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Quantitative Cosmology with the Lyman-α Forest

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We use LUQAS, a sample of 27 high resolution high signal-to-noise UVES quasar (QSO) spectra (Kim *et al.* 2004), and the Croft et al. (2002) sample together with a set of high resolution large box size hydro-dynamical simulations to recover the linear dark matter power spectrum at $z > 2$ and at scales of $1 - 40\,h^{-1}$ Mpc. These scales cannot be probed by any other observable. We address some of the uncertainties in the theoretical modelling of the Lyman-α forest structures such as the difference between full hydro-dynamical simulations and a more simplified scheme based on the HPM (Hydro Particle Mesh) technique. We combine this estimate with Cosmic Microwave Background (CMB) data in order to get tighter constraints on cosmological parameters. We focus on the recovered values of the power spectrum amplitude, the primordial spectral index and the running of the primordial spectral index. We explore implications for the mass of a warm dark matter particle.

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1. The Lyman-α forest data set: the flux power spectrum

The LUQAS sample (Large Sample of UVES Quasar Absorption Spectra) consists of 27 quasar (QSO) spectra taken with the Ultra-Violet Echelle Spectrograph (UVES) on VLT. Most of the spectra have been taken as part of the Large ESO Observing programme UVESLP (P.I.: J. Bergeron). The median redshift of the sample is $z = 2.125$ 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 a more detailed description of the sample and the data reduction we refer to Kim *et al.* [5]. We combine this sample with that of Croft et al. (2002) [2], which consists of 30 Keck HIRES spectra and 23 Keck LRIS spectra and has a median redshift of $z = 2.72$. These two data sets seem to be in good agreement with the flux power spectrum obtained by McDonald *et al.* [6, 8] from a large sample of low-resolution SDSS spectra. Although some differences between the different data sets are present, at the level of the error bars that we are going to quote, these discrepancies are not relevant. The power spectrum of the observed flux in high-resolution Lyman-α forest data constrains the dark matter (DM) power spectrum on scales of $0.003\,\mathrm{s/km} < k < 0.03\,\mathrm{s/km}$ (roughly corresponding to scales 1-40 h^{-1} Mpc). At larger scales the errors due to uncertainties in fitting a continuum to the absorption spectra become large while at smaller scales the contribution of metal absorption systems becomes dominant [5, 6]. In all the data sets the systematic uncertainties are larger than the statistical errors [5, 6, 10].

2. Theoretical modelling of Lyman-α forest spectra

The method used to infer the dark matter power spectrum from the observed flux is the 'effective bias method' that has been proposed by [2] (C02) and has been improved by [3] and [10] (VHS). The method relies on hydro-dynamical simulations to calibrate a bias function between flux and matter power spectrum: $P_F(k) = b^2(k)\ P(k)$, on the range of scales of interest, and has been found to be robust [3]. This relation assumes that the flux power spectrum $P_F(k)$ at a given k depends linearly on the linear real space matter power spectrum $P(k)$ at the same wave-number and implicitly takes into account all the possible non linear effect via the bias function. The idea is to r un a grid of full hydro-dynamical simulations and to find the bias function which best fits the observed flux power spectrum. Then, using the above relation, the observed linear dark matter power spectrum can be inferred. Full hydro-dynamical simulations are needed in order to properly simulate the thermal state and the distribution of the Intergalactic Medium (IGM).

One of the main uncertainties in the theoretical modelling of the Lyman-α forest consists in the discrepancies found by different simulators (see discussion in [10]). In particular, here we focus on the differences between full hydro dynamical simulations and HPM (Hydro Particle Mesh) simulations a simplified scheme originally proposed by Gnedin & Hui ([4]). Basically, we address the effect of these parameters on the 1D flux power spectrum. For this study only we will use a box size of 15 comoving Mpc$/h$ and 2×200^3 particles, run with GADGET [7]. The first parameter is the size of the PM grid which is used by the code (we label this as PMGRID). The second one is the smoothing of the pressure field which is made before taking its derivative (we label this as HPM smoothing). Since this field is more prone to local shot noise than the gravitational potential we follow here the implementation of [4] and we perform such a smoothing. The third parameter refers

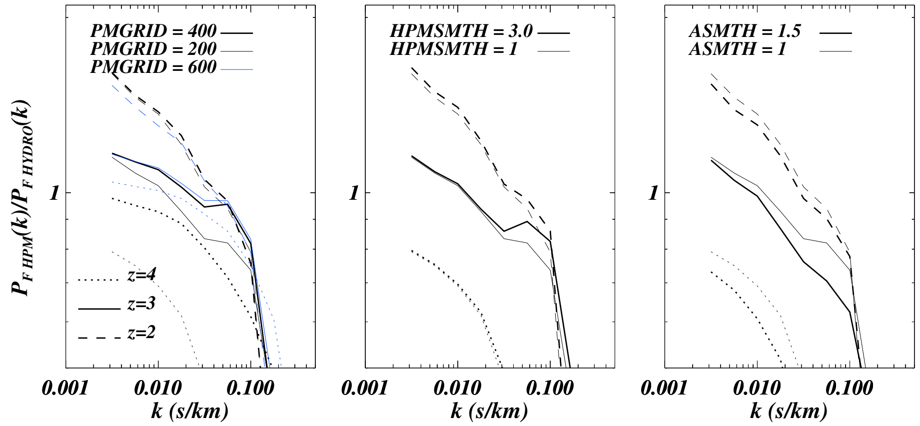

Figure 1: Ratio between the flux power spectrum of a full hydro simulations and a HPM simulation at three different redshifts and for different values of the parameters of the HPM method. The simulations are for $2x200^3$ gas + DM particles in a 15 h^{-1} comoving Mpc box at three different redshifts (z=2,3,4 - dashed, continuous, dotted line respectively) and for three different values of the PM grid (left panel) of the HPM smoothing (the pressure field smoothing, center) and of the ASMTH smoothing (the force smoothing, right). The values are in units of the mesh cells.

to the smoothing of the HPM force in units of the mesh cells (we label this as A smoothing). This parameter should control the level of force anisotropies on the scale of the mesh grid. In Figure 1 we plot the ratio of 1D flux power spectra of different models and a ‘fiducial model’ in which the above three parameters are fixed to the following values: PMGRID = 200, A smoothing = 1 and HPM smoothing = 1.5. In the left panel we show the effect of the PMGRID by doubling its value (in blue we report the result for PMGRID=600). One can clearly see that for $z < 3$ the differences are usually less of 5% (note that the flux power spectra have not been scaled to the same mean flux) in the range $k < 0.03$ s/km, while for $z = 4$ the differences are of the order of 20% even at large scales. In the middle panel we explore the effect of doubling the value of the HPM smoothing parameter. The flux power spectrum appears to be not very sensitive to this statistics (differences of the order of $\sim 3\%$) for $k < 0.03$ (s/km), while at smaller scales the differences become larger. In the right panel we check for the effect of a different value of A smoothing and we set its value to 1.5. Here, again, the differences at large k are of the order of 5% for the $z = 3$ and $z = 2$ model, while is much larger for the higher redshift output (up to 20%). The conclusion of this section is that some caution is appropriate when using HPM simulations to interpret the data set.

3. Cosmological parameters

We combine the Lyman-α forest data to the WMAP data to infer cosmological parameters. The main results can be summarized here (see for a more detailed analysis [11]). The recovered cosmological parameters for the power spectrum amplitude and the spectral index are (1σ error bars): $\sigma_8 = 0.94 \pm 0.08$ and $n_s = 0.99 \pm 0.03$. The best fit model with a running spectral index has parameters $n_s = 0.959 \pm 0.036$ and $n_{run} = -0.033 \pm 0.025$. Thereby the data do not require a running of the spectral index. The other cosmological parameters values are $\tau = 0.157 \pm 0.068$,

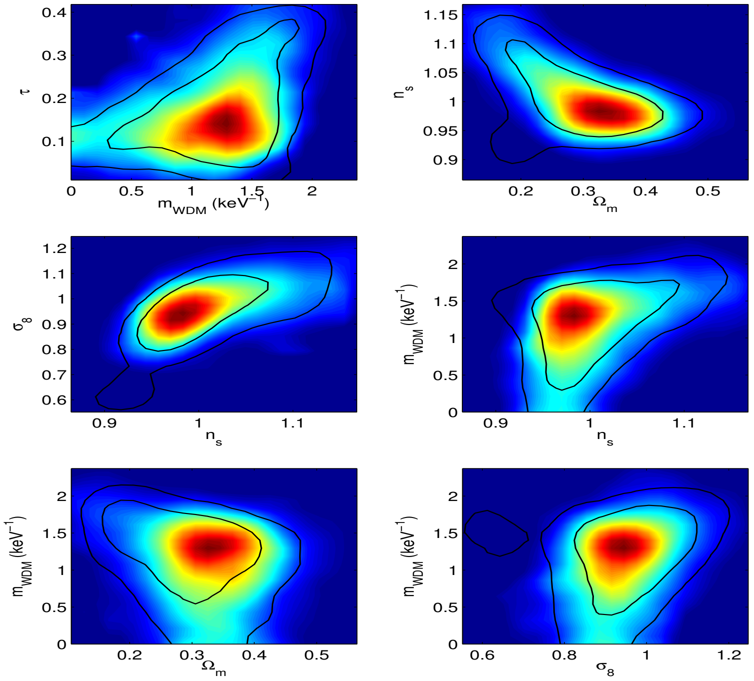

Figure 2: Likelihood plots for some cosmological parameters obtained with COSMOMC when combining the Lyman-α forest data to WMAP. The colors refer to the average likelihood while the lines are for the marginalized likelihood.

$h = 0.704 \pm 0.047$, $\Omega_b h^2 = 0.022 \pm 0.009$ and $\Omega_c h^2 = 0.124 \pm 0.013$. The implication for WDM (Warm Dark Matter) scenarios has been explored by [9]. There the main result is that for a WDM model the mass of a WDM particle has to be $m_{WDM} > 550$eV (2σ), while if the particle is a sterile neutrino this bound becomes $m_{WDM} > 2$keV (2σ).

References

[1] A. Lewis and S. Bridle, Phys. Rev. D **66**, 103511 (2002).

[2] Croft R.A.C., Weinberg D. H., Bolte M., Burles S., Hernquist L., Katz N.,Kirkman D., Ty tler D., 2002, ApJ, 581, 20

[3] Gnedin N.Y., Hamilton A.J.S., 2002, MNRAS, 334, 107

[4] Gnedin N.Y., Hui 1998, MNRAS, 296, 44

[5] Kim T.-S., Viel M., Haehnelt M.G., Carswell R.F., Cristiani S., 2004, MNRAS, 347, 355 (K04)

[6] McDonald P. et al., 2004, submitted to ApJ, astro-ph/0405013

[7] Springel V., Yoshida N., White S.D.M., 2001, NewA, 6, 79

[8] Viel et al., 2004, proceedings of the XXXIXth Rencontres de Moriond on "Exploring the Universe", La Thuile, (Italy), astro-ph/0405584

[9] Viel M., Lesgourgues J., et al., 2004, in preparation

[10] Viel M., Haehnelt M.G., Springel V., 2004, MNRAS, 354, 684

[11] Viel M., Weller J., Haehnelt M.G., 2004, MNRAS, 355, 23L