today for the COD Experiment. Selecting objects from published catalogues, we find 91 QSOs brighter than  $m=16.5$ , out of which 25 have redshift

between 2 and 4, and the number of suitable objects should increase with the large, all-sky photometric surveys planned in the coming years



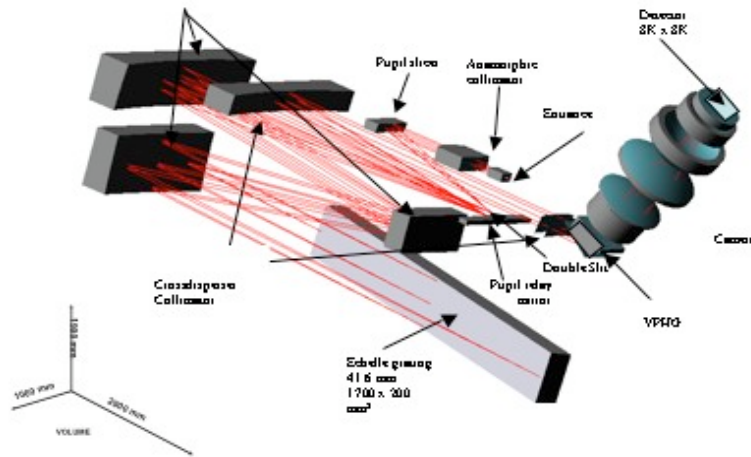
**Fig. 2:** Flux difference of two simulated, noiseless Ly $\alpha$  forest spectra at  $z = 3.1$  taken  $\Delta t = 10$  years apart for different cosmological parameters as indicated and  $H_0 = 70$  km/s/Mpc.



**Fig. 3:** Telescope+CODEX efficiency vs. telescope diameter. The total S/N ratio of 12000, the integration time of 2000 hours and a QSO magnitude of  $V=16.5$  has been fixed. The plot shows the total efficiency that the system should have to reach the goal within the above assumptions. The red horizontal line is the measured UVES + VLT efficiency.

#### 4. THE INSTRUMENT CONCEPT

We have therefore developed an instrument design concept with the characteristics given in Table 1. In order to obtain a resolving power of 150000 on a seeing limited ELT (1 arcsecond aperture on a 60 m telescope or 0,65 arcsecond on a 100 m), five identical spectrographs are foreseen. To obtain the highest stability, each spectrograph will be contained in a vacuum tank, hosted in a temperature stabilized room nested in an environmentally quiet laboratory. In order to keep a limited size for each spectrograph, several new concepts (pupil anamorphysm and slicing, special crossdisperser) have been adopted, and each spectrograph (cfr. Figure 4) will have an echelle grating only twice the size of the UVES ones and an 8Kx8K  $15 \mu$  square pixel detector.



**Fig. 4:** Optical design of one CODEX spectrograph.

While it is possible to predict the behavior of the single CODEX parts, it will be extremely difficult trying to model the whole system, including, for instance, the complex interactions with the telescope. We therefore anticipate that a full CODEX unit, exactly similar to one of the five installed at OWL, has to be developed and operated for several years at the VLT, to gain the experience and to (im)prove the CODEX concept.

Acceptance aperture on the sky	1 arcsec for 60m, 0.65 arcsec for 100m
Location	Underground in nested thermally stabilized environment
Feed	Coude feed
Peak DQE including injection losses (with GLAO)	14% (Coude feed)
Number of spectrographs	5
Spectral resolution	150 000
Wavelength coverage	446 - 671 nm in 35 orders
Spectrograph layout	White pupil
Echelle	41.6 l/mm, R4, 170 x 20 cm, 4 x 1 mosaic
Crossdisperser	VPHG 1500 l/mm operated off-Littrow
Camera	Dioptric F/2.3; image quality 30 $\mu$ m
Detector	CCD 8K x 8K, 15 $\mu$ m pixels, Stabilized to a few mK
Noise performance	Photon shot noise limited for $M_v = 16.5$ in 10 minutes
Sampling	4 pixels per FWHM

#### 4.1. Chasing the systematics

When aiming at precise measurements, which go almost a factor 100 beyond the present performances, special care must be taken to account for subtle systematic effects which, if neglected, could jeopardize the whole experiment. “Local” forms of noise are relevant; and an evaluation of the barycentric correction terms is given in Table 2, which shows that the corrective terms are under control and within reach at present. One important value, missing in Table 2, is the value of the acceleration of the Sun in the Galaxy, which is comparable to the amount of the cosmic signal. This important term can in principle be measured by CODEX observing QSOs well distributed in the sky, but it will be determined with superior accuracy by the ESA GAIA satellite at a level of 0.5 mm/sec/year, that is ten times smaller than the cosmic signal.

The accuracy of the Wavelength calibration is another concern (we shall recall that a shift of 1 cm/sec corresponds to about three angstroms shift on the detector). Tests made with HARPS indicate that the Th-Ar lamps used in most spectrographs are not suitable for such an accuracy, and that a new calibration system should be aimed. In addition, such a novel calibration system shall be perfectly reproducible and stable in the long term (20 years or more) of the duration of the experiment. We are investigating with the Max Plank fur Quantenoptik the possibility of using new superb standards based on laser frequency combs.

Table 2: Sensitivity matrix of the accuracy of the barycentric correction with regard to their input parameters

Parameter	Induced error on the correction [cm s <sup>-1</sup> ]	Comment
Earth orbital velocity - <i>Solar system ephemerides</i>	< 0.1	JPL DE405
Earth rotation - <i>Geoid shape</i> - <i>Observatory coordinates</i> - <i>Observatory altitude</i> - <i>Precession/nutation corrections</i>	~ 0.5 < 0.1 < 0.1 < 0.1	Any location in atm. along photon path may be chosen
Target coordinates - <i>RA and DEC</i> - <i>Proper motion</i> - <i>Parallax</i>	? ~ 0 ~ 0	70 mas → 1 cm s <sup>-1</sup> negligible negligible
Relativistic corrections - <i>Local gravitational potential</i>	< 0.1	
Timing - <i>Flux-weighted date of observation</i>	?	0.6 s → 1 cm s <sup>-1</sup>

## 5. CODEX BEYOND THE MEASUREMENT OF THE COSMIC SIGNAL

The scientific applications of CODEX, as an high resolution spectrograph with extremely high performances fed by OWL, will go well beyond the main experiment proposed above. In the following we give a glimpse of three outstanding applications:

### 5.1. Search for variability of fundamental constants

Fundamental constants cannot be deduced from first principles and are supposedly universal and invariable quantities. They play an important role in our understanding of nature, since they *capture at once our greatest knowledge and our greatest ignorance about the universe* (J. Barrow). Testing for their variability probes fundamental physics. Measured variations would have far reaching consequences for the unified theories of fundamental interactions, for the existence of extra dimensions of space and/or time and for the existence of scalar fields acting in the late universe. Only astronomical observations hold the potential to probe the values of fundamental constants in the past, and in remote regions of space. In 2001, observations of spectral lines of distant astronomical objects brought the first hints that the fine-structure constant,  $\alpha$  - the central parameter in electromagnetism - might change its value over time (Murphy et al. 2001), but recent observations are consistent with a null result. An effective two – three order-of-magnitude precision gain is foreseen with a spectrograph with  $R \approx 150000$  at OWL, stemming equally from the higher resolving power of the spectrograph and from the larger photon collecting area. The accuracy of the  $\Delta\alpha/\alpha$  variations will be of a few units  $10^{-9}$ , that is more precise than any other astronomical and geological measurement.

## 5.2. Search for other earths

Exo-planets and, in particular, terrestrial planets in habitable zones will be one of the main scientific topics of the next decades, and one of the main OWL science drivers. CODEX@OWL will lead the discoveries in exo-planetary science in at least three main cases, providing with unique capabilities and observations: i) discovery and confirmation of rocky planets, ii) the search for long-period planets, iii) the search of Jupiter mass planets around faint stars.

The need for a ground based follow-up facility capable of high radial velocity accuracy has been stressed in the recent ESO-ESA working group report on solar planets, which states in the Summary of Follow-Up facilities required (p. 63): *a) 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.* The concept is re-iterated in the first recommendation to ESO by the committee, which reads: *Support experiments to improve radial velocity mass detection limits, e.g. based on experience from HARPS, down to those imposed by stellar surface phenomena (ESA-ESO report, Section 5, p. 72).*

As far as Hot Jupiters are concerned, CODEX will allow to search for these planets around solar mass stars in different environments and star forming histories, such as globular clusters and the nearby companions to the Galaxy.

## 5.3. Primordial nucleosynthesis

Standard Big bang nucleosynthesis presents a pressing cosmological conundrum. There is some evidence suggesting a cosmological origin for  ${}^6\text{Li}$ , and the stellar value for primordial  ${}^7\text{Li}$  does not agree with primordial D from QSOs and with WMAP  $\Omega_b$ . Although Li observations in low metallicity Galactic halo stars are plagued by possible systematic uncertainties due to modeling of stellar atmospheres and the treatment of convection, it is appealing that both the discrepancies can be reconciled with physics beyond the standard model during the Quark-Hadron phase. CODEX will allow first observations of  ${}^7\text{Li}$  and  ${}^6\text{Li}$  in dwarf stars in galaxies of the Local Group and it will make possible to measure for the first time the interstellar  ${}^7\text{Li}/{}^6\text{Li}$  ratio in unprocessed material of High Velocity Clouds. The latter is a direct and robust probe of BBN yields providing important insights on whether new physics is playing a role in early universe nucleosynthesis.

In addition to these selected applications, many other science cases emerged in the last years, mostly from the superb observations obtained worldwide with high resolution spectrographs and at ESO with UVES at the VLT or with HARPS at the 3.6m telescope. Stellar oscillations, the study of the most metal poor stars in our Galaxy and in its local group companions, the use of cosmochronometers to determine the age of the Universe, the history of the metal enrichment of the Universe, the evolution of the CMB temperature with redshift... All these cases (and surely many more) will receive from CODEX@OWL an impressive boost, far beyond what can be now conceived.

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