Measuring the redshift drift of the Lyα forest - a direct measurement of the dynamical evolution of the Universe
“It should be possible to choose between various models of the expanding universe if the deceleration of a given galaxy could be measured. Precise predictions of the expected change in $z = d\lambda/\lambda_0$ for reasonable observing times (say 100 years) is exceedingly small. Nevertheless, the predictions are interesting, since they form part of the available theory for the evolution of the universe”

1. Title

Monitoring the redshift-drift of the Lyman-alpha forest – a direct measurement of the dynamical evolution of the Universe

2. Abstract / Total Time Requested

Total Amount of Time: 3660h  
Total Number of Semesters: 30

We propose to monitor the redshift drift of the Lyα forest and associated metal lines of a sample of high (1000-3300) S/N spectra of 30 very bright QSOs in the redshift range 2 < z < 4.5 with the ultra-stable high resolution optical spectrograph on the E-ELT for a period of 15 yrs. The redshift drift is sensitive to the difference of the expansion rate today and the expansion rate at the redshift of the absorbing structures and is directly related to the acceleration of the Universe. With the proposed observations we can achieve an overall measurement accuracy of 3.2 cm/s. By monitoring the drift of the Lyα forest over a wide redshift range we will measure the instantaneous expansion rate of the Universe today and the expansion rate at high redshift. The measurement of the expansion rate and its evolution at high redshift will be an important test of General Relativity. The measurement of the instantaneous expansion rate will test whether the Universe expands today at the rate expected from other astronomical measurements which generally constitute the measurements of the expansion rate averaged over hundred Myrs or more. The observations proposed can be used as a first epoch measurement for more accurate measurements by future generation of astronomers and will thus leave a long lasting legacy. The acquired spectra will represent a unique resource for a wide range of QSO absorption line studies.

A 80 UVES 122h any d ≤ 0.8′′ PHO s
B 81 UVES 122h any d ≤ 0.8′′ PHO s
C 82 UVES 122h any d ≤ 0.8′′ PHO s
D 83 UVES 122h any d ≤ 0.8′′ PHO s
E 83 UVES 122h any d ≤ 0.8′′ PHO s
F 83 UVES 122h any d ≤ 0.8′′ PHO s
G 83 UVES 122h any d ≤ 0.8′′ PHO s
H 83 UVES 122h any d ≤ 0.8′′ PHO s
I 83 UVES 122h any d ≤ 0.8′′ PHO s
J 83 UVES 122h any d ≤ 0.8′′ PHO s
K 83 UVES 122h any d ≤ 0.8′′ PHO s
L 83 UVES 122h any d ≤ 0.8′′ PHO s

Following runs moved to box 3a, last page...

4. Principal Investigator: L. Pasquini  (ESO, D, lpasquin@eso.org)
Col(s): M. Haehnelt (IoA, UK), on behalf of the CODEX team (OTHER, OTHER), and the ESO-ELT SWG (OTHER, OTHER)
Measuring $\dot{z}$

\[
dz = \frac{\partial z}{\partial t_0} dt_0 + \frac{\partial z}{\partial t_e} dt_e
\]

\[
\dot{z} = \frac{dz}{dt_0} = \frac{\partial z}{\partial t_0} + \frac{\partial z}{\partial t_e} dt_e = \frac{\ddot{a}(t_0)}{a(t_0)} - \frac{\ddot{a}(t_e) a(t_0)}{a(t_e) a(t_e)} \frac{1}{1+z}
\]

\[
\dot{z} = (1+z)H_0 - H(t_e).
\]
\dot{z} = (1 + z) \, H_0 - H(t_e)
The Signal is SMALL!
The HARPS Experience

Th-Th < 10 cm/sec

O-C < 80 cm/sec
S. Udry¹, X. Bonfils², X. Delfosse³, T. Forveille³, M. Mayor¹, C. Perrier³, F. Bouchy⁴, C. Lovis¹, F. Pepe¹, D. Queloz¹, and J.-L. Bertaux⁵

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Abstract. This Letter reports on the detection of two super-Earth planets in the Gl 581 system, already known to harbour a hot Neptune. One of the planets has a mass of 5 M⊕ and resides at the “warm” edge of the habitable zone of the star. It is thus the known exoplanet which most resembles our own Earth. The other planet has a 7.7 M⊕ mass and orbits at 0.25 AU from the star, close to the “cold” edge of the habitable zone. These two new light planets around an M3 dwarf further confirm the formerly tentative statistical trend for i) many more very low-mass planets being found around M dwarfs than around solar-type stars and ii) low-mass planets outnumbering Jovian planets around M dwarfs.

Key words. stars: individual: Gl 581, stars: planetary systems – techniques: radial velocities – techniques: spectroscopy
Spectrograph builders are confident that they can reach wavelength accuracy of 1cm/s over long periods of time.
Novel Calibration System: Laser Frequency Comb

Metrology labs recently revolutionized by introduction of femtosecond-pulsed, self-referenced lasers driven by atomic clock standards (Nobel prize 2005)

Cesium atomic clock (or even GPS signal!)

- Result is a reproducible, stable “comb” of evenly spaced lines whose frequencies are known \textit{a priori} to better than 1 in $10^{12}$
Comb spectrum simulation with
$R = 100k, \Delta \nu = 15\text{GHz}, \lambda = 5000\text{Å}$

Detailed study carried out by ESO in collaboration with Max Planck Institute for Quantum Optics.
Spectrograph builders are confident that they can reach wavelength accuracy of 1 cm/s over long periods of time.

Redshift drift measurements will then be photon-noise limited.

Need spectra of bright objects with many sharp features.
Where too look?

**Masers**: in principle good candidates: lines are very narrow and measurements accurate: they sit, however, at the center of deep potential wells: large peculiar motions, larger than the cosmic signal are expected.

**Radio Galaxies with ALMA**: as for Masers, local motions of the emitters swamp the cosmic signal.

**Lyα forest**: Absorption from the many intervening lines in front of high redshift QSOs are the most promising candidates. Simulations and observations have shown that the Lyα forest are produced by density fluctuations of a warm IGM which traces the Hubble flow very well.
QSO absorption lines

Lyman limit
Lyβ
Lyα forest
Lyαem
NVem
SilVem
CIVem

Wavelength

Lyman limit
Lyβ
Lyα forest
Lyαem
NVem
SilVem
CIVem
But this is for $10^7$ years… Having much less time at our disposal the shift is much smaller.
Results of simulation (1): real spectrum

Dependence on cumulative S/N/pixel (0.015 Å)

$q0000spA @ R=100'000$
The forest thickens with increasing redshift.
Simulations of the $z$ dependence of the measurement accuracy

For fixed photon flux accuracy first increases with increasing redshift due to the larger number of lines and then saturates when lines start to overlap.
The simulation results for the accuracy in the photon-noise limited case can be summarized into a simple scaling law

$$\sigma_v = 1.4 \times \left(\frac{2350}{(S/N)}\right) \left(\frac{30}{N_{\text{QSO}}}\right)^{0.5} \left(\frac{5}{(1+Z)}\right)^{1.8} \text{cm/sec}$$

for a pixel size of 0.0125 Angstrom. The contribution from metal lines associated with the Ly\(\alpha\) forest is included.
How well can we do with known QSOs?

S/N has been verified with adapted results from ELT exposure time calculator. The exposure time calculator in its present form is not directly suitable for a seeing limited high-resolution spectrograph.
How well can we do with known QSOs?

S/N has been verified with adapted results from ELT exposure time calculator. The exposure time calculator in its present form is not directly suitable for a seeing limited high-resolution spectrograph.
A compromise between sample size redshift coverage and total number of photons collected:
30 bright known QSOs accessible in the southern hemisphere

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Average Mag.</th>
<th>N Obj</th>
<th>S/N per QSO</th>
<th>Tot exp (hours)</th>
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<td>3</td>
<td>3275</td>
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<td>2.25-2.5</td>
<td>15.56</td>
<td>3</td>
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<td>313</td>
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<tr>
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<td>16.13</td>
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Total exposure time: 3658h
### 12. List of targets proposed in this programme

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<th>δ(J2000)</th>
<th>ToT</th>
<th>Mag.</th>
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</tr>
</tbody>
</table>
That is what we get

$\Delta t = 15 \text{ yr}$

Can be improved with brighter QSOs (new surveys, variability) and the use of the Ly$\beta$ forest.
V=16.5
14 % efficiency
CODEX @ E-ELT

ESO:
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Others:
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(St-Petersburg), L. Moscardini (OABo-INAF), S. Zucker (Tel Aviv),
T. Wilklind (ESA)
QUESTIONS

• wavelength range
• diameter
• seeing limited vs GLAO
Why should we do it?
Robertson-Walker metric

\[ ds^2 = c^2 dt^2 - R^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 (d\Theta^2 + \sin^2 \Theta \, d\Phi^2) \right] \]

- \( k = 0 \) flat space
- \( k = 1 \) spherical
- \( k = -1 \) hyperbolical

R-W metric is maximally symmetric. It is the simplest metric that describes a homogeneous and isotropic Universe.
Cosmological redshifts

emitted

\[ r = r_e \]
\[ \lambda_e = c \Delta t_e \]

\[ t_e \quad t_e + \Delta t_e \]

received

\[ r = r_0 \]
\[ \lambda_0 = c \Delta t_0 \]

\[ t_0 \quad t_0 + \Delta t_0 \]

\[ z = \frac{\lambda_0 - \lambda_e}{\lambda_e} \]

\[ 1 + z = \frac{\lambda_0}{\lambda_e} \]
photons:

\[ ds^2 = 0 = c^2 dt^2 - R^2(t) \left( \frac{dr^2}{1 - kr^2} \right) \]

radial light path \( d\Theta = d\Phi = 0 \)

Photons travel from \( r_e \) to \( r_0 = 0 \):

\[
\int_{t_e}^{t_0} \frac{dt}{R(t)} = \frac{1}{c} \int_{r_e}^{0} \frac{dr}{\sqrt{1 - kr^2}} = \int_{t_e + \Delta t_e}^{t_0 + \Delta t_0} \frac{dt}{R(t)}
\]

\[
\int_{t_e}^{t_0} \frac{dt}{R(t)} = \int_{t_e + \Delta t_e}^{t_0 + \Delta t_0} \frac{dt}{R(t)}
\]
To first order in $\Delta t$:

\[
\frac{\Delta t_0}{R(t_0)} = \frac{\Delta t_e}{R(t_e)}
\]

\[1 + z = \frac{\lambda_0}{\lambda_e} = \frac{\Delta t_0}{\Delta t_e} = \frac{R(t_0)}{R(t_e)}\]
Redshift drift maps the expansion history without any further model assumptions and without reference to a theory of gravity.
Luminosity distances

\[ D_L(z_e) = \frac{c}{H_0} \frac{(1 + z_e)}{\sqrt{|1 - \Omega_{\text{tot}}|}} \left\{ \frac{\sin}{\sinh} \right\} \left( \sqrt{|1 - \Omega_{\text{tot}}|} \int_0^{z_e} \frac{H_0}{H(z)} \, dz \right) \left\{ \begin{array}{l} \text{spherical} \\ \text{flat} \\ \text{hyperbolical} \end{array} \right\} \]

Involves integral over z and need to know curvature.
Geometry of space time \[ G_{\mu\nu} = T_{\mu\nu} + \Lambda g_{\mu\nu} \] Gravity

cosmological constant
General Relativity $\Rightarrow$ Friedmann equation

\[
H^2 = \left( \frac{\dot{R}}{R} \right)^2 = \frac{8\pi G}{3} \rho - \frac{k c^2}{R^2} + \frac{\Lambda c^2}{3} \quad \rho = \rho_{\text{mat}} + \rho_{\text{rad}}
\]

\[
H^2(t) = H_0^2 \left( \Omega_{\text{mat},0} (1 + z)^3 + \Omega_{\text{rad},0} (1 + z)^4 + \Omega_{k,0} (1 + z)^2 + \Omega_{\Lambda,0} \right)
\]

\[
\Omega_{k,0} = 1 - \Omega_{\text{mat},0} - \Omega_{\text{rad},0} - \Omega_{\Lambda,0}
\]