Report on the workshop of the French "National Cosmology Program" (PNC): Cosmology with the European Extremely Large Telescope (E-ELT)
IAP, 31 May 2007

The meeting was held at the IAP on 31 May 2007. The goal of this meeting was to review the current status of the E-ELT project and to identify the primary science drivers for cosmology. Because of an unfortunate conflict with several other meetings, including the CNRS recruitment campaign, only about 20 people could attend the workshop. This document summarizes the discussions that took place during the meeting. It will serve as a basis for the Scientific Council of the PNC to prioritize and support the implication of French teams in cosmology-oriented projects for the E-ELT. The presentations are available at http://www2.iap.fr/pnc/ELT2007/index.html.

I. Context

In 2006, the ESO Council has authorized detailed studies for the European Extremely Large Telescope (E-ELT). These studies potentially open the way, in three years time, to the construction of an optical/infrared telescope with a diameter around 42m. The goal is for the E-ELT to be ready for operation in 2017.

The plan for the first suite of instruments for the E-ELT is still preliminary. Only a few instruments have been pre-selected, and others are under study. Adaptive optics (AO) modules must also be developed for these instruments. The current situation is summarized in the table below:

INSTRUMENT	WAVELENGTH DOMAIN	FIELD	REFERENCE STUDY	TIMEFRAME
WF, Multi IFU NIR Spectrograph + AO	0.8 to 2.3 μm (R ~ 5000)	5'×5' (Goal 10'×10')	EAGLE	Contract to be in place by July 2007
High Resolution Visible Spectrograph	0.38 to 0.70 μm (R ~ 150,000)	Point Source	CODEX	Study Specs to be fully defined by 4Q 2007
Planetary Imager Spectrograph + AO	0.7 to 2.5 μm (R > 15)	2" to 4"	EPICS	Study Specs to be fully defined by 4Q 2007
MIR Instrument + AO	1.2 to 28 μm		MIDIR	Contract to be in place by 4Q 2007
Single Field, Wide Band Spectrograph				Call to be launched in 3Q, replies in 4Q 2007
Multi-Conjugate AO Module				Contract to be in place by July 2007
Multi-Conjugate AO Camera				Call to be launched in 3Q, replies in 4Q 2007
Laser Tomography AO Module				Call to be launched in 3Q, replies in 4Q 2007
New Instrument Concept-1				Contract to be in place by 1st Q 2008
New Instrument Concept-2				Contract to be in place by 1st Q 2008

The French community is most actively involved in the design of two instruments in this list: EAGLE for cosmology programs and EPICS for the observation of exoplanets. In addition, the French community may participate to the development of other instruments, such as MIDIR.

It is useful to situate the E-ELT in the context of the other large observing facilities that will become available in the next decade, and which will allow the achievement of complementary science goals in cosmology. These facilities are summarized in the table below:

FACILITY	WAVELENGTH DOMAIN	MAIN INTEREST FOR COSMOLOGY	FRENCH INVOLVEMENT	YEAR
LOFAR	0.01 to 0.22 GHz (1.4 to 30 m)	• Reionization (gas) • First radio galaxies	FLOW	2007
Herschel	60 to 670 μm	• High-z dusty galaxies	HIFI, PACS, SPIRE	2008
Planck	30 to 1000 GHz (0.3 mm to 1 cm)	• Cosmological parameters • Early Universe physics • Reionization (E-mode CMB polarization) • Primordial gravity waves (B-mode polarization) • Large-scale SZ survey	HIFI	2008
LMT	75 to 350 GHz (0.85 to 4 mm)	• High-z dusty galaxies • Cluster SZ survey	None	2008
ALMA	30 to 950 GHz (0.3 mm to 1 cm)	• First galaxies (small FOV) • Reionization (Ostriker-Vishniac CMB anisotropies) • Cluster SZ survey	ESO	2010
JWST	0.6 to 28 μm	• First stars and galaxies • Reionization (sources)	NIRSpec (0.6-5 μm; R < 3000), MIRI	2013
SKA	0.15 to 25 GHz (1.2 cm to 2 m)	• Reionization (gas) • Dark energy (BAO at z~1.5)	SKADS EMBRACE	2013-2020
TMT	0.3 to 30 μm (R < 100,000 in 0.3 to 1.0 μm range)	• First stars and galaxies • Reionization (sources) • Abundance measurements of faint stars • Abundance, kinematics and physical conditions in IGM	None (USA, Canada, Japan?)	2015
GMT	0.3 to 28 μm (R < 120,000 in 1.0 to 5.0 μm range)	• Abundance measurements of faint stars • IGM tomography at z~2 • Dark energy (BAO at z~6) • Dark energy (accurate distances to LISA sources)	None (USA, Australia)	2016

This table shows that the E-ELT is most directly comparable to the *Thirty Meter Telescope* (TMT; 30m diameter) and the *Giant Magellan Telescope* (GMT; 21.5m equivalent diameter) that will also become available in about a decade. These telescopes will complement the planned facilities providing a longer-wavelength view of the Universe (LOFAR, Herschel, Planck, SKA) and will offer an important complement to JWST in a similar wavelength domain.

From the point of view of cosmology, the huge light-collecting power of the E-ELT, the high spatial resolution offered by the planned adaptive optics corrections, the extremely high spectral resolution and the wide optical/infrared spectral coverage are most relevant to observations of distant sources in the early Universe. This includes studies of the first reionization sources and of the evolution of the intergalactic medium (IGM) and the expansion of the Universe, by means of spectroscopic observations of distant quasars and primeval galaxies. Compared to the TMT, the E-ELT provides a gain of a factor of 2 in collecting area, and therefore in observing time for most cosmological programs (the gain at the diffraction limit is even higher and can reach a factor of 4). This is crucial, as many programs will be of statistical and long-term nature, requiring large amounts of observing time.

II. Outcome of the PNC workshop discussions

- The direct measurement of the dynamics of the Universe using high-resolution spectroscopy of quasars at redshifts z~1.5-4 is often put forward as a major cosmological motivation for the E-ELT. The goal is to measure the cosmic expansion between two epochs using the Doppler shifts in the Lyα and metallic lines of foreground absorbers (measure of dz/dt). The longer the time base, the larger the cosmic signal. The planned *Cosmic Dynamics Experiment* (CODEX) instrument ambitions to measure wavelength differences to an unprecedented (and challenging) radial velocity accuracy close to 1 cm/sec over 10 years (R~150,000). The signal-to-noise ratio and large number of target quasars required for this program imply a major investment (of the order 20-30%) of the E-ELT time over a period of 10 years, with results in 2028 at the earliest. The audience expressed various doubts during the meeting. First, despite the huge investment in time and technical resources, the foreseen constraints on dz/dt did not seem to be able to convincingly discriminate between different cosmological models. This would be the case even for a 100m *Overwhelmingly Large* (OWL) telescope, for which the CODEX science case was originally developed. Second, the participants were concerned about the influence of potential astrophysical systematic effects on the results (e.g., large-scale motions of the target quasars). Third, rough estimates of the density of bright, distant quasars suitable for this experiment appeared critically low. To clarify these issues, the Scientific Council of the PNC will appoint a working group to examine more thoroughly the pertinence of the CODEX primary science case and its competitiveness relative to the science cases of other experiments, which will have brought new constraints on the expansion of the Universe by 2028 (e.g., type-Ia supernovae, baryonic acoustic oscillations, weak lensing).
- A high-resolution spectrograph such as CODEX has great potential for studies of the metal enrichment of the underdense IGM by galactic super-winds (R~50,000) and of the clustering of metal-rich gas (R>100,000). In fact, such studies may be a promising (cosmological) science driver for this instrument, although they do not answer all questions about the IGM. For example, the characterization of the IGM topology requires 3-dimensional mapping of the Lyα and metal-absorption systems by means of medium-resolution spectroscopy of background quasars and high-surface-brightness Lyman-break galaxies at redshifts z~2-4. For this science goal, the availability of an optical multi-object/multi-IFU spectrograph at medium resolution (~10,000) should be explored thoroughly. Elucidating the interplay between galaxies and the IGM further requires obtaining redshifts for the foreground galaxy population, which could be achieved with the same instrument or with EAGLE. It is worth noting that the large collecting area of the E-ELT will allow moderate- to high-resolution spectroscopy (between the OH lines) to significantly fainter limits than JWST (this is not the case for imaging, where JWST will take full advantage of the low sky background from space).
- High-resolution spectroscopy with CODEX on the E-ELT will provide opportunities for other types of cosmological studies, even though these may not come across as primary science drivers.

Such studies include new constraints on (*i*) Big-Bang Nucleosynthesis by means of high-resolution spectroscopy of metal-poor stars in the Milky Way and nearby galaxies, and (*ii*) the spatial and temporal variations of fundamental "constants", such as the fine-structure constant (α) and the proton-to-electron mass ratio (μ), by means of high-resolution spectroscopy of distant quasars (yielding constraints on $\Delta\alpha/\alpha$ and $\Delta\mu/\mu$ roughly 100 times tighter than with current telescopes; this study does not require spectral resolution as high as 150,000).

- The E-ELT will also provide unique constraints on theories of galaxy formation through the exploration of the first galaxies in the early Universe with instruments such as EAGLE. This instrument will allow detailed spectroscopic studies of populations of primeval galaxies to a fainter magnitude limit than achievable with JWST (the higher imaging capabilities of JWST will be useful for providing spectroscopic targets for detailed study with the E-ELT). Moreover, detailed studies of those sources that are gravitationally amplified should revolutionize our understanding of the physical conditions in primeval galaxies: the combination of the large light-collecting power of the E-ELT and medium-resolution spectroscopy will allow determinations of morphologies and rotation curves for these sources, based on reconstructions of images and velocity fields. The PNC supports the investment of French teams in the construction and exploitation of EAGLE and will invite the PI to present the instrument, along with a more detailed science case, in front of its Scientific Council in the next few months.
- The spectroscopic follow-up of the afterglows of Gamma-Ray Bursts (GRBs) is another potential cosmological program for the E-ELT, which would be most appropriate for the foreseen (presumably X-Shooter-like) optical/infrared wide-band spectrograph. High-redshift GRB afterglows are valuable probes of the interstellar medium of distant galaxies and of the foreground intergalactic medium. The large light-collecting power of the E-ELT will allow spectroscopic follow-up of fainter targets than is currently possible with 8-10 m class telescopes. The challenge of such observations is that they require fast response and rapid pointing (~1 hour to 1 day, depending on redshift). GRBs also provide optically unbiased samples of distant galaxies.

In conclusion, the E-ELT will mark the start of a new observational era in which the combination of large light-collecting power, high spatial resolution (adaptive optics), high spectral resolution and wide optical/infrared spectral coverage will boost our exploration of the distant Universe.

It was felt at the meeting that the current plan for the first generation of E-ELT instrumentation should answer the needs of most cosmological science drivers, while complementing at the same time the capabilities of JWST. The very high spectral resolution offered by CODEX will be most important for exploring the physical conditions and the metal enrichment of the intergalactic medium out to high redshifts. This could well represent the main cosmological science driver for this instrument. In fact, the feasibility of primary science case originally put forward for CODEX (the measurement of the expansion of the Universe) must be carefully examined and challenged against what can be achieved using other facilities, such as Planck, JDEM, Cosmic Vision, SKA, etc. The PNC will appoint a working group to look into this issue over the next few months. Secondary science drivers for CODEX include Big-Bang Nucleosynthesis and the spatial and temporal variations of fundamental "constants". The EAGLE instrument proposed by the French community will be at least as important for cosmology as CODEX. In particular, EAGLE will be fundamental for exploring the sources of reionization and the first primeval galaxies at the end of the dark ages. This is another primary cosmological science driver for the E-ELT, which is among the scientific priorities of the PNC, and for which a clear (i.e. quantitative) scientific program must soon be defined. Follow-up spectroscopy of

GRB afterglows is an interesting cosmological program for the E-ELT, presumably to be carried out with the foreseen wide-band spectrograph, but which does not come across as a primary science driver. The implementation of this program should be evaluated by considering its time requirements. An important science case, which cannot quite be answered by the current instrumentation plan, is the characterization of the topology of the IGM. This science topic could be addressed by means of an optical multi-object/multi-IFU spectrograph at medium resolution (~10,000), such as that envisioned for the GMT.

The PNC will follow in detail the evolution of the CODEX and EAGLE science cases in the coming months and will organize a meeting to make a new point of the situation in 2008. By then, we should also know more about the participation of the French community to the development of the MIDIR instrument. The planned capabilities of combined infrared imaging and high-resolution spectroscopy for this instrument would have a clear interest for cosmology, which should be examined with regard to other future facilities such as JWST.