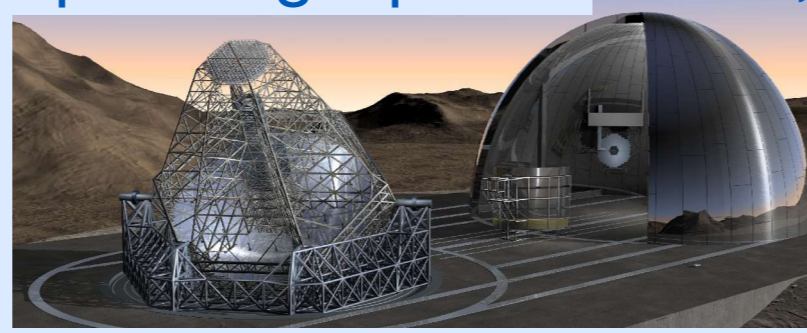


1. Introduction

In many classical and modern tests cosmological parameters are determined by using the smooth background geometry and/or the clustering of density perturbations. However, as first shown by Sandage (1962), it is in principle also possible to measure the dynamics of the smooth cosmological background, i.e. **to directly measure the history of the Hubble flow**: the evolving expansion rate of the universe causes a small systematic drift in the redshifts of cosmologically distant sources as a function of time. CODEX is a concept study initiated and led by ESO to examine the possibility of observing this drift with a high-resolution optical spectrograph on **OWL**, ESO's vision of a future 60-100m telescope.



2. Evolving redshifts

It is straightforward to derive the connection between the rate of change in the redshift of a distant object and the evolution of the expansion rate:

$$\frac{d}{dt_0} \left[1+z = \frac{a(t_0)}{a(t_e)} \right] \Rightarrow \frac{dz}{dt_0} = (1+z) H_0 - H(z)$$

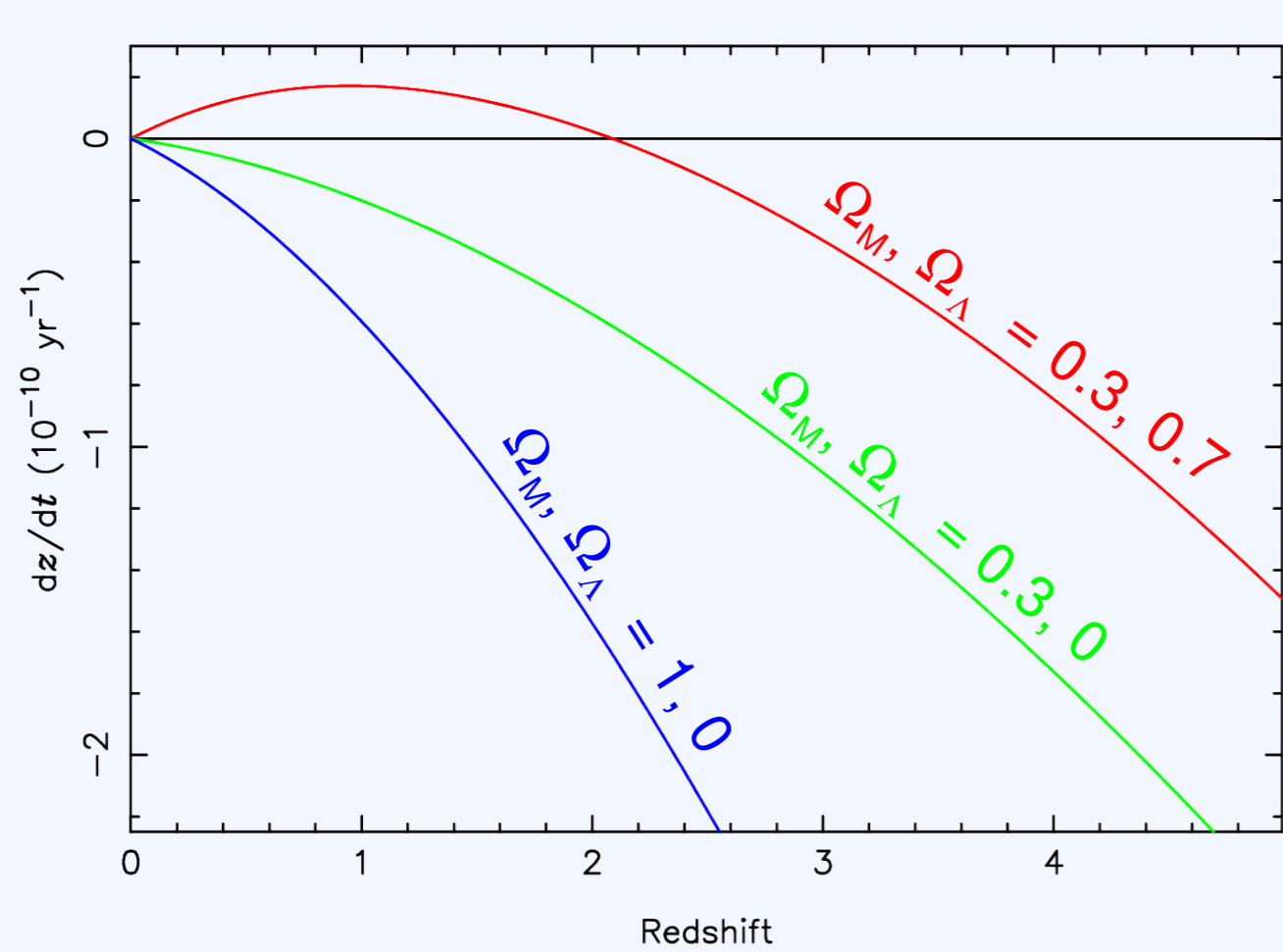


Fig. 1: dz/dt as a function of redshift for different cosmological parameters as indicated and $H_0 = 70$ km/s/Mpc.

For $\Delta t = 10$ yr @ $z = 4$:
 $\Delta z \sim 9 \times 10^{-10}$
 $\Delta \lambda \sim 1 \times 10^{-6}$ Å
 $\Delta v \sim 5.4$ cm/s

3. Where can we measure dz/dt ?

Tiny signal \rightarrow need lots of sharp spectral features \rightarrow requires cold emitters or absorbers \rightarrow generally found in dense regions \rightarrow deep potential wells \rightarrow large peculiar accelerations \rightarrow although random with respect to the Hubble flow, could swamp the cosmic signal.

This rules out many candidate targets, such as masers or molecular absorption lines towards radio galaxies. However, there is one class of objects that meets the requirement of tracing the Hubble flow:

4. The high redshift Lyman α forest

The Ly α forest is a well-studied phenomenon, both observationally (~ 100 high-resolution spectra from VLT/UVES and Keck/HIRES) and theoretically (full hydrodynamic simulations). Its intergalactic nature implies shallow potential wells and simulations yield peculiar accelerations a factor of 10 below the cosmic signal. **Hence the Ly α forest reliably traces the Hubble flow.** The trade-off lies in the relatively large line widths of 15-50 km/s. However, this is mostly offset by the huge number of absorption features.

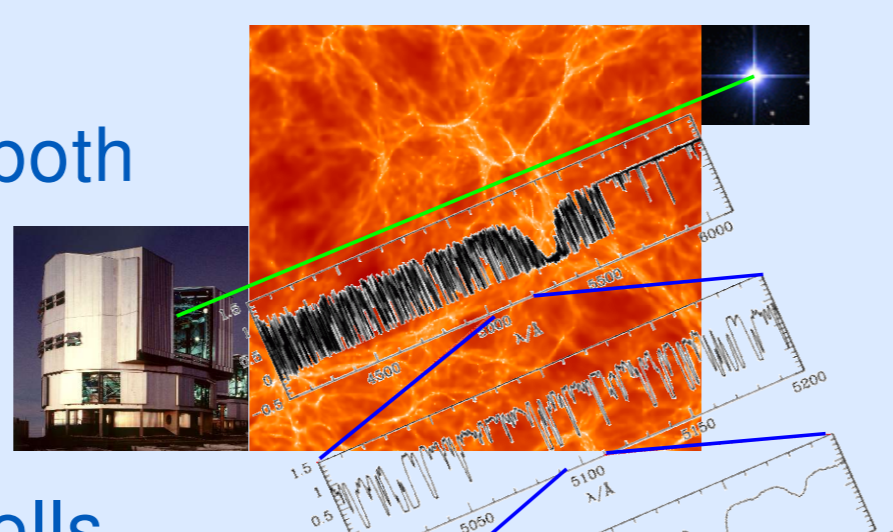
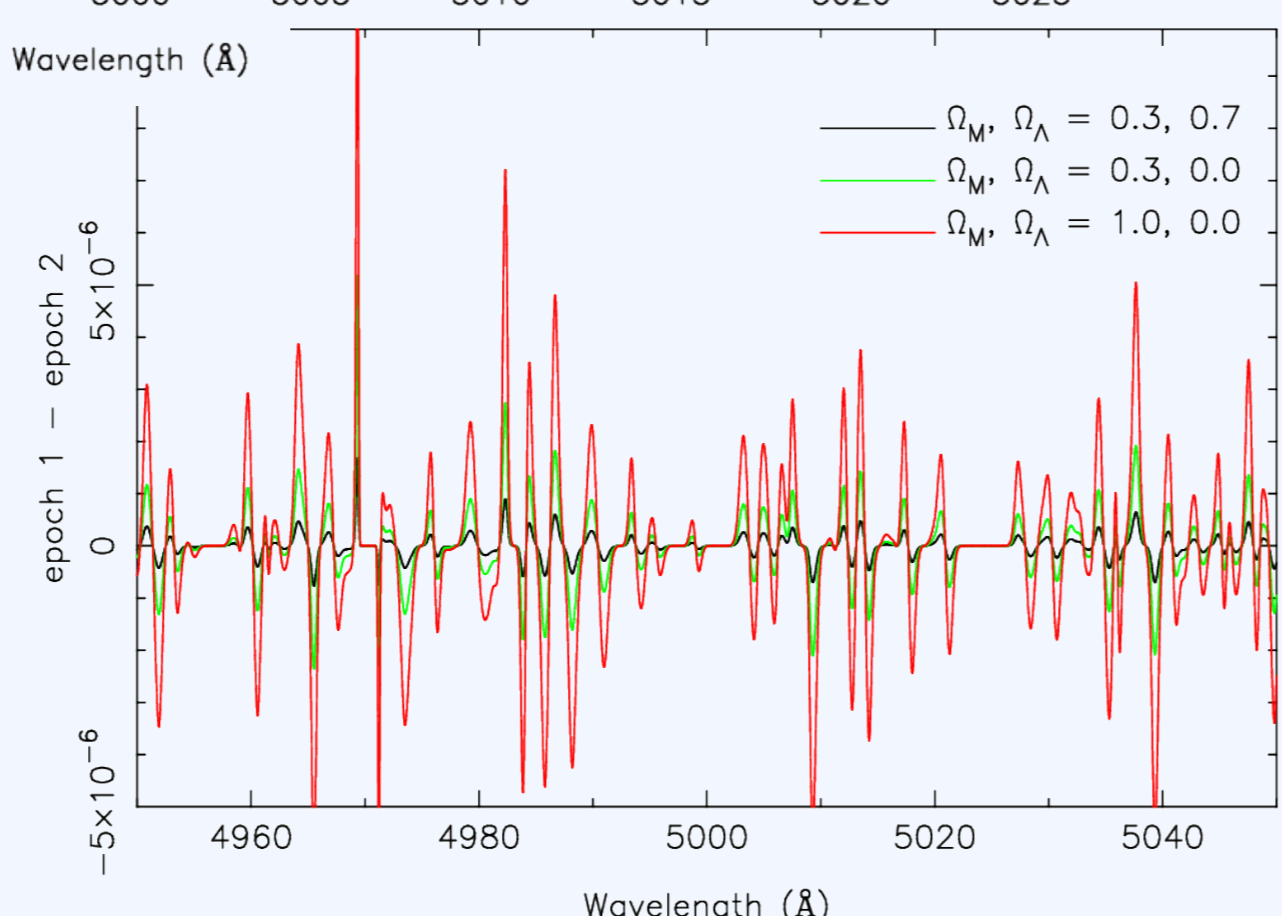


Fig. 2: The redshift drift in a simulated Ly α forest spectrum for $\Delta t = 10^7$ yr.

Fig. 3: The difference of two simulated noiseless Ly α forest spectra taken $\Delta t = 10$ yr apart.



5. Simulations

Fig. 1 shows that a 3σ detection of the redshift drift at $z = 4$ requires a radial velocity accuracy of order $\sigma_v \approx 2$ cm/s. Given the properties of the Ly α forest, how many spectra of which resolution and S/N are required to achieve this accuracy? How does σ_v depend on redshift?

To answer these questions we have performed Monte Carlo simulations using an empirical parametrisation of the Ly α forest. We find:

$$\sigma_v = 2 \left[\frac{S/N}{1400} \right]^{-1} \left[\frac{N_{QSO}}{30} \right]^{\frac{1}{2}} \left[\frac{1+z_{QSO}}{5} \right]^{-1.8} \text{ cm/s}$$

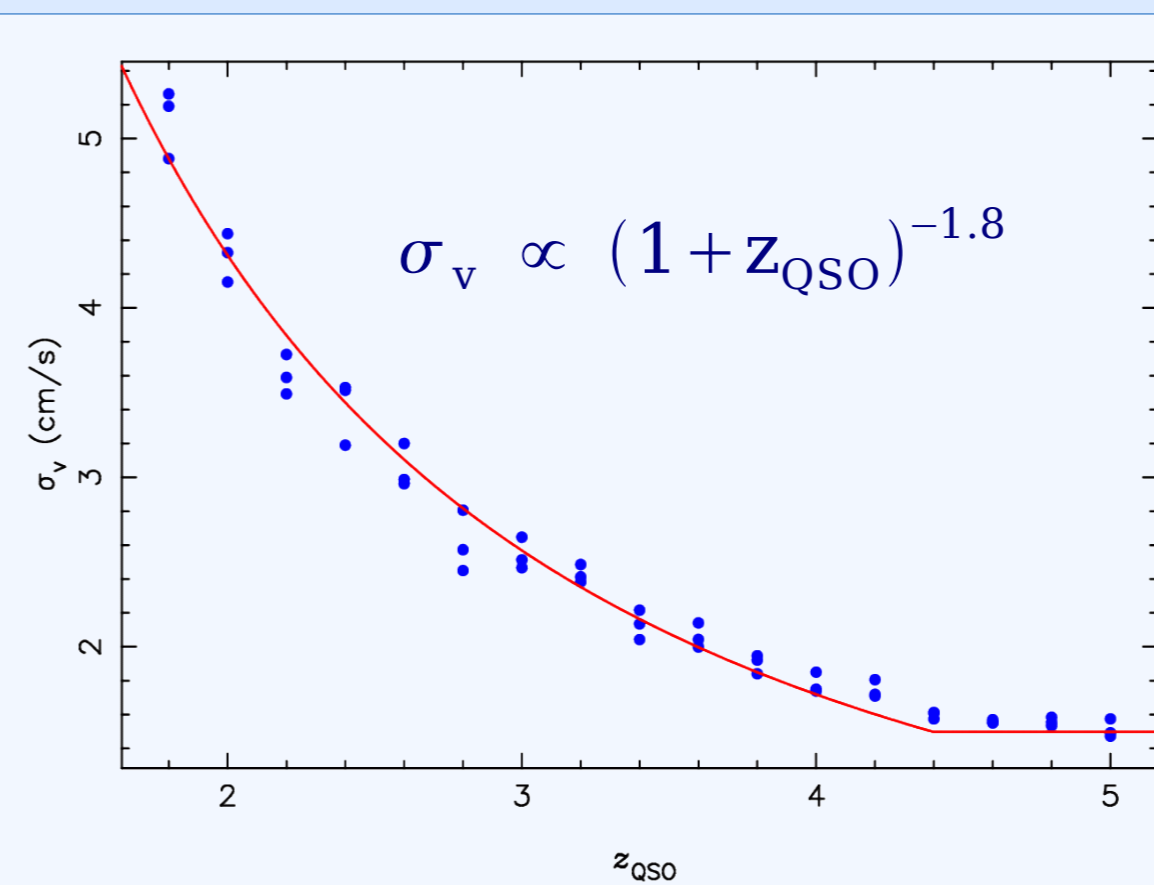


Fig. 4: Redshift dependence of σ_v .

where the S/N is per 0.0125 Å pixel. σ_v does not depend on the spectral resolution as long as the absorption lines are resolved, i.e. $R > 50000$. The z -dependence is the result of (i) the density evolution of the Ly α forest, (ii) the broadening of absorption lines in wavelength space and (iii) the increase of a spectrum's useful fraction with $(1+z)$.

6. Target flux, telescope size, efficiency and integration time

Does a feasible combination of these four parameters exist which results in the required S/N above?

Fig. 5: For a given telescope size we show the total efficiency required for a 3σ detection of the redshift drift in a 16.5 mag QSO at $z = 4$ in 1000 h integration time per epoch ($\Delta t = 10$ yr). The red line shows the efficiency achieved with VLT/UVES.

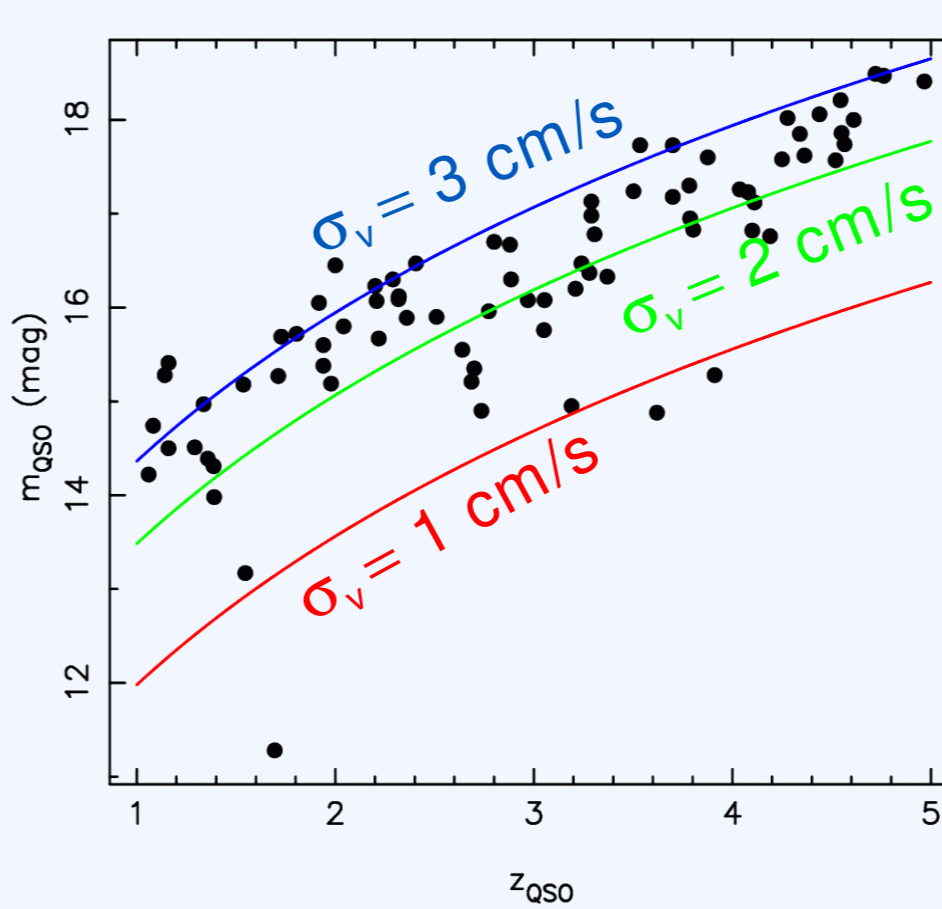
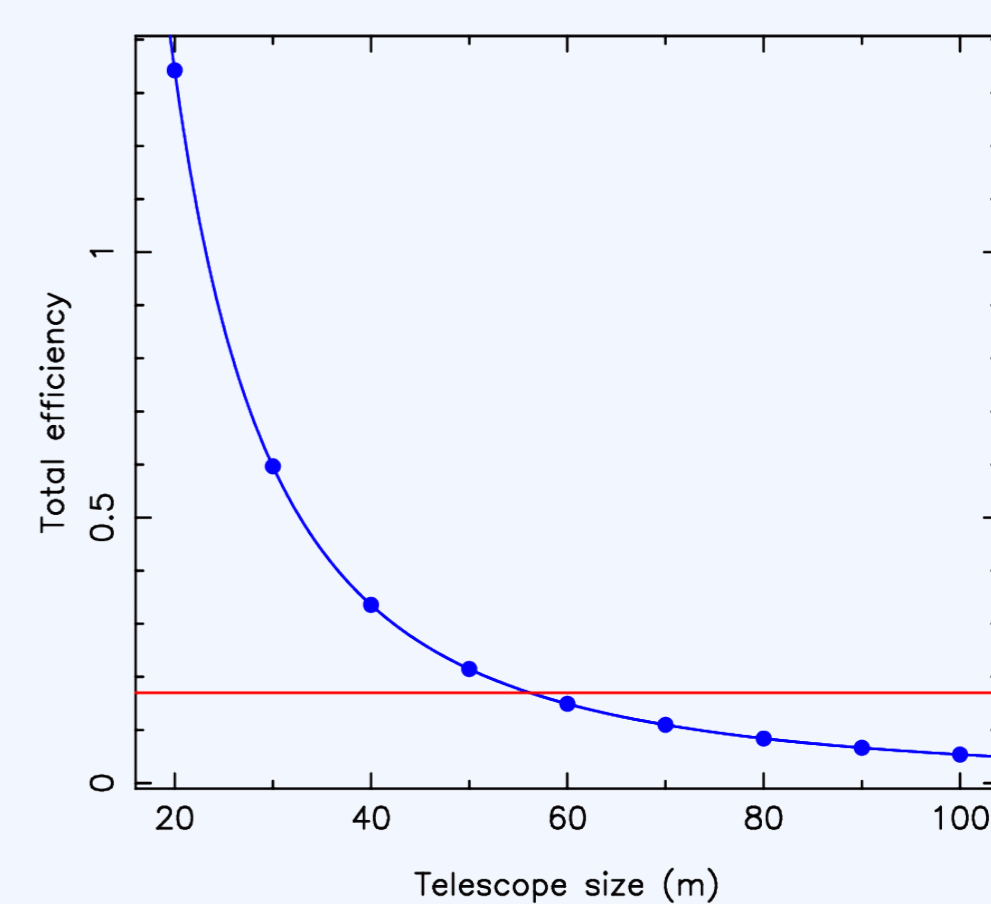
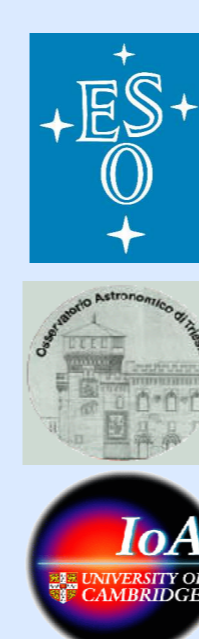


Fig. 6: The brightest objects from the Véron-Cetty & Véron QSO catalogue. We also show lines of constant σ_v , assuming: 100m telescope, 9% efficiency, 1000 h integration time.

The above figures show that the photon flux from known QSOs is sufficient to achieve the required S/N with ~ 1000 h of integration time on a 100m class telescope with efficiency $\sim 10\%$.

7. Summary

We conclude that it is indeed possible to detect the cosmological redshift drift with a high-resolution optical spectrograph on a future 100m class telescope, and hence to attempt a direct and purely dynamical reconstruction of the universe's expansion history. A discussion of calibration issues and potential sources of systematics (which are clearly of prime importance to CODEX) is beyond the scope of this poster, but several have been investigated and so far no show-stoppers have been encountered. Hence, an instrument design has been developed and several areas requiring further R&D have been identified.



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