

How Cold Is Cold Dark Matter? Small-Scales Constraints from the Flux Power Spectrum of the High-Redshift Lyman- α Forest

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We present constraints on the mass of warm dark matter (WDM) particles derived from the Lyman- α flux power spectrum of 55 high-resolution HIRES spectra at $2.0 < z < 6.4$. From the HIRES spectra, we obtain a lower limit of $m_{\text{WDM}} \geq 1.2$ keV (2σ) if the WDM consists of early decoupled thermal relics and $m_{\text{WDM}} \geq 5.6$ keV (2σ) for sterile neutrinos. Adding the Sloan Digital Sky Survey Lyman- α flux power spectrum, we get $m_{\text{WDM}} \geq 4$ keV and $m_{\text{WDM}} \geq 28$ keV (2σ) for thermal relics and sterile neutrinos. These results improve previous constraints by a factor of 2.

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Introduction.—Warm dark matter (WDM) has been advocated in order to solve the apparent problems of standard cold dark matter scenarios at small scales (e.g., [1]), most notably the excess of the number of galactic satellites, the cusiness and high (phase space) density of galactic cores, and the large number of galaxies filling voids. These and other problems could be alleviated if the dark matter (DM) is made of warm instead of cold particles. The main effect of the larger thermal velocities would be to suppress structures below the Mpc scale. However, poorly understood astrophysical processes governed by the baryonic component of galaxies, along with numerical, observational, and theoretical aspects [2–4], have also to be considered in order to reliably model the spatial distribution of dark matter at small scales. The Lyman- α absorption produced by the intervening neutral hydrogen in the spectra of distant quasars (QSOs), the so-called Lyman- α forest, is a powerful tool for constraining dark matter properties. It probes the matter power spectrum in the mildly nonlinear regime over a large range of redshifts ($z = 2$ –6) down to small scales (1 – $80h^{-1}$ Mpc) [5]. In previous work, Ref. [6] used two samples of high-resolution QSO Lyman- α forest spectra at $z \sim 2.5$ to set a lower limit of 550 eV for the mass of a thermal warm dark matter candidate (2 keV in the case of a sterile neutrino). More recently, Refs. [7,8], using the Sloan Digital Sky Survey (SDSS) QSO data set at higher redshift and with different methods significantly improved this limit by a factor of ~ 4 . Among the possible WDM candidates, the most promising appears to be a sterile neutrino with a mass in the keV range, which could be part of many particle physics models with grand unification (e.g., [9]). Because of a nonzero mixing angle between active and sterile flavor states, x-ray flux observations can also constrain the abundance and decay rate of such DM particles (e.g., [10]). The constraints from

Lyman- α forest data and those from the x-ray fluxes of astrophysical objects together put considerable tension on the parameter space still allowed for a sterile neutrino particle with the phase-space distribution proposed by Dodelson and Widrow (DW) [11], although other non-standard scenarios must be explored [12]. Here, we use a new large set of high-resolution Lyman- α forest spectra in order to improve limits on the mass of a WDM particle.

Data sets.—We use two different data sets: (i) the high-resolution HIRES data set presented in [13], which consists of 55 QSOs spanning the range $2.0 < z < 6.4$; (ii) the SDSS Lyman- α forest data of McDonald *et al.* [14], which consists of 3035 quasar spectra at low resolution ($R \sim 2000$) and low signal to noise spanning a wide range of redshifts ($z = 2.2$ –4.2). We have calculated the flux power spectrum from the HIRES data for four redshift bins with median redshifts $z = 2.5, 3.5, 4.5, 5.5$, and 20 logarithmically spaced bins in wave numbers spanning $0.002 < k$ (s/km) < 0.287 . Note, however, that we use only 12 bins in the range $0.003 < k$ (s/km) < 0.077 for our present analysis (a total of 48 points). The total redshift path of the HIRES sample is $\Delta z = 29.1$. The redshift path of the lowest redshift bin is comparable to that of the LUQAS sample of high-resolution spectra ($\Delta z = 13$) which we used previously [15], while the other three redshift bins have smaller redshift paths of approximately equal length. Note that our previous work based on the LUQAS sample used only the range $0.003 < k$ (s/km) < 0.03 . For the SDSS data set we use 132 flux power spectrum measurements $P_F(\mathbf{k}, z)$ that span 11 redshift bins and 12 k -wave numbers in the range $0.00141 < k$ (s/km) < 0.01778 (roughly corresponding to scales of 5–50 comoving Mpc). Since the HIRES spectra have higher resolution than the SDSS spectra we can use the flux power spectrum obtained from the HIRES data to extend our analysis to

smaller scales. We have removed the damped Lyman- α systems (DLAs) from the observed HIRES spectra but decided not to attempt to remove the metal lines. We rely on the measurement of the contribution of metal absorption to the flux power spectrum at $z = 2.13$ by [15]. We use this estimate to correct our measurement of the flux power spectrum at $z = 2.5$ and apply a smaller correction for the measurement at $z = 3.5$. For the two highest redshift bins we do not apply any correction to our measurements of the flux power spectrum as the metal contribution should be very small at these redshifts. The contribution of the metal absorption to the flux power spectrum at the scales considered here depends only weakly on wave number and is degenerate with the value of the assumed effective optical depth [16]. Marginalizing over the observed range of the effective optical depth in our parameter analysis will (implicitly) account for a possibly different contribution to the flux power spectrum than we have assumed. We have tested the effect of continuum fitting errors by calculating the flux power spectrum of each observed Lyman- α forest spectrum at $z > 4$ for 100 continuum fit realizations where we have adjusted the continuum level of the observed spectra randomly by a factor $1 + \epsilon$ with ϵ in the range $[-0.1, 0.1]$. This should be a reasonable estimate of the effect of continuum fitting errors at high redshift. At smaller redshifts the continuum fitting errors should be below 4%. The variations of the flux power for these 100 realizations lies well within the statistical errors of the flux power spectrum of our full sample and estimates differ by less than 5% from the case with $\epsilon = 0$. We have decided not to try to explicitly account for continuum fitting errors. The covariance matrix of the flux power spectrum for the HIRES data set was calculated with a jackknife estimator.

Method.—Modeling the flux power spectrum of the Lyman- α forest for given cosmological parameters down to the required small scales is not straightforward, and accurate numerical supercomputer simulations are required. Here, we model the flux power spectrum with full hydrodynamical simulations using a second order Taylor expansion around a best fitting model. This allows us to obtain a reasonably accurate prediction of the flux power spectrum for a large range of parameters, based on a moderate number of simulations [17]. The method was first introduced in Ref. [16], and we refer to this work for further details. Note that while in Ref. [16] the prediction for the flux power was made using a first-order Taylor expansion, here the expansion is made to second order; i.e., the parameter dependence of the flux power spectrum $P_F(\mathbf{k}, z, \mathbf{p})$ is locally described by a second-order polynomial function for any redshift z , set of wave numbers \mathbf{k} , and cosmological or astrophysical parameters \mathbf{p} . In this Letter, we use as input in the hydrodynamical simulations a linear matter power spectrum as in [6,18], and we assume that the sterile neutrino phase-space distribution is equal to that of active neutrinos multiplied by a suppression factor.

Deviations from this first-order approximation were computed in [19], but typically these corrections lower the bounds on the warm dark matter mass by only 10% [7].

For our best estimate of the flux power spectrum of our fiducial model we used a simulation of a box of length $60h^{-1}$ comoving Mpc with 2×400^3 gas and cold DM particles (gravitational softening $2.5h^{-1}$ kpc). The fiducial flux power spectrum has been corrected for box size and resolution effects. Note that resolution corrections are large at high redshift and redshift or scale dependent: they reach 50% (300%) at the smallest scales at $z = 4.5$ ($z = 5.5$). We performed a number of additional hydrodynamical simulations with a box size of $20h^{-1}$ comoving Mpc and 2×256^3 gas and DM particles (gravitational softening $1h^{-1}$ kpc) for WDM models with a (thermal) warm dark matter of mass $m_{\text{WDM}} = 1, 4, 8$ keV to calculate the derivatives of the flux power spectrum with respect to changes of the WDM particle mass and other astrophysical and cosmological parameters of interest in this analysis. We have checked the convergence of the flux power spectrum on the relevant scales using several additional simulations (following the approach of [20]) with 2×256^3 gas and DM particles and box sizes of $10h^{-1}$ Mpc (gravitational softening $2h^{-1}$ kpc), $5h^{-1}$ Mpc (gravitational softening $1h^{-1}$ kpc) and a $5h^{-1}$ Mpc simulation with 2×448^3 (gravitational softening $0.27h^{-1}$ kpc).

We then used a modified version of the code COSMOMC [21] to derive parameter likelihoods from the HIRES and SDSS Lyman- α data. For the HIRES data, we had a set of 18 parameters: 7 cosmological parameters; 6 parameters describing the thermal state of the intergalactic medium: parametrization of the gas temperature-gas density relation $T = T_0(z)(1 + \delta)^{\gamma(z)-1}$ as a broken power law at $z = 3$ with the two astrophysical parameters $T_0^A(z)$ and $\gamma^A(z)$ describing the amplitude; 4 parameters describing the evolution of the effective optical depth with redshift (slope τ_{eff}^S and amplitude τ_{eff}^A at $z = 3$ and $z = 5$) since a single power law has been shown to be a poor approximation over this wide redshift range (see [13]); 1 parameter describing the spatial fluctuations of the ultraviolet (UV) background f_{UV} .

In estimating the effect of UV fluctuations on the flux power we adopt a conservative approach and consider the model of [22], where the UV fluctuation has a large impact on the flux. The model assumes that the UV background and its spatial fluctuations are produced by Lyman-Break galaxies and QSOs and uses as input the QSOs and Lyman-Break luminosity functions at $z = 3.5, 4, 5$, and 6. At $z = 5.5$ the flux power in the model with UV fluctuations is larger by 4% at the largest scales increasing to 20% at $k = 0.2$ s/km (not included in the analysis), compared to the case without UV fluctuations. At $z = 4$ and $z = 3.5$ the only differences arise at scales $k > 0.3$ s/km, which are not considered in the present analysis. Further details on the UV model can be found in [22] (but see other ap-

proaches [23]). We parametrize the effect of UV fluctuations on the flux power with a multiplicative factor f_{UV} constrained to be in the range $[0, 1]$. For the SDSS data we have used a total of 28 parameters: 15 parameters used for the HIRES spectra (without f_{UV} and the 2 parameters describing the effective optical depth evolution at $z = 5$) plus 13 noise-related parameters: 1 parameter which accounts for the contribution of DLAs and 12 parameters modeling the resolution and the noise properties of the SDSS data set (see [24]). We do not address the role of different reionization scenarios on the flux power. To do this self-consistently would require radiative transfer simulations beyond present numerical capabilities, and the effect of the reionization history should be subdominant and degenerate with the thermal state of the gas. In computing the likelihood a crucial input is the covariance matrix of the two data sets. The covariance matrix of the SDSS flux power is provided by the authors of [14]. We found the covariance matrix of our HIRES data set to be rather noisy (especially at high redshift), preventing a reliable inversion. To overcome this problem we use the suggestion of [25]. We regularize the observed covariance matrix using the correlation coefficients as estimated from the simulated spectra, $\text{cov}_d(i, j) = r_s(i, j)\sqrt{\text{cov}_d(i, i)\text{cov}_d(j, j)}$ with $r_s(i, j) = \text{cov}_s(i, j)/\sqrt{\text{cov}_s(i, i)\text{cov}_s(j, j)}$, where cov_s and cov_d are the covariance matrices of the observed and simulated spectra, respectively. Note that this procedure implicitly assumes that observed and simulated data have similar covariance properties. We have applied moderate priors to the thermal history to mimic the observed thermal evolution as in [16] and *a priori* on the Hubble constant (72 ± 8 km/s/Mpc), but note that the final results for the mass constraint are not affected by these priors.

Results.—In Fig. 1 we show the best fit model for the HIRES data set (continuous curve, $m_{WDM} = 8$ keV) and a model with a smaller mass for the thermal WDM particle (dashed line, $m_{WDM} = 2.5$ keV). The constraining power of the small scales at high redshift is immediately evident. The χ^2 value of the best fit model is ~ 40 for 36 d.o.f., and with a probability of 16% this is a reasonable fit. As noted in Ref. [7] at high redshifts, the mean flux level is lower and the flux power spectrum is closer to the linear prediction making the flux power data points very sensitive to the free-streaming effect of WDM. We confirm that there are no strong degeneracies between m_{WDM} and the other parameters, demonstrating that the effect of a WDM particle on the Lyman- α flux power is unique, and that the other cosmological and astrophysical parameters considered here cannot mimic its effect.

The 2σ lower limits for the mass of the warm dark matter particle are 1.2 keV, 2.3 keV, and 4 keV, for the HIRES, SDSS, and SDSS + HIRES data sets, respectively. The corresponding limits for DW sterile neutrino are 5.6, 13, and 28 keV (see [6] for how the masses are related for the two cases). The χ^2 of the best fit model of the joint

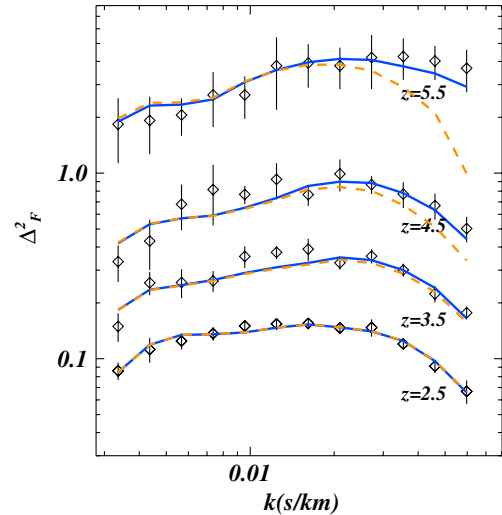


FIG. 1 (color online). Flux power spectrum of the HIRES data set at different redshifts and best fit models (solid curve) with $m_{WDM} = 8$ keV and a model with $m_{WDM} = 2.5$ keV (dashed curve).

analysis ~ 198 for 170 d.o.f. which should occur in 7% of the cases. The sample of HIRES spectra improves our previous constraint from high-resolution spectra obtained from the LUQAS sample by a factor of 2. Dropping the highest redshift bin ($z = 5.5$) weakens the limit to 0.8 keV (3.3 keV) for the mass of a thermal (sterile) neutrino. The SDSS data alone is still more constraining than the HIRES data alone, due to the smaller statistical errors of the SDSS flux power spectrum and the finer coverage of a large redshift range which helps to break some of the degeneracies between astrophysical and cosmological parameters. Combining the SDSS data and the HIRES results in an overall improvement of a factor of ~ 2 and gives the strongest limits on the mass of WDM particles from Lyman- α forest data to date. In Table I we summarize the constraints obtained for the most relevant astrophysical and cosmological parameters (1σ) for our analysis of the

TABLE I. Marginalized estimates (1σ errors).

Parameter	HIRES + SDSS	HIRES
n	0.97 ± 0.03	0.97 ± 0.05
σ_8	0.96 ± 0.07	1.0 ± 0.2
Ω_m	0.25 ± 0.03	0.28 ± 0.09
$\tau_{\text{eff}}^A(z = 3)$	0.35 ± 0.01	0.33 ± 0.03
$\tau_{\text{eff}}^S(z = 3)$	3.17 ± 0.07	3.02 ± 0.37
$\gamma^A(z = 3)$	1.44 ± 0.12	1.54 ± 0.33
$\tau_{\text{eff}}^A(z = 5)$	1.53 ± 0.09	1.54 ± 0.19
$\tau_{\text{eff}}^S(z = 5)$	4.77 ± 0.44	4.92 ± 0.5
$T_0(z = 3)(10^4)$ K	2.23 ± 0.30	1.54 ± 0.34
f_{UV}	0.65 ± 0.25	0.58 ± 0.28
$1/m_{WDM}$ (keV $^{-1}$)	0.09 ± 0.07	0.44 ± 0.22

HIRES only and HIRES + SDSS data sets. We note that, similar to [6], there is a preference for a nonzero $1/m_{\text{WDM}}$ value which is at present not statistically significant (less than 2σ). The data also prefer models with nonzero UV background fluctuations.

Discussion.—We have used a sample of high-resolution Lyman- α forest spectra which is sensitive to the suppression in the matter power spectrum at small scales caused by the free streaming of WDM particles. We have modeled the observed flux power spectrum by using high-resolution hydrodynamical simulations that incorporate the relevant physical processes. We also improved previous analyses by extending the parameter space, performing a Taylor expansion order of the flux power spectrum in the cosmological and astrophysical parameters to second instead of first order, and including UV fluctuations that should be important at the high redshifts considered here. We confirm that the observed Lyman- α forest flux power spectrum at small scales and high redshifts requires significantly more power on small scales than provided by the models that try to reproduce the cores of dwarf galaxies with a warm dark matter particle by [4]. We improve previous lower limits on the mass of warm dark particles of [7] by a factor of 2 and those of [8] by a factor of 3. This further decreases the rather small gap between the limits on the mass of DW sterile neutrinos from Lyman- α forest data and those on mass and mixing angle from the diffuse x-ray background (e.g., [26]). We note that all the limits quoted here refer to the thermal production mechanism for sterile neutrinos and could be potentially 10%–20% weaker in the case of nonthermality [26].

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