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From CODEX to ESPRESSO to HIRES@E-ELT: a view on cosmology and fundamental physics from the IGM perspective

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Abstract. The Italian community, thanks to the strong technological and scientific tradition in the field of high-resolution spectroscopy and the study of the Intergalactic Medium, has played a key role in the conception of a high-resolution spectrograph for the new generation of giant telescopes (initially focused on the COsmic Dynamics EXperiment at OWL). This expertise is being exploited in the construction of a precursor: the ESPRESSO instrument that will start operations at the ESO VLT in 2017 and will pave the way to the HIRES instrument at the E-ELT. Here we discuss the role that the (evolving) scientific themes of cosmology and fundamental physics - from the Intergalactic Medium perspective - have played and are playing to shape the E-ELT high resolution instrument.

Key words. Cosmology: observations – Instrumentation: spectrographs

1. Introduction

The study of Cosmology & Fundamental Physics is one of the four main scientific drivers of the E-ELT (Kissler-Patig & Lyubenova 2011).

Our present understanding of the Universe is based on a *Standard Cosmological Model*, a Friedmann-Robertson-Walker (FRW) Universe with no curvature, resting on four fundamental pillars: Hubble expansion, Cosmic Microwave Background, Big Bang Nucleosynthesis (BBN), growth of large-scale structures, and on a *Standard Model of Particle Physics*.

The physical cause of the observed late-time acceleration of the expansion of the Universe is generally attributed either to some exotic form of mass-energy with significantly negative pressure ("dark energy") or to a large-scale breakdown of the field equations of General Relativity describing gravity. In either case, the acceleration of the expansion points towards new physics, and its discovery has sparked intense interest in mapping the expansion history of the Universe. All the current expansion probes are geometric in the sense that they deduce the evolution of the expansion by mapping out our present-day past light-cone. None of these actually directly probe the global dynamics of the FRW metric. Sandage (1962) first discussed the possibility of measuring the redshifts of cosmologically distant objects slowly drifting with time. If observed, the redshift drift-rate, dz/dt, would constitute evidence of the Hubble flows deceleration or acceleration between redshift z and today. Indeed, as emphasized by Liske et al. (2008), this observation would offer a direct, non-geometric, model-independent measurement of the Universes expansion history and would uniquely probe the global dynamics of the metric.

Nature is characterized by a set of physical laws and fundamental dimensionless couplings, historically assumed to be spacetime-invariant. Fundamental couplings are known to run with energy, and in many extensions of the standard model they will also run in time and depend on the local environment. In particular, this is the case in theories with additional spacetime dimensions, such as string theory. A detection of varying fundamental couplings would automatically prove that the Einstein Equivalence Principle is violated (and therefore that gravity cannot be purely geometry), and that there is a fifth force of nature. In theories where a dynamical scalar field yields, for example, a variation of the fine-structure constant $\alpha \equiv e^2/\hbar c$ the other gauge and Yukawa couplings are expected to vary too. In particular, in Grand Unified Theories the variation of α is related to that of energy scale of Quantum Chromodynamics, where the nucleon masses necessarily vary when measured in an energy scale that is independent of QCD (such as the electron mass). It then follows that a variation of the proton-electron mass ratio $\mu \equiv m_p/m_e$ is also expected, although the relative size of both variations will be model-dependent.

Light element abundances, when analyzed in conjunction with the power spectrum of temperature anisotropies of the cosmic background radiation, can improve constraints on cosmological parameters, primarily the spectral index of primordial fluctuations (Pettini et al. 2008), and on the effective number of light fermion species, N_{eff} (e.g. Simha & Steigman 2008). Among the light elements created in the BBN, deuterium is one of those that have attracted the attention of many recent works.

Although a satisfactory scenario describing the hierarchical assembly of dark matter halos is now well established, our physical understanding in particular of feedback effects in the build-up of the baryonic component of galaxies is only fragmentary and fundamentally incomplete. The present observational frontier in the observation of galaxies and QSOs at high redshift is the epoch of reionization, a transformational period in the early Universe. Within one billion years of the Big Bang, essentially all of the hydrogen in the Universe was once again ionized. The re-ionization of hydrogen is believed to have been caused by ultraviolet photons from the first stars and galaxies, most of which are too faint to be observed directly, even with JWST. Determining when and how reionization occurred therefore offers critical insight into both the history of baryons in the IGM and the formation of the first luminous objects.

Table 1. Summary of the HIRES science requirements for fundamental physics and cosmology (E=essential; D=desirable)

Science case	Spectral resolution ($\lambda/\Delta\lambda$)	Wavel. range (μm)	Wavel. accuracy (m/s)	Stability (m/s)	Multi plex	Backgr. subtr
Sandage test	E 100,000	0.37 – 0.67	0.02	0.02	none	not critical
	D 150,000	0.33 – 0.8	0.01	0.01	none	desirable
Fundamental constants	E 80,000	0.37 – 0.67	2	2	none	not critical
	D 100,000	0.33 – 0.8	1	1	none	desirable
Deuterium abundance	E 50,000	0.37 – 0.7	50	not critical	none	not critical
	D 100,000	0.33 – 1.0	50	not critical	none	< 1%
3D IGM mapping	E 5,000	0.4 – 1.3	60000	not critical	5	< 1%
	D 20,000	0.37 – 1.3	30000	not critical	10	< 0.1%
Reionization	E 50,000	0.6 – 1.8	6000	not critical	none	< 1%
	D 100,000	0.6 – 2.4	3000	not critical	2	< 1%

2. A high-resolution spectrograph on the E-ELT

High resolution spectroscopy has provided, during the past twenty years, an increasing fundamental tool enabling major progresses in cosmology and fundamental physics, as well as in other areas of astrophysics. More than 40% of the scientific output of the VLT is based on its suite of high-resolution spectrographs (Grothkopf & Meakins 2015). The scientific output of these high-resolution spectrographs rises above 50% when including the La Silla telescopes (HARPS). In the area of high resolution spectroscopy, where "photon starving" is the main limiting factor, the discovery space enabled by larger telescopes will be huge.

ESO commissioned nine phase A studies for E-ELT instrument concepts that included one optical (CODEX) and one near-IR high-resolution spectrograph (SIMPLE). Based on the result of these phase A studies, ESO published in 2011 an instrumentation roadmap that foresees a high-resolution spectrograph, E-ELT HIRES, as either instrument Nr 4 or Nr 5. In the meantime the CODEX and SIMPLE consortia have merged.

A high-resolution ($R \sim 100,000$) spectrograph with a large simultaneous wavelength range (from 370 to 1800 nm - though the extension to 330 nm is desirable in particular for the deuterium observations) would allow to address all the scientific issues described in the previous section (Tab. 1, Maiolino et al. 2013).

- **Sandage Test**. The drift-rate is expected to be extremely small: $\sim$ 6 cms^{-1}decade^{-1} at $z = 3$ (Cristiani et al. 2007; Liske et al. 2008). Nevertheless, Loeb (1998) proposed the Ly$-\alpha$ forest of absorption lines seen towards background quasars as a promising target: the lines are numerous, ubiquitous, reasonably narrow ($\sim 10 - 30$ km s^{-1}) and should be sufficiently immune to peculiar accelerations.
- **Fundamental Constants**. Currently, the best way to measure cosmological variations in α is to measure relative velocity shifts between metal transitions in QSO absorption systems. Recent works (e.g. King et al. 2012) suggest a parts-per-million spatial variation of the fine-structure constant α at redshifts $2 - 3$ (but see also Evans et al. 2014), with no corresponding variation seen in μ. 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.
- **BBN Deuterium**. High resolution spectroscopic observations of metal-poor hydrogen clouds at high redshift have delivered the most precise measurement of the abundance of deuterium produced in BBN. At present there are just five systems in which this measure can be obtained with a high

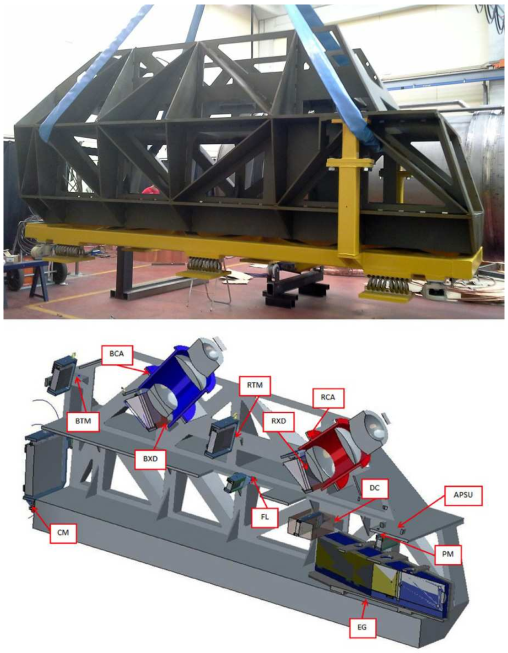

Fig. 1. Opto-mechanics of the ESPRESSO spectrograph. Top: optical bench as of July 2015. Bottom: scheme (APSU: Anamorphic Pupil-Slicer Unit, BCA: Blue Camera, BTM: Blue Transfer Mirror, BXD: Blue Cross-Disperser, CM: Main Collimator, DC: Dichroic, EG: Echelle Grating, FL: Field Lens, PM: Field Mirror, RCA: Red Camera, RTM: Red Transfer Mirror, RXD: Red Cross-Disperser.

level of accuracy (Cooke et al. 2014), the sample needs to be increased by observing suitable cases at fainter magnitudes.

– **Galaxy Formation and Reionization**. The detection of elements synthesized by the first stars in the Universe and the measurement of their spatial distribution requires an HIRES@E-ELT to test the enrichment directly in the reionization epoch.

3. ESPRESSO@VLT as a precursor of HIRES@E-ELT

In the road towards an HIRES at the E-ELT a fundamental role is played by ESPRESSO, an ultra-stable, fiber-fed echelle spectrograph which combines and enhances the capabilities of UVES (Dekker et al. 2000), HARPS (Mayor et al. 2003), and HARPS-N (Cosentino et al. 2012). Its first light is foreseen for 2017. It will operate at very high (130,000 to 200,000) and high (55,000) resolution using respectively one or all four VLT Unit Telescopes (UT), thanks to its location in the Coudé combined laboratory of Paranal. In the 4-UT mode, the equivalent collecting area will be the same of a 16 meter telescope; in the 1-UT mode, the wavelength accuracy will be better than 10 cm s^{-1}. All these specifications are meant to bridge the gap towards E-ELT high-resolution spectrograph, which will use similar solutions (vacuum vessels and thermal chambers) to maintain stability.

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