# Can Sterile Neutrinos Be Ruled Out as Warm Dark Matter Candidates?

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(Received 1 June 2006; revised manuscript received 13 July 2006; published 17 August 2006)

We present constraints on the mass of warm dark matter (WDM) particles from a combined analysis of the matter power spectrum inferred from the Sloan Digital Sky Survey Lyman-$\alpha$ flux power spectrum at $2.2 < z < 4.2$, cosmic microwave background data, and the galaxy power spectrum. We obtain a lower limit of $m_{\rm WDM} \gtrsim 10$ keV ($2\sigma$) if the WDM consists of sterile neutrinos and $m_{\rm WDM} \gtrsim 2$ keV ($2\sigma$) for early decoupled thermal relics. If we combine this bound with the constraint derived from x-ray flux observations of the Coma cluster, we find that the allowed sterile neutrino mass is $\sim$10 keV (in the standard production scenario). Adding constraints based on x-ray fluxes from the Andromeda galaxy, we find that dark matter particles cannot be sterile neutrinos, unless they are produced by a nonstandard mechanism (resonant oscillations, coupling with the inflaton) or get diluted by a large entropy release.

DOI: 10.1103/PhysRevLett.97.071301 PACS numbers: 95.35.+d, 14.60.Pq, 14.60.St, 98.80.Es

*Introduction.*—Warm dark matter (WDM) has been advocated in order to solve some apparent problems of standard cold dark matter (CDM) scenarios at small scales (see [1] and references therein): namely, the excess of galactic satellites, the cuspy and high density of galactic cores, and the large number of galaxies filling voids. Moreover, recent observational results suggest that the shape of the Milky Way halo is spherical [2] and cannot easily be reproduced in CDM models. All these problems would be alleviated if the dark matter (DM) is made of warm particles, whose effect would be to suppress structures below the Mpc scale. Detailed studies of the dynamics of the Fornax dwarf spheroidal galaxy suggest shallower cores than predicted by numerical simulations of CDM models and put an upper limit on the mass of a putative WDM particle [3]. One of the most promising WDM candidates is a sterile (right-handed) neutrino with a mass in the keV range, which could explain the pulsar velocity kick [4], help in reionizing the Universe at high redshift [5], and emerging from many particle physics models with grand unification (e.g., [6,7]). Because of a small, nonzero mixing angle between active and sterile flavor states, x-ray flux observations can constrain the abundance and decay rate of such DM particles. The Lyman-$\alpha$ absorption caused by neutral hydrogen in the spectra of distant quasars is a powerful tool for constraining the mass of a WDM particle, since it probes the matter power spectrum over a large range of redshifts down to small scales. In a previous work [8], we used the Large Uves Quasar Absorption Sample (LUQAS) of high-resolution quasar absorption spectra to set a lower limit of 2 keV for the sterile neutrino mass. More recently, exploiting the small statistical errors and the large redshift range of the SDSS (Sloan Digital Sky Survey) Lyman-$\alpha$ forest data, Seljak *et al.* [9] found a lower limit of 14 keV. If the latter result is correct, a large fraction of the sterile neutrino parameter space can be ruled out (assuming that all the DM is made of sterile neutrinos); together with constraints from x-ray fluxes, this discards the possibility that DM consists of sterile neutrinos produced by nonresonant active-sterile neutrino oscillations [6] (still, they could be produced by resonant oscillations caused by a large leptonic asymmetry in the early Universe [10], considerably diluted by some large entropy release [9–11], or generated in a radically different manner, e.g., from their coupling with the inflaton [12]). More recently, some joint analyses of the SDSS flux power spectrum and the WMAP year three data [13] have been presented in Refs. [14,15] for standard $\Lambda$CDM models. The authors of Ref. [14] found some moderate disagreement between the inferred power spectrum amplitudes. Instead, from an independent analysis of the SDSS data [16], the authors of Ref. [15] find good agreement in their joint analysis. Here we extend the analysis of Ref. [16] to constrain the mass of WDM particles.

*Data sets and method.*—We use here the SDSS Lyman-$\alpha$ forest data of McDonald *et al.* [17], which consist of 3035 quasar spectra with low resolution ($R \sim 2000$) and a low signal-to-noise ratio spanning a wide range of redshifts ($z = 2.2$–$4.2$). The data set differs substantially from the LUQAS and C02 samples used [8], which contain mainly high-resolution, high signal-to-noise spectra at $z \sim 2.5$. More precisely, we use the 132 flux power spectrum measurements $P_F(k, z)$ that span 11 redshift bins and 12 $k$ wave numbers in the range $0.001\,41 < k$ (s/km) $< 0.017\,78$ (roughly corresponding to scales of 5–50 comoving Mpc). It is not straightforward to model the flux power spectrum of the Lyman-$\alpha$ forest for given cosmological parameters, and accurate numerical simulations are required. McDonald *et al.* [17] modeled the flux power spectrum using a large number of hydroparticle mesh simulations [18], calibrated with a few small-box-size full hydrodynamical simulations. Here, instead, we model the flux power spectrum using a Taylor expansion around a best fitting model: This allows a reasonably accurate prediction of the flux power spectrum for a large range of parameters, based on a moderate number of full hydrodynamical simulations [19]. The method was first introduced in Ref. [16], and we refer to this work for further details. The fiducial flux power spectrum has been extracted from simulations of 60 $h^{-1}$ comoving Mpc and $2 \times 400^3$ gas and DM particles (gravitational softening 2.5 $h^{-1}$ kpc) corrected for box size and resolution effects. We performed a number of additional hydrodynamical simulations with a box size of 20 $h^{-1}$ comoving Mpc and with $2 \times 256^3$ gas and DM particles (gravitational softening 1 $h^{-1}$ kpc) for a WDM model with a sterile neutrino of mass $m_s = 1, 4, 6.5$ keV, to calculate the flux power spectrum with respect to changes of the WDM particle mass. We have checked the convergence of the flux power spectrum on the scales of interest using additional simulations with $2 \times 256^3$ gas and DM particles and box sizes of 10 $h^{-1}$ Mpc (gravitational softening 0.5 $h^{-1}$ kpc). We then used a modified version of the code COSMOMC [20] to derive the parameter likelihoods from the combination of the Lyman-$\alpha$ data with cosmic microwave background (CMB) and galaxy power spectrum data, from WMAP [13], ACBAR [21], CBI [22], VSA [23], and 2dF [24]. In total, we used a set of 29 parameters: 7 cosmological parameters; 1 parameter describing a free light-to-mass bias for the 2dF galaxy power spectrum; 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 $z = 3$ in the two astrophysical parameters $T_0(z)$ and $\gamma(z)$]; 2 parameters describing the evolution of the effective optical depth with redshift (slope and amplitude at $z = 3$); 1 parameter which accounts for the contribution of damped Lyman-$\alpha$ systems; and 12 parameters modeling the resolution and the noise properties (see [25]). We applied moderate priors to the thermal history to mimic the observed thermal evolution as in Ref. [26], but the final results in terms of sterile neutrino mass are not affected by this.

*Results.*—We assume the Universe to be flat, with no tensor or neutrino mass contributions. We further note that adding CMB and large scale structure data has very little effect on the results for $m_s$, since the freestreaming effect of WDM particles is visible only on the scales probed by the Lyman-$\alpha$ flux power spectrum [27].

In Fig. 1, we show the two-dimensional marginalized likelihoods for the most important cosmological and as-

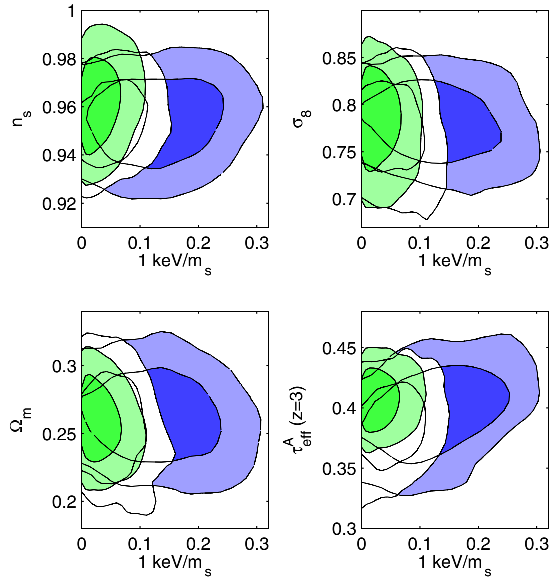


FIG. 1 (color online). Two-dimensional marginalized likelihoods (68% and 95% confidence limits) for $n_s$, $\sigma_8$, $\Omega_m$, and the effective optical depth at $z = 3$, using the SDSS data at $z \leq 4.2$ (left, green), $z \leq 3.6$ (middle, white), and $z \leq 3.2$ (right, blue).

trophysical parameters: $\sigma_8$, $n_s$, $\Omega_m$, and the effective optical depth amplitude measured at $z = 3$, $\tau^A_{\rm eff}$, all plotted as a function of the parameter $(1\ \text{keV})/m_s$. The constraints on $m_s$ get stronger for the Lyman-$\alpha$ forest data in the highest redshift bins. To demonstrate this, we plot the likelihood contours for data in three different redshift ranges: $z \leq 3.2$ (blue), $z \leq 3.6$ (white), and $z \leq 4.2$ (green), which is the whole data set. The constraints improve by a factor almost 3 (2) for the whole data set compared to the $z \leq 3.2$ ($z \leq 3.6$) subsamples. At high redshifts, the mean flux level is lower and the flux power spectrum is closer to the linear prediction, making the SDSS data points very sensitive to the freestreaming effect of WDM [9]. We find no strong degeneracies between $m_s$ and the other parameters, showing that the signature of a WDM particle in the Lyman-$\alpha$ flux power is very distinct and that other considered cosmological and astrophysical parameters cannot mimic its effect.

In Fig. 2, we show the one-dimensional marginalized likelihoods for $(1\ \text{keV})/m_s$ for several redshift ranges. The $2\sigma$ lower limits for the sterile neutrino mass are 3.9, 8.3, 8.1, 8.6, and 10.3 keV for $z \leq 3.2$, 3.4, 3.6, 3.8, and 4.2, respectively. The corresponding limits for an early decoupled thermal relic are 0.9, 1.7, 1.6, 1.7, and 1.9 keV (see [8] for the correspondence between the two cases). Also shown (dotted black line) is the constraint obtained in Ref. [8] using the LUQAS and C02 samples [26,30]. The SDSS data improve the constraint from the high-resolution data at $z \sim 2.5$ by a factor of 5. This is mainly due to the extension to higher redshift where the flux power spectrum is most sensitive to the effect of WDM. The smaller

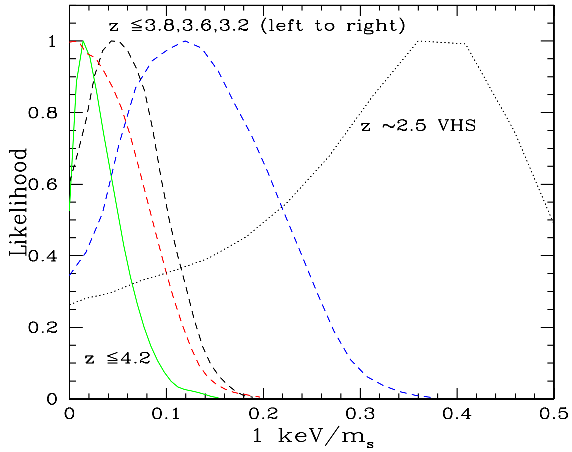


FIG. 2 (color online). One-dimensional marginalized likelihoods for the parameter $(1\ \mathrm{keV})/m_s$ for the SDSS Lyman-$\alpha$ data for the redshift ranges $z \leq 3.2$, 3.6, 3.8, and 4.2 and the Viel-Haehnelt-Springel (VHS) [26] data.

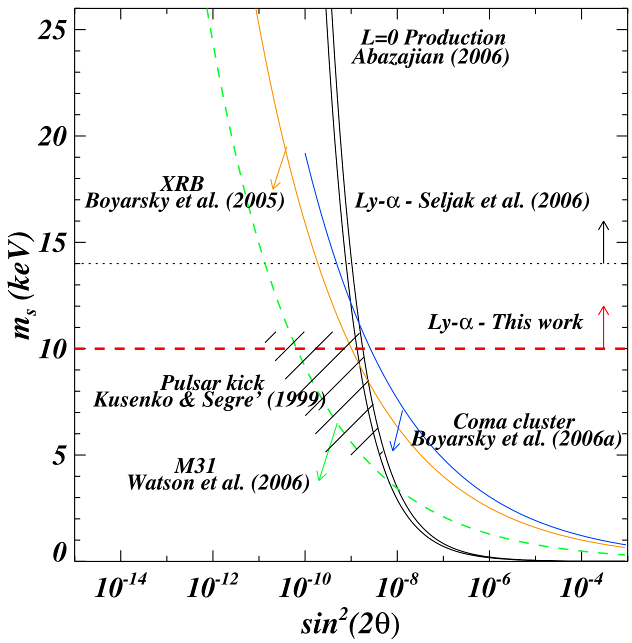


FIG. 3 (color online). This plot summarizes some of the parameter space constraints (at the 95% C.L.) for the sterile neutrino models, assuming that they constitute the dark matter. Limits are explained in the text.

statistical errors of the flux power spectrum and the coverage of a substantial range in redshift help to break some of the degeneracies between astrophysical and cosmological parameters and also contribute to the improvement. Our independent analysis confirms the limits found in Ref. [9] for the SDSS Lyman-$\alpha$ data and a small sample of high-resolution data that also extends to high redshift. Note, however, that our lower limit for essentially the same data set is $\sim$30% smaller [indeed, when using only SDSS Lyman-$\alpha$ data, Ref. [9] obtains $m_s > 12$ keV ($2\sigma$), which includes a 10% correction caused by the nonthermal momentum distribution of sterile neutrinos [29]: so, for the assumption made here, they would get $m_s > 13$ keV].

*Discussion.*—In Fig. 3, we summarize a number of current constraints for sterile neutrinos in the $(m_s, \sin^2 2\theta)$ plane, where $\theta$ is the vacuum $2 \times 2$ mixing angle between active and sterile neutrinos [31]. We show the limits obtained from different types of x-ray observations: x-ray diffuse background (XRB, orange curve [32]); flux from the Coma cluster (blue curve [33]); and finally, flux from the Andromeda galaxy (M31) halo (95% C.L., green dashed curve [34]). In addition, we plot the Lyman-$\alpha$ constraints obtained in this work (red dashed line) and in Ref. [9] (black dotted line). The region which can explain observed pulsar kicks [4] is shown as the hatched area. Finally, according to Ref. [7], sterile neutrinos produced from nonresonant oscillations (i.e., in the absence of significant leptonic asymmetry, $L = 0$) with a density $\Omega_{\mathrm{DM}} = 0.23 \pm 0.04$ should lie between the two black solid curves [the computation in Ref. [7] is based on simplifying assumptions concerning the QCD phase transition; the effect of hadronic corrections is currently under investigation [35] and could shift the allowed region in the $(m_s, \sin^2 2\theta)$ plane]. If all these constraints are correct, then there is no room for sterile neutrinos as DM candidates in the standard case. Models in which the decay of massive particles release some entropy and dilutes the dark matter by a factor $S$ can alleviate the tension between the Lyman-$\alpha$ and x-ray bounds [11], but a very large $S$ is needed [9,10]. As mentioned in the introduction, the sterile neutrino remains a viable WDM candidate for alternative production mechanisms (e.g., resonant oscillations with $L \neq 0$ or coupling with the inflaton). Recently, Ref. [10] questioned the results based on the Large Magellanic Cloud and the Milky Way because of uncertainties in modeling the dark matter distribution and also those based on detecting emission lines in cluster spectra [33], which used a fixed phenomenological model for x-ray emission (not shown in the figure but 30% more constraining than Ref. [32]). If these observational constraints are inaccurate, then a sterile neutrino mass in the range $9 \lesssim m_s\ (\mathrm{keV}) \lesssim 11.5$ and $\sin^2 2\theta \sim 2 \times 10^{-9}$ would be marginally consistent with the XRB bound and the Lyman-$\alpha$ forest data, but it is strongly excluded by the robust limit obtained by Ref. [34] (which is very conservative, since the bound quoted as $2\sigma$ by the authors requires a signal a few times larger than the background). The corresponding emission line for such a decaying sterile neutrino would be at $E \sim 5.5$ keV (close to, or possibly contaminated by, the recently discovered chromium line [36]). If, instead, all x-ray constraints are correct, but the two recent Lyman-$\alpha$ forest constraints are not accurate, then a mass of $m_s \sim 2$ keV is still possible and compatible with the robust and conservative lower limit from Ref. [8]. It would also satisfy the requirement from the dynamical analysis of the Fornax dwarf galaxies [3]. However, the latter possibility appears unlikely. Even if the highest redshift bins of the SDSS Lyman-$\alpha$ forest data were affected by not yet considered systematic errors, the analysis of the data with $z \leq 3.2$ still gives a lower limit of about $\sim$3.5 keV (see [34]). Appealing to an insufficient resolution of the hydrodynamical simulations would also not help, since an increase in resolution could only increase the flux power spectrum at small scales and raise the lower limits. We have, furthermore, checked explicitly that this is not the case and that other possible effects on the flux power have a different signature than that of WDM. A potentially big improvement on the quality of the constraints from Lyman-$\alpha$ forest data could be achieved by an analysis of a large set of high-redshift, high-resolution data to extend the measurement of the flux power spectrum at high redshift to smaller scales. This would, however, also require accurate modeling of the thermal history and the contribution of associated metal absorption to the small scale flux power spectrum.

Simulations were done at the United Kingdom Cosmology Supercomputer Center in Cambridge funded by PPARC, HEFCE, and Silicon Graphics/Cray Research. We thank A. Lewis for technical help and K. Abazajian, S. Hansen, A. Kusenko, J. Sanders, M. Shaposhnikov, and C. Watson for useful comments.

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