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Cutoff in the Lyman-α forest power spectrum: Warm IGM or warm dark matter?

Antonella Garzilli [a,*], Alexey Boyarsky [a], Oleg Ruchayskiy [b]

[a] Lorentz Institute, Leiden University, Niels Bohrweg 2, Leiden, NL-2333 CA, The Netherlands
[b] Discovery Center, Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark

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ABSTRACT

We re-analyse high redshift and high resolution Lyman-α forest spectra considered in [1], seeking to constrain the properties of warm dark matter particles. Compared to this previous work, we consider a wider range of thermal histories of the intergalactic medium. We find that both warm and cold dark matter models can explain the cut-off observed in the flux power spectra of high-resolution observations equally well. This implies, however, very different thermal histories and underlying reionization models. We discuss how to remove this degeneracy.

1. Introduction

Dark matter is a central ingredient of the current standard cosmological model. It drives the formation of structures, and explains the masses of galaxies and galaxy clusters. If dark matter is made of particles, these yet-unseen particles should have been created in the early Universe long before the recombination epoch. If such particles were relativistic at early times, they would stream out from overdense regions, smoothing out primordial density fluctuations. The signature of such *warm dark matter* (WDM) scenario would be the suppression of the matter power spectrum at scales below their free-streaming horizon. From cosmological data at large scales (CMB and galaxy surveys) we know that such a suppression should be sought at comoving scales well below a Mpc.

The Lyman-α forest has been used for measuring the matter power spectrum at such scales [2–4]. In previous works only upper bounds had been reported on the mass of the thermal relic [5–10]. However, while in the SDSS spectra there is no cut-off in the transmitted flux power spectrum, there is a cut-off in the high resolution spectra, for example [4,11,7]. Recently [1] has observed the cut-off of the flux power spectrum at scales $k \sim 0.03$ s/km and redshifts $z = 4.2$–5.4.

However, the Lyman-α forest method measures not the distribution of dark matter itself, but only the neutral hydrogen density as a proxy for the overall matter density. The process of reionization heats the hydrogen and prevents it from clustering at small scales at the redshifts in question [12]. Therefore, the observed hydrogen distribution eventually stops to follow the DM distribution. Indeed, it was demonstrated in [1] that within ΛCDM cosmology there exists a suitable thermal history of intergalactic medium (IGM) that is consistent with the observed cutoff. This does not mean, however, that this scenario is realized in nature.

In this Letter we investigate this issue in depth. We ask whether *the cutoff in the flux power spectrum can be attributed to the suppression of small scales with warm dark matter* and what this means for the thermal history of IGM. To this end we reanalyze the data used in [1]. We use *the same* suite of hydrodynamical simulations of the IGM evolution with cold and warm dark matter models as in [1] and demonstrate that the data is described equally well by the model, where flux power spectrum suppression is mainly due to WDM.

2. Data and model

The data set is constituted by 25 high-resolution quasar spectra, in the redshift interval $4.48 \le z_{\rm QSO} \le 6.42$. The spectra were taken with the Keck High Resolution Echelle Spectrometer (HIRES) and the Magellan Inamory Kyocera Echelle (MIKE) spectrograph on the Magellan clay telescope. The QSO spectra are divided into four

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* Corresponding author.
E-mail address: garzilli@lorentz.leidenuniv.nl (A. Garzilli).

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redshift bins centered on: $z = 4.2, 4.6, 5.0, 5.4$. The resulting range of wave-numbers probed by this dataset is $k = 0.005–0.08$ s/km.

At these redshifts, the IGM is thought to be in a highly ionized state, being photo-ionized and photo-heated by early sources. Both the WDM cosmology and the IGM temperature affect the amount of flux power spectrum at small scales through three distinct physical mechanisms: (1) a suppression in the initial matter power spectrum; (2) Jeans broadening; and (3) Doppler broadening of the absorption lines [12–17]. The first mechanism is cosmological, the latter two are astrophysical. The Doppler broadening is a one dimensional smoothing effect that originates from observing the hot IGM along a line of sight. The Maxwellian distribution of velocities in the gas then leads to the broadening effect. The Jeans broadening smooths the three-dimensional underlying gas distribution relative to the dark matter.

The level of ionization is captured by *the effective optical depth*, $\tau_{\rm eff}$, that is computed from the mean flux, $\langle F\rangle$, through the relation $\langle F(z)\rangle = \exp(-\tau_{\rm eff}(z))$. Because the IGM spans a wide range of density, describing the IGM temperature may be complicated in principle. But, assuming that the IGM is heated by photo-heating, the temperature of the IGM follows a simple power-law *temperature-density relation* [18]:

$$T(\delta) = T_0(z)\big(1+\delta\big)^{\gamma(z)-1}, \qquad (1)$$

where $\delta = \delta\rho_{\rm m}/\bar{\rho}_{\rm m}$ is the matter overdensity and $T_0(z)$, $\gamma(z)$ are unknown functions of redshift. The results of Ref. [1] are based on single power-law parametrizations, $T_0(z)$ and $\gamma(z)$. In this letter we let the parameters of the IGM thermal state vary independently in each redshift bin, with a total of 8 parameters describing the IGM thermal state ($T_0(z_i)$ and $\gamma(z_i)$ in 4 distinct redshift intervals).[1]

We want to point out that T_0 and γ are not varied in post-processing. The original work of [1] considered 9 simulation runs with distinct thermal histories for each cosmology considered. The different thermal histories are realized by changing the photo-heating function in the simulations. The resulting values of T_0 and γ are approximately distributed on a regular grid. In [1] the effect of Jeans smoothing is accounted by considering two additional simulation runs, where the time at which the ultraviolet background is switched on, $z_{\rm reion}$, is varied. We caution the reader that the resulting constraints on $z_{\rm reion}$ must not be intended as a measurement of the time of reionization, because this depends on the details of the implementation of the ultraviolet background. Instead, varying $z_{\rm reion}$ must be considered as a way to account for the unknown level of Jeans smoothing. Finally, as in [1], we allow the effective optical depth vary independently in each redshift bin, $\tau_{\rm eff}[z_i]$.

It should be noted that this interpolation scheme between simulations with different temperatures may also vary the amount of Jeans broadening (also known as the "filtering scale"). While the degeneracy between the WDM cosmologies and the Doppler smoothing has been extensively considered in the literature, the degeneracy between Jeans smoothing and WDM cosmology has not been considered in depth so far. In particular this has not been done for the suite of simulations in the original work [1] on which we base our analysis. We leave the study of the degeneracy between the Jeans smoothing and WDM for future work.

The results also depend on the cosmological parameters n_s, Ω_M, σ_8, H_0. However the small scale Lyman-α data by itself does not sufficiently constrain the cosmological parameters. Therefore, in the final likelihood function for these parameters we used best fit Planck values [19] with Gaussian priors (as in [1]), $\Omega_M = 0.315 \pm 0.017$, $\sigma_8 = 0.829 \pm 0.013$, $n_s = 0.9603 \pm 0.0073$.

Table 1
Parameter estimation from Bayesian analysis. We show the 1-σ and 2-σ confidence intervals. We only show the parameters that are constrained at 1 or 2-σ level.

parameter	mean	1-σ	2-σ
H_0 [km/s/Mpc]	63	< 67	–
$m_{\rm WDM}$ [keV]	3.9	[143, 2.3]	> 2.1
$T_0(z=4.2)$ [10^3 K]	10.6	[9.4, 11.8]	[8.3, 12.9]
$T_0(z=4.6)$ [10^3 K]	9.8	[8.6, 11.1]	[7.5, 12.2]
$T_0(z=5.0)$ [10^3 K]	4.0	[2.0, 5.6]	< 6.9
$T_0(z=5.4)$ [10^3 K]	3.8	< 4.5	< 8.2
$\tau_{\rm eff}(z=4.2)$	1.12	[1.05, 1.19]	[1.00, 1.25]
$\tau_{\rm eff}(z=4.6)$	1.30	[1.21, 1.39]	[1.15, 1.47]
$\tau_{\rm eff}(z=5.0)$	1.88	[1.74, 2.00]	[1.64, 2.13]
$\tau_{\rm eff}(z=5.4)$	2.91	[2.69, 3.10]	[2.54, 3.31]
$\gamma(z=4.2)$	1.3	> 1.1	–
$\gamma(z=5.4)$	1.3	> 1.1	–

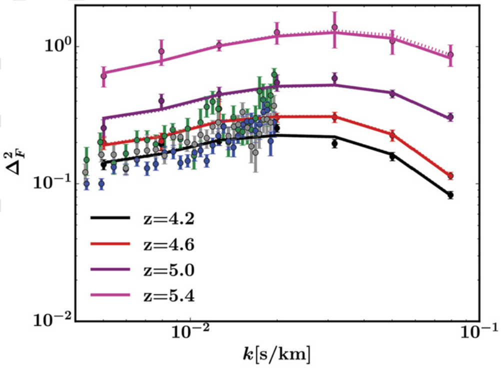

Fig. 1. Measured flux power spectrum in dimensionless units, $\Delta_F^2(k) = P_F(k) \times k/\pi$, compared with the theoretical model with the best-fitting values of the astrophysical and cosmological parameters for WDM and CDM cosmologies. The solid refer the best-fitting values for WDM cosmology. The dotted lines refer to the best-fitting case for CDM cosmology. These best-fitting models largely overlap, except at the highest redshift and on the smallest scales. The blue, gray and green points are SDSS-III/BOSS DR9 data for $z = 4.0$, $z = 4.2$ and $z = 4.4$ from [20]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

In Table 1 we give the result of the parameter estimation. Fig. 1 shows the theoretical flux power spectrum for the mean values of the parameters, compared with the MIKE and HIRES data used in this analysis. In order to clarify the effect of different thermal histories on our constraints, we show the effect of changing the thermal parameters (T_0 and γ) and ionization parameters ($\tau_{\rm eff}$) and the mass of the thermal relic ($1/m_{\rm wdm}$) in Fig. 2, analogous to Figs. 5 and 6 of [1].

In Fig. 3 we show the 2D confidence regions between $m_{\rm wdm}$, and $T_0 \equiv T(\delta = 0)$ (marginalizing over the other parameters). We see that at redshifts $z = 4.2$, 4.6 there is no degeneracy and an IGM temperature $T_0 \sim 10^4$ K is needed to explain the observed flux power spectrum independently of $m_{\rm wdm}$. If dark matter is "too warm" ($m_{\rm wdm} < 1.5$ keV) it produces too sharp of a cut-off in the power spectrum and is inconsistent with the data.

At the $z = 5.0$ bin the situation is different. For the masses $m_{\rm wdm} \sim 2.2–3.3$ keV even very low temperatures $T_0 \lesssim 2500$ K are consistent with the data. In this case the cutoff in the flux power spectrum is explained by WDM rather than by the temperature. The situation is analogous at $z = 5.4$. Table 1 summarizes the parameter estimation.

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[1] Ref. [1] also performed such a "binned analysis", see the detailed comparison below.

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