Can Sterile Neutrinos Be the Dark Matter?

Uroš Seljak,[2,1,3] Alexey Makarov,[1] Patrick McDonald,[4] and Hy Trac[5]

[1]*International Center for Theoretical Physics, Trieste, Italy*
[2]*Physics Department, Princeton University, Princeton, New Jersey 08544, USA*
[3]*Institute for Theoretical Physics, University of Zurich, Winterthur Strasse 190, 8057 Zurich, Switzerland*
[4]*Canadian Institute for Theoretical Astrophysics, University of Toronto, ON M5S 3H8, Canada*
[5]*Princeton University Observatory, Princeton, New Jersey 08544, USA*

(Received 20 February 2006; revised manuscript received 22 September 2006; published 8 November 2006)

We use the Ly-α forest power spectrum measured by the Sloan Digital Sky Survey and high-resolution spectroscopy observations in combination with cosmic microwave background and galaxy clustering constraints to place limits on a sterile neutrino as a dark matter candidate in the warm dark matter scenario. Such a neutrino would be created in the early Universe through mixing with an active neutrino and would suppress structure on scales smaller than its free-streaming scale. We ran a series of high-resolution hydrodynamic simulations with varying neutrino masses to describe the effect of a sterile neutrino on the Ly-α forest power spectrum. We find that the mass limit is $m_s > 13$ keV at 95% C.L. (9 keV at 99.9%), which is above the upper limit allowed by x-ray constraints, excluding this candidate from being all of the dark matter in this model.

DOI: 10.1103/PhysRevLett.97.191303 PACS numbers: 95.35.+d, 14.60.St, 98.62.Ra

One of the major unsolved mysteries in cosmology is the nature of the dark matter in the Universe. Observational evidence points towards cold dark matter (CDM), for which random velocities are negligible. Two of the leading particle physics candidates, the lightest supersymmetric partner and axions, both require extensions beyond the standard model. At the same time, neutrino experiments over the past decade have shown that neutrinos oscillate from one flavor to another, which is possible only if they have mass. Current data from atmospheric and solar neutrino experiments [1,2] are compatible with mixing between the three active neutrino families. Perhaps the simplest way to incorporate these neutrino phenomena into the standard model is to add right-handed neutrinos, just as for other fermions.

Given this extension of the standard model, it is natural to ask if these (almost) sterile right-handed neutrinos can also explain the dark matter [3]. At least two sterile neutrinos are required to explain the origin of neutrino mass and existence of different mass mixing scales in solar and atmospheric neutrinos, so in a model with three families of sterile neutrinos a third one can act as dark matter [4]. Such neutrinos free-stream and erase all fluctuations on scales smaller than the free-streaming length. This length is roughly proportional to the temperature and inversely proportional to the mass of neutrinos. Thus, if the neutrino mass is sufficiently high, or the temperature sufficiently low, then it acts just like CDM and can satisfy all of the observational constraints from structure formation. Current constraints require the neutrino mass to be above 1.8 keV [5,6]. This is below the 3–8 keV upper limits from the absence of detection of x-ray photons from radiative decays [7–11]. A massive neutrino in the keV range has also been suggested as a possible explanation for high pulsar velocities [12], and such a model can possibly explain baryon asymmetry in the Universe [13].

A sterile neutrino is not completely sterile if it is to provide the origin of mass for active neutrinos: It interacts with active neutrinos, and the interaction strength is parametrized by the active-sterile mixing angle Θ, which in this model is required to be very small, $\Theta < 10^{-4}$. In this regime, sterile neutrinos never reach thermal equilibrium [3]. In general, a sterile neutrino decays into active ones, but the lifetime can be well above the age of the Universe over a broad range of masses and mixing angles of interest, so it is effectively stable. If the interaction rate is energy-independent, then the momentum distribution of sterile neutrinos is simply a reduced version of the distribution of active neutrinos [3]. In practice, the interaction rate is not constant over the range of masses of interest, because at temperatures above the QCD transition more interaction channels become available [8,14,15]. In this Letter, we use the latest calculation [8], which, however, has only a minor effect relative to the constant interaction rate, reducing the derived mass limits by about 10% [16].

For keV masses of interest, the corresponding free-streaming length is of the order of a megaparsec (Mpc) and below. Distinguishing between cold and warm dark matter thus requires a sensitive probe of linear fluctuations on small scales, but nonlinear evolution erases the initial conditions on these scales today. Of the current tracers of density fluctuations, the one that is most suitable for warm dark matter (WDM) is the Ly-α forest [17]. It is measured from the absorption observed in quasar spectra by neutral hydrogen in the intergalactic medium and has been shown to accurately trace the dark matter distribution [18]. It probes fluctuations down to sub-Mpc scales at redshifts between 2 and 4, so nonlinear evolution, while not negligible, has not erased all of the primordial information.

Current WDM constraints from the Ly-α forest [5] do not include the latest measurements of the Ly-α forest from the Sloan Digital Sky Survey (SDSS) [19,20]. The goal of this Letter is to derive new limits by incorporating these observational constraints and combining them with a series of new hydrodynamic simulations which accurately describe the effect of a massive neutrino on the Ly-α forest.

The linear theory calculations of WDM using CMBFAST [22] result in the matter power spectra shown, relative to CDM, in the upper left panel in Fig. 1. We plot the ratio of WDM to CDM power for $m_\nu = 6.5$, 10, 14, and 20 keV. One can see the suppression of power on scales smaller than the free-streaming length, which depends on the neutrino mass. In addition to the usual 3D power spectrum, we also plot the corresponding 1D projection, which is more relevant for the comparison to the 1D Ly-α forest observations. In 1D projection, the suppression is evident at a smaller wave vector than the corresponding 3D case. While for $m_\nu > 10$ keV there is hardly any effect for $k < 5$ h/Mpc in 3D (see also the relevant figures in [5,6]), the corresponding 1D power spectrum shows more of an effect because small scale modes in 3D are projected to large scale modes in 1D. For example, for $m_\nu = 20$ keV there is essentially no effect in 3D for $k < 3$ h/Mpc, and even at $k = 5$ h/Mpc the power suppression is only 2%. SDSS measurements of the flux power in 1D do not extend above 2 h/Mpc, and high-resolution spectra are reliable up to 5 h/Mpc. So if one were interpreting them as measuring 3D power, then it would be very difficult to detect neutrino masses in this mass range. However, the corresponding 1D case in Fig. 1 shows a 3% power suppression at 2 h/Mpc and 15% at 5 h/Mpc. This rapidly increases with declining mass, so that for a 6.5 keV neutrino the power suppression is 15% at $k = 2$ h/Mpc and a factor of 2 at $k = 5$ h/Mpc.

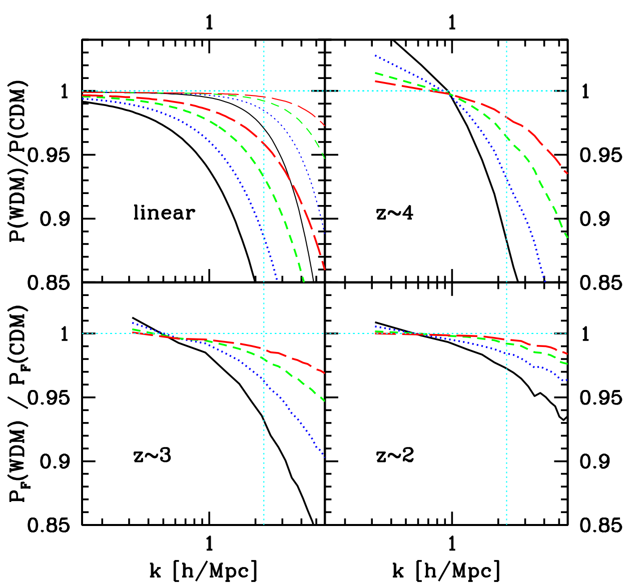

FIG. 1 (color online). Ratio of WDM power spectrum relative to CDM shown over the relevant observational range. From left to right, the sterile neutrino masses are 6.5, 10, 14, and 20 keV. The top left corner shows 1D (thick line) and 3D (thin line) linear power spectrum, while the other 3 panels show the ratios from hydrodynamic simulations at redshifts 2, 3, and 4. We used concordance cosmology with $\Omega_m = 0.28$ and $H_0 = 71$ km/s/Mpc.

Nonlinear evolution and hydrodynamic effects further modify the linear predictions, which must be addressed with simulations. We ran hydrodynamic simulations for a series of neutrino masses ranging from 3.4 to 20 keV. Many convergence tests and comparisons between different hydrodynamic codes have been performed, which will be presented in a separate publication. These tests confirm the accuracy of the original analysis in Ref. [21], which was based on a grid of hydro-PM simulations sparsely calibrated with hydrodynamic simulations. For the hydrodynamic simulations in this Letter, we used the Eulerian moving frame TVD + PM code described in Ref. [23]. The Eulerian conservation equations are solved in a frame moving with the fluid where numerical Mach numbers are minimized, allowing thermodynamic variables to be accurately calculated for both subsonic and supersonic gas. Our standard simulations used 20 Mpc/h boxes with 256^3 particles for dark matter and 512^3 cells for gas. We used 10 Mpc/h boxes with equal or twice this resolution to test convergence. We find that the resolution effects are below the observational errors.

Simulation results are shown in Fig. 1 for redshifts 2, 3, and 4 that span the observational range. We have adjusted the level of the UV background to match the mean absorption as measured from the data. The results show that for $m_\nu = 20$ keV there are 1%–2% effects at $k = 2$ h/Mpc at $z = 4$, increasing to 11% for $m_\nu = 6.5$ keV. At $k = 5$ h/Mpc, the effects are 6% suppression for $m_\nu = 20$ keV mass and a factor of 1.5 for $m_\nu = 6.5$ keV. These are redshift-dependent: While there is little differentiating power between models at low redshift, the differences become significantly larger at high redshift, where the mean level of absorption is higher and the linear power is better preserved. Finally, we note that the suppression of small scale power also affects the large scale bias of the flux power spectrum, which explains why the ratios do not converge to unity on large scales.

In addition to the Ly-α forest flux power spectrum from SDSS [19], we have added earlier high-resolution Ly-α forest constraints in a weak form [24,25]. When testing the robustness of the derived constraints, we also include the more recent high-resolution Ly-α forest data [26,27]. While galaxy clustering and cosmic microwave background (CMB) data do not constrain WDM, they are useful for constraining the remaining cosmological parameters. We use as inputs the SDSS galaxy power spectrum [28] and CMB power spectrum from a Wilkinson microwave anisotropy probe 3 yr analysis [29,30]. Our analysis is based on the Monte Carlo Markov chain (MCMC) method [31] and uses CMBFAST [22] to output both CMB spectra and the corresponding matter power spectra $P(k)$. The output transfer functions are interpolated onto a grid of simulations using the matter power spectra rather than the neutrino mass, since it is the matter spectrum that is most directly related to the observations. Our most general cosmological parameter space has 9 parameters, which are the Hubble constant, matter and baryon density, amplitude, slope and running of the primordial power spectrum, tensor to scalar ratio, optical depth, and neutrino mass. Since in most models of inflation tensors and running are expected to be small, we also explore the constraints when they are set to zero. We assume that the active neutrinos have a negligible contribution to the dark matter.

We compare the theoretical flux power spectrum $P_F(k)$ directly to the measured power spectrum. This is particularly important for the WDM analysis, where one cannot use the 3D linear power spectrum amplitude and slope constraints as given in Ref. [21], since as emphasized there these are valid only in the context of standard CDM models without WDM. The Ly-α forest contains several nuisance parameters which we are not interested in for the cosmological analysis, so they are marginalized over. These include the UV background intensity, temperature-density relation of the gas, and the filtering length (related to the Jeans scale [32]). We also include a marginalization over several additional physical effects, such as fluctuations in the UV background and galactic winds [21,33]. Finally, we marginalize over all of the cosmological parameters except WDM mass.

Applying the standard MCMC analysis to the WDM case, we find no evidence of WDM: The limit is $m_\nu > 13.1$ keV at 95 % C.L. (9.0 keV at 99.9% C.L.). The corresponding limit for neutrinos which were in thermal equilibrium at a high temperature, when the Universe had more degrees of freedom, and then decoupled, is $m_\nu < 2.4$ keV at 95% C.L. This constraint is obtained in our 9 parameter space, but reducing the parameter space to the minimal 7 parameters without running and tensors does not change the results. The Ly-α forest data, best fitted CDM model, and corresponding WDM model for $m_\nu = 6.5$ keV are shown in Fig. 2. One can see how the suppression of power on small scales in WDM makes the fit worse. For this figure, where we have not adjusted all the other parameters to their best fitted value, the increase in χ^2 with WDM is 77—when the Ly-α forest model parameters and power spectrum amplitude and slope are fitted, $\Delta\chi^2$ is still 27. Even without high-resolution constraints, the poor fit to the SDSS data is apparent, especially at higher redshifts. Removing the high-resolution data only weakens the bounds by 15%. The converse, however, is not true: Without SDSS, the previously found constraint (after 10% adjustment for nonthermal momentum distribution) is $m_\nu > 1.8$ keV (95% C.L.) [5]. This is because within the high-resolution data there are degeneracies between WDM and many of the nuisance parameters such as the temperature of the intergalactic medium, UV flux, and filtering scale. These can be removed by adding the large scale flux power spectrum measured by the SDSS data. Finally, we note that using the more recent high-resolution Ly-α forest data [26,27] does not improve the limits obtained above.

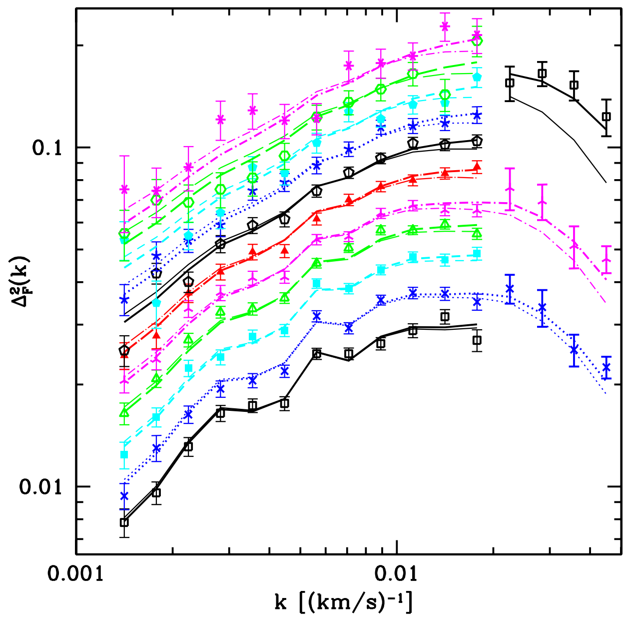

FIG. 2 (color online). To the left are the observed SDSS Ly-α forest flux power spectra $\Delta^2_F(k) = kP_F(k)/2\pi$ as a function of redshift from 2.2 (bottom) to 4.2 (top) in steps of 0.2. To the right are the power spectra from the high-resolution data compiled at redshifts 2.4, 3.0, and 3.9. For each redshift, the thick lines are from the best fitted CDM model, while the (generally lower at high k) thin lines are for the corresponding WDM model with the 6.5 keV sterile neutrino. The latter is discrepant with both SDSS and high-resolution data, with most of the distinguishing power coming from higher redshifts.

Sterile neutrinos that couple to active ones also decay, and their radiative decays result in photons with energy peaking at close to one-half of the neutrino mass, which for keV masses can be searched for in x rays from either clusters or from their cumulative contribution in a random direction. Absence of such x-ray emission in the Virgo cluster results in an upper limit on the mass of 8–9 keV [8,34], 6 keV in the Coma cluster [34], and 3.5 keV in our own Galaxy [11], while recent evaluation of x-ray background constraints gives an upper limit of 5 keV for the value of mixing angle that matches the required density of sterile neutrinos [10], using the calculations of active neutrino interaction rate around QCD phase transition [8]. These are all below our 99.9% lower limit, suggesting that sterile neutrinos cannot be the dark matter in this model.

In Ref. [35], it has been argued that the bounds are modified if there is entropy injection into active neutrinos and photons after the dark matter sterile neutrino has already decoupled, so that its effective temperature is lower than that of active neutrinos today. Such entropy injection could, for example, be achieved by the decay of the two more massive right-handed neutrinos. For entropy injection S, the mass bounds from Ly-α forest scales as $S^{-1/3}$

and the lower limit is lowered. However, a decrease in concentration must be accompanied by an increase in the mixing angle to match the same dark matter density. As a result, the upper limit from x-ray constraints become lower, too, scaling as $S^{-0.3}$ to $S^{-0.4}$, very similar to the scaling of the Ly-α forest constraint. Entropy injection by itself thus does not open up an allowed window. One must instead invoke more nonstandard mechanisms, such as the postulate that there are additional interactions in the early Universe that generate an abundance of right-handed neutrinos even prior to their generation through mixing from active neutrinos, or invoke mirror models [36].

Can the bounds presented here be invalidated by some additional physical effect in the Ly-α forest that is not included in our model? This is unlikely but cannot be ruled out completely. There are possible physical effects that can, in principle, affect the Ly-α forest power spectrum, and, while most of them have been shown to be negligible or are already part of our standard analysis [33,37], there remains a possibility that something else will turn out to be important. The 2-sigma difference between WMAP3 and Ly-α forest amplitude may be an indication of this, although it could also be a statistical fluctuation. However, it is important to recognize how specific the WDM signature is as a function of scale and redshift. Any potential effects that may be missing in the current analysis are constrained by the remarkable agreement of the simplest CDM model with the data. It seems unlikely that if we lived in a WDM universe its signature were erased exactly by some (yet to be discovered) physical effect. Barring any such cancellations, we may conclude that the simplest model of sterile neutrinos as the dark matter is ruled out, since the upper limit from their decays and the lower limit from their effect on large scale structure no longer leave an open window.

U. S. is supported by the Packard Foundation, NASA No. NAG5-1993 and NSF No. CAREER-0132953. H. T. acknowledges NASA Grant No. NNG04GC50G. We thank Alexander Kusenko, Misha Shaposhnikov, and Alexei Smirnov for useful discussions.

[1] Y. Ashie *et al.*, Phys. Rev. Lett. **93**, 101801 (2004).
[2] Q. R. Ahmad *et al.*, Phys. Rev. Lett. **87**, 071301 (2001).
[3] S. Dodelson and L. M. Widrow, Phys. Rev. Lett. **72**, 17 (1994).
[4] T. Asaka, S. Blanchet, and M. Shaposhnikov, Phys. Lett. B **631**, 151 (2005).
[5] M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese, and A. Riotto, Phys. Rev. D **71**, 063534 (2005).
[6] K. Abazajian, Phys. Rev. D **73**, 063513 (2006).
[7] K. Abazajian, G. M. Fuller, and W. H. Tucker, Astrophys. J. **562**, 593 (2001).
[8] K. Abazajian, Phys. Rev. D **73**, 063506 (2006).
[9] M. Mapelli and A. Ferrara, Mon. Not. R. Astron. Soc. **364**, 2 (2005).
[10] A. Boyarsky, A. Neronov, O. Ruchayskiy, and M. Shaposhnikov, JETP Lett. **83**, 133 (2006).
[11] A. Boyarsky, A. Neronov, O. Ruchayskiy, M. Shaposhnikov, and I. Tkachev, astro-ph/0603660.
[12] A. Kusenko and G. Segrè, Phys. Lett. B **396**, 197 (1997).
[13] T. Asaka and M. Shaposhnikov, Phys. Lett. B **620**, 17 (2005).
[14] A. D. Dolgov and S. H. Hansen, Astropart. Phys. **16**, 339 (2002).
[15] K. Abazajian, G. M. Fuller, and M. Patel, Phys. Rev. D **64**, 023501 (2001).
[16] We assume throughout the Letter a negligible lepton asymmetry and do not consider the possibility of a resonant enhancement in neutrino production.
[17] V. K. Narayanan, D. N. Spergel, R. Davé, and C. Ma, Astrophys. J. Lett. **543**, L103 (2000).
[18] R. A. C. Croft, D. H. Weinberg, N. Katz, and L. Hernquist, Astrophys. J. **495**, 44 (1998).
[19] P. McDonald *et al.*, Astrophys. J. Suppl. Ser. **163**, 80 (2006).
[20] The exception is Ref. [6], where, however, the linear power spectrum determination of Ref. [21], valid only for CDM, was applied to WDM models, making the results overly conservative.
[21] P. McDonald *et al.*, Astrophys. J. **635**, 761 (2005).
[22] U. Seljak and M. Zaldarriaga, Astrophys. J. **469**, 437 (1996).
[23] H. Trac and U. Pen, New Astron. Rev. **9**, 443 (2004).
[24] P. McDonald, J. Miralda-Escudé, M. Rauch, W. L. W. Sargent, T. A. Barlow, R. Cen, and J. P. Ostriker, Astrophys. J. **543**, 1 (2000).
[25] P. McDonald, J. Miralda-Escudé, M. Rauch, W. L. W. Sargent, T. A. Barlow, and R. Cen, Astrophys. J. **562**, 52 (2001).
[26] R. A. C. Croft, D. H. Weinberg, M. Bolte, S. Burles, L. Hernquist, N. Katz, D. Kirkman, and D. Tytler, Astrophys. J. **581**, 20 (2002).
[27] T. Kim, M. Viel, M. G. Haehnelt, R. F. Carswell, and S. Cristiani, Mon. Not. R. Astron. Soc. **347**, 355 (2004).
[28] M. Tegmark *et al.*, Astrophys. J. **606**, 702 (2004).
[29] G. Hinshaw *et al.*, astro-ph/0603451.
[30] L. Page *et al.*, astro-ph/0603450.
[31] U. Seljak, P. McDonald, and A. Makarov, Mon. Not. R. Astron. Soc. **342**, L79 (2003).
[32] N. Y. Gnedin and L. Hui, Mon. Not. R. Astron. Soc. **296**, 44 (1998).
[33] P. McDonald, U. Seljak, R. Cen, P. Bode, and J. P. Ostriker, Mon. Not. R. Astron. Soc. **360**, 1471 (2005).
[34] A. Boyarsky, A. Neronov, A. Neronov, O. Ruchayskiy, and M. Shaposhnikov, astro-ph/0603368.
[35] T. Asaka, A. Kusenko, and M. Shaposhnikov, Phys. Lett. B **638**, 401 (2006).
[36] R. N. Mohapatra and S. Nasri, Phys. Rev. D **71**, 053001 (2005).
[37] K. Lai, A. Lidz, L. Hernquist, and M. Zaldarriaga, Astrophys. J. **644**, 61 (2006).