COSMOLOGY WITH THE LYMAN-α FOREST IN THE WMAP ERA

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In the WMAP era of high precision cosmology an accurate determination of the matter power spectrum from Lyman-α forest data becomes crucial. When combining the matter power spectrum derived from CMB experiments with that inferred from Lyman-α absorption an evidence for a running spectral index and a primordial index $n < 1$ arises (Verde et al. 2003). In this talk, I will describe some results obtained from a sample of 27 high resolution and high signal-to-noise quasar spectra (the LUQAS sample) and I will address possible systematic errors that can affect the estimate of the flux power spectrum.

1 Introduction

The Lyman-α forest offers a unique probe of our Universe at redshift and scales not probed by any other observable. Thus, the use of absorption spectra to probe the dark matter power spectrum has been widely investigated by a large number of authors (e.g. Croft et al. [1]; Gnedin & Hamilton [2]; Zaldarriaga et al. [13]). At these scales the matter power spectrum is sensitive to possible cut-off expected if the dark matter were warm dark matter, can give constraints on the matter fraction in neutrinos and allows to investigate the gravitational growth of structure and possibly the redshift evolution of dark energy (Viel et al. [10]; Mandelbaum et al. [6]; Lidz et al. [5]).

Croft et al. [1] found that the power spectrum inferred from Lyman-α forest is consistent with a ΛCDM model ($\Omega_\Lambda = 0.6, \Omega_M = 0.4, h = 0.65$) with $n = 0.93$ and $\sigma_8 = 0.7$. Hui et al. [3] made a very detailed study of possible systematic effects which can occur in this estimate. Verde et al. [9] combined Croft et al. data points with WMAP results and concluded that there is evidence for a running spectral index and for a tilt in the primordial power spectrum. However, a recent analysis made by Seljak et al. [7], who argued for a larger error bar and for a smaller value of the effective optical depth, showed that there is no evidence for a running spectral index nor for a tilt in the power spectrum. An accurate determination of the power spectrum is thereby crucial especially now that with new data set coming out a precision of the order of few percent could be achieved (Mandelbaum et al. [6]). In this talk, I will describe some systematics errors which can significantly affect the estimate of the flux power spectrum.

2 The LUQAS sample: systematic errors in the flux power spectrum

The LUQAS sample[a] (Large Uves Quasar Absorption Spectra) consists of 27 QSOs. The median redshift of the sample is $z = 2.25$ and the total redshift path is $\Delta z = 13.75$. The typical signal-to-noise ratio is ~ 50 and the pixel size is 0.05 Å. For the data reduction and a more extensive description of the sample we refer to Kim et al. [4]. In the left panel of Figure 1 we show the

[a] www.ast.cam.ac.uk/~rtnigm/luqas.html

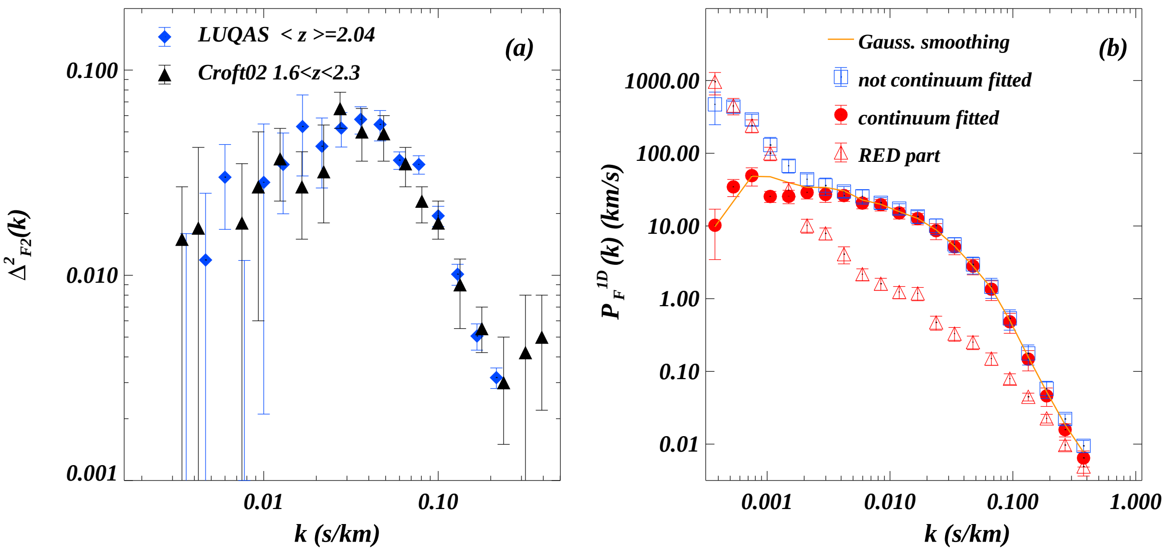

Figure 1: Left: 3D flux power spectrum plotted in adimensional units from the LUQAS sample at $<z>= 2.04$ (diamonds) and from Croft et al. (2002, triangles). Right: Effect of continuum fitting on the 1D flux power spectrum for different flux estimators: the fitted spectra (red circles); the not continuum fitted spectra (squares); the not continuum fitted spectra smoothed with a Gaussian filter with $\sigma = 25$ Å(continuous line); the part of the flux spectrum redward of Lyman-α emission (triangles). Error bars are jack-knife estimates.

3D flux power spectrum from a subsample of the LUQAS sample at a median redshift $z = 2.04$ (diamonds) and we compare it with the results of Croft et al. 2002 (triangles). There is good agreement between the two estimates over a wide range of wave-numbers. In particular, we find the same fluctuation amplitude at $k \sim 0.03$ s/km and a shallower slope at large scales $k < 0.03$ s/km than Croft et al. (2002) but consistent within the errors.

2.1 Continuum fitting errors and metal lines

In the right panel of Figure 1 we show the effect of continuum fitting on the flux power spectrum. Red circles show the one dimensional flux power spectrum computed from the *continuum fitted* spectra, while the empty squares have been obtained from the *not continuum fitted* spectra. There is more power for the latter at $k < 0.003$ s/km: this is where the continuum fluctuations from the distant source start to dominate. In Figure 1 we plot the flux power spectrum redward of Lyman-α emission (1265 Å- 1393Å) which is consistent with the other two for $k < 0.003$ s/km, supporting the conclusion that at these scales and for these spectra the power is continuum dominated. In the same Figure the continuous line represents the power spectrum of the observed flux obtained by a local estimate of the mean flux with a Gaussian filter with $\sigma = 25$Å: the result is consistent with the fitted flux power spectrum. This indicates that simple way of continuum fitting the spectra, such as a Gaussian filtering to obtain a local estimate of the mean flux, are promising. In Kim et al. [4] we quantify the effect of metal lines on the flux power spectrum which is less than 10% at scales $k < 0.01$ s/km and rises up to 50% at smaller scales. This estimate has been obtained from a subset of 13 quasar spectra of the LUQAS sample for which we have the metal lines list.

2.2 Strong absorption systems

In the left panel of Figure 2 we show the contribution to the 3D flux power spectrum from absorbers with different column densities (Viel et al. [11]). From a subset of 8 spectra of the

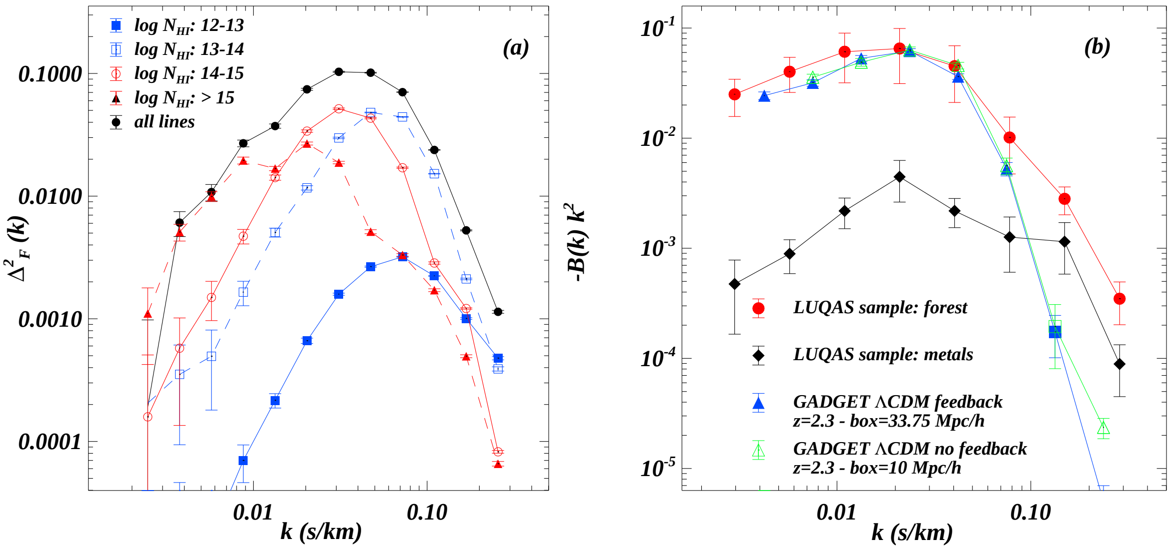

Figure 2: Left: Contribution of absorbers in different column density ranges to the 3D flux 'random' power spectrum. Right: The flux bispectrum: the LUQAS flux bispectrum in the range $2 < z < 2.4$ (filled circles); bispectrum of the metal lines (diamonds); bispectrum from hydro-dynamical simulations with different box sizes and with and without feedback (filled and empty triangles, respectively).

LUQAS sample fitted with VPFIT we create a new sample of 300 'random' spectra for which the positions of the lines have been randomly shifted along the spectrum. We split the contribution of different absorbers by selecting only the lines in a given column density range when creating the new set of spectra. The strongest contribution comes from lines $13.5 < \log(N_{HI}/cm^{-2}) < 14.5$. These are lines where the "curve of growth" which describes the relation between equivalent width and column density changes from the linear to the flat regime due to saturation. However, the contribution of systems with $\log N_{HI} > 14$ at wavenumbers $k < 0.01$ s/km is significant and dominates at large scales. In addition, the contribution of these systems to the mean flux decrement is of the order of 20% (Viel et al. [11]).

This will have profound implications for attempts to use numerical simulations together with quasar absorption spectra to infer amplitude and slope of the dark matter power spectrum with high accuracy. In fact, numerical simulations of the Lyman-α forest often underpredict the number of strong absorption systems. The calibration of numerical simulations which underreproduce observed strong absorption is likely to underestimate the inferred *rms* fluctuation amplitude and the slope of the primordial dark matter power spectrum. In a combined analysis with other data which constrain the dark matter power spectrum on large scales, this can result in a spurious detection of a running spectral index.

3 The flux bispectrum

In the right panel of Figure 2 we show the one dimensional flux bispectrum (Viel et al. [12]). The circles have been obtained from the LUQAS sample ($2 < z < 2.4$), the diamonds represent the metal lines contribution which is significant at $k > 0.1$ s/km. Typical errors on the observed bispectrum as obtained from a jack-knife estimate are of the order of 50%.

In this Figure the flux bispectrum from two hydro-dynamical simulations with feedback (full triangles) and without feedback (empty triangles) is reported. There is substantial agreement between these two estimates (including galactic feedback changes the bispectrum by less than 10%), showing that feedback in the form of strong winds from star forming galaxies does not affect this statistic (see Theuns et al. [8] for other statistics). This supports the idea that the volume filling factor of the feedback regions is small and thereby the Lyman-α forest is an unbiased probe of the Universe at these redshifts. In the range 0.007 s/km $< k <$ 0.07 s/km there is agreement between hydro simulations and data, while the discrepancy at smaller scales is due to the presence of metal lines. An analytical prediction based on second order perturbation theory in the framework of the fluctuating Gunn-Peterson approximation is also in rough agreement with the data. For the LUQAS sample the error bars are too large to discriminate between models with very different 3D distribution of Lyman-α absorption. In fact, we found that the bispectrum computed from a set of randomized absorption spectra, for which a shift in wavelength has been added to absorption lines identified with VPFIT, is in agreement with the observed one. If it were possible to reduce these error bars with a larger sample the bispectrum can become an important tool for probing the growth of gravitational structures in the Universe at $z > 2$ (Viel et al. [12]).

4 Conclusions

In this talk I presented some results from the LUQAS sample which consists of 27 high resolution quasar spectra at a median redshift $z = 2.25$. The main conclusions are here summarized: *i)* the flux power spectrum is consistent with the results found by Croft et al. (2002); *ii)* the continuum fitting errors affect the power spectrum at $k < 0.003$ s/km; *iii)* strong absorptions systems have been found to contribute significantly (up to 50 %) to the flux power spectrum at large scales and to the mean flux decrement ($\sim 20\%$); *iv)* the flux bispectrum is a promising and robust statistics which needs to be further investigated with a larger sample.

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