Weighing neutrinos with large-scale structure

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While it is established that the effect of neutrinos on the evolution of cosmic structure is small, the upper limits derived from large-scale structure could help significantly to constrain the absolute scale of the neutrino masses. Current results from cosmology set an upper limit on the sum of the neutrino masses of $\sim 1$ eV, somewhat depending on the data sets used in the analyses and assumed priors on cosmological parameters. In this review we discuss the effects of neutrinos on large-scale structure which make these limits obtainable. We show the impact of neutrino masses on the matter power spectrum, the cosmic microwave background and the clustering amplitude. A summary of derived cosmological neutrino mass upper limits is given, and we discuss future methods which will improve the mass upper limits by an order of magnitude.

1. INTRODUCTION

The wealth of new data from the cosmic microwave background (CMB) and large-scale structure (LSS) in the last few years indicate that we live in a flat Universe where $\sim 70\%$ of the mass-energy density is in the form of dark energy, with matter making up the remaining $30\%$. The WMAP data combined with other large-scale structure data \cite{wmap} give impressive support to this picture. Furthermore, the baryons contribute only a fraction $f_b = \Omega_b/\Omega_m \sim 0.15$ ($\Omega_b$ and $\Omega_m$ are, respectively, the contribution of baryons and of all matter to the total density in units of the critical density $\rho_c = 3H_0^2/8\pi G = 1.879 \times 10^{-29}h^2$ g cm$^{-3}$, where $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$ is the present value of the Hubble parameter) of this, so that most of the matter is dark. The exact nature of the dark matter in the Universe is still unknown. Relic neutrinos are abundant in the Universe, and from the observations of oscillations of solar and atmospheric neutrinos we know that neutrinos have a mass $\lesssim 50$ eV and will make up a fraction of the dark matter. However, the oscillation experiments can only measure differences in the squared masses of the neutrinos, and not the absolute mass scale, so they cannot, at least not without extra assumptions, tell us how much of the dark matter is in neutrinos. From general arguments on structure formation in the Universe we know that most of the dark matter has to be cold, i.e. non-relativistic when it decoupled from the thermal background. Neutrinos with masses on the eV scale or below will be a hot component of the dark matter. If they were the dominant dark-matter component, structure in the Universe would have formed first at large scales, and smaller structures would form by fragmentation (the ‘top-down’ scenario). However, the combined observational and theoretical knowledge about large-scale structure gives strong evidence for the ‘bottom-up’ picture of structure formation, i.e. structure formed first at small scales. Hence, neutrinos cannot make up all of the dark matter (see e.g. \cite{review} for a review). Neutrino experiments give some constraints on how much of the dark matter can be in the form of neutrinos. Studies of the energy spectrum in tritium decay \cite{tritium} provide an upper limit on the effective electron neutrino mass involved in this process of $2.2$ eV (95 \% confidence limit). For the effective neutrino mass scale involved in neutrinoless double beta decay a range 0.1-0.9 eV has been inferred from the claimed detection of this process \cite{dubna}. If confirmed, this result would not only show that neutrinos are Majorana particles (i.e. their own antiparticles), but also that
the neutrino masses are in a range where they are potentially detectable with cosmological probes.

The structure of this review is as follows. Sections 2 and 3 discuss the effect of massive neutrinos on structure formation and on the CMB anisotropies. In section 4 we give an overview of recent cosmological neutrino mass limits and in Section 5 we discuss challenges for the future.

2. THE EFFECT OF MASSIVE NEUTRINOS ON STRUCTURE FORMATION

The relic abundance of neutrinos in the Universe today is straightforwardly found from the fact that they continue to follow the Fermi-Dirac distribution after freeze-out, and their temperature is related to the CMB temperature $T_{\text{CMB}}$ today by $T = (4/11)^{1/3}T_{\text{CMB}}$, giving

$$n_{\nu} = \frac{6\zeta(3)}{11\pi^2}T_{\text{CMB}}^3,$$  \hspace{1cm} (1)

where $\zeta(3) \approx 1.202$, which gives $n_{\nu} \approx 112$ cm$^{-3}$ at present. By now, massive neutrinos will have become non-relativistic, so that their present contribution to the mass density can be found by multiplying $n_{\nu}$ with the total mass of the neutrinos $m_{\nu, \text{tot}}$, giving

$$\Omega_{\nu}h^2 = \frac{m_{\nu, \text{tot}}}{94 \text{ eV}}$$ \hspace{1cm} (2)

for $T_{\text{CMB}} = 2.726$ K. Several effects could modify this simple relation. If any of the neutrino chemical potentials were initially non-zero, or there were a sizable neutrino-antineutrino asymmetry, this would increase the energy density in neutrinos and give an additional contribution to the relativistic energy density. However, from Big Bang Nucleosynthesis (BBN) one gets a very tight limit on the electron neutrino chemical potential, since the electron neutrino is directly involved in the processes that set the neutron-to-proton ratio. Also, within the standard three-neutrino framework one can extend this limit to the other flavours as well. Within the standard picture, equation (2) should be accurate, and therefore any constraint on the cosmic mass density of neutrinos should translate straightforwardly into a constraint on the total neutrino mass, according to equation (2). If a fourth, light ‘sterile’ neutrino exists, sterile-active oscillations would modify this conclusion. Beacom et al. showed that extra couplings, not yet experimentally excluded, of neutrinos may allow them to annihilate into light bosons at late times, and thus make a negligible contribution to the matter density today. If so, equation (2) is not valid, and hence neutrino mass limits derived from large-scale structure do not apply. We shall assume that no such non-standard couplings of neutrinos exist.

Finally, we assume that the neutrinos are nearly degenerate in mass. Current cosmological observations are sensitive to neutrino masses $\sim 1$ eV or greater. Since the mass-square differences are small, the assumption of a degenerate mass hierarchy is therefore justified. This is illustrated in Figure 1, where we have plotted the mass eigenvalues $m_1, m_2, m_3$ as functions of $m_{\nu, \text{tot}} = m_1 + m_2 + m_3$ for $\Delta m_{32}^2 = 7 \times 10^{-5}$ eV$^2$ (solar) and $\Delta m_{32}^2 = 3 \times 10^{-3}$ eV$^2$ (atmospheric), for the cases of a normal hierarchy ($m_1 < m_2 < m_3$), and an inverted hierarchy ($m_3 < m_1 < m_2$). As seen in the Figure, for $m_{\nu, \text{tot}} > 0.4$ eV the mass eigenvalues are essentially degenerate.

Here we look at cosmological models with four components: baryons, cold dark matter, massive neutrinos, and a cosmological constant. Furthermore, we restrict ourselves to adiabatic, linear perturbations. The basic physics is then fairly simple. Light, massive neutrinos can move unhindered out of regions below a certain limiting length scale, and will therefore tend to damp a density perturbation at a rate which depends on their rms velocity. The presence of massive neutrinos therefore introduces a new length scale, given by the size of the co-moving Jeans length when the neutrinos became non-relativistic. In terms of the comoving wavenumber, this is given by

$$k_{nr} = 0.026 \left( \frac{m_{\nu}}{1 \text{ eV}} \right)^{1/2} \Omega_m^{1/2} h \text{Mpc}^{-1},$$ \hspace{1cm} (3)

for three equal-mass neutrinos, each with mass $m_{\nu}$. The growth of Fourier modes with $k > k_{nr}$ will be suppressed because of neutrino free-streaming. The free-streaming scale varies with
The cosmological epoch, and the scale and time dependence of the power spectrum cannot be separated, in contrast to the situation for models with cold dark matter only.

The power spectrum of the matter fluctuations can be written as

\[ P_m(k, z) = P_*(k) T^2(k, z), \]

where \( T(k, z) \) is the ‘transfer function’, \( P_*(k) \) is the primordial spectrum of matter fluctuations, commonly assumed to be a simple power law \( P_*(k) = A k^n \), where \( A \) is the amplitude and the spectral index \( n \) is close to 1. It is also common to define power spectra for each component, see [17] for a discussion. Note that the transfer functions and power spectra are independent of the value of the cosmological constant as long as it does not shift the epoch of matter-radiation equality significantly.

The transfer function is found by solving the coupled fluid and Boltzmann equations for the various components. This can be done using one of the publicly available codes, e.g. CMBFAST [18] or CAMB [19]. In Figure 2 we show the transfer functions for models with \( \Omega_m = 0.3, \Omega_b = 0.04, h = 0.7 \) held constant, but with varying neutrino mass \( m_\nu \). One can clearly see that the small-scale suppression of power becomes more pronounced as the neutrino fraction \( f_\nu \equiv \Omega_\nu / \Omega_m \) increases.

The effect is also seen in the power spectrum, as shown in Figure 3 (top). Note that the power spectra shown in the Figure have been convolved with the 2dFGRS window function, as described in [20]. Furthermore, we have taken the possible bias of the distribution of galaxies with respect to that of the dark matter into account by leaving the overall amplitude of each power spectrum as a free parameter to be fitted to the 2dFGRS power spectrum data (the vertical bars in the Figure). For a discussion of bias in the context of neutrino mass limits, see [21]. Because the errors on the data points are smaller at small scales, these points are given most weight in the fitting, and hence the power spectra in the Figure actually deviate more and more from each other on large scales as \( m_\nu \) increases. One can see from the Figure that a neutrino mass of \( m_\nu = 0.5 \text{ eV} \).
Figure 2. Ratio of the transfer functions (at $z = 0$) for various values of $\Omega_\nu$ to the one for $\Omega_\nu = 0$. The other parameters are fixed at $\Omega_m = 0.3$, $\Omega_b = 0.04$, $h = 0.7$. The solid line is for $m_\nu = 0.1$ eV, the dashed line is for $m_\nu = 0.3$ eV, the long-dashed line is for $m_\nu = 0.5$ eV, and the dot-dashed line corresponds to $m_\nu = 2$ eV.

or larger is in conflict with the data. The suppression of the power spectrum on small scales is roughly proportional to $f_\nu$:

$$
\frac{\Delta P_m(k)}{P_m(k)} \approx -8f_\nu.
$$

(5)

This result can be derived from the equation of linear growth of density perturbations and the fact that only a fraction $(1 - f_\nu)$ of the matter can cluster when massive neutrinos are present [22].

3. CONSTRAINTS FROM THE CMB ALONE

Neutrino masses also give rise to effects in the CMB power spectrum. If their masses are smaller than the temperature at recombination $\sim 0.3$ eV, their effect is very similar to that of massless neu-

Figure 3. Top Figure: Power spectra for $m_\nu = 0$ (full line), $m_\nu = 0.1$ (dotted line), $m_\nu = 0.3$ (dashed line), $m_\nu = 0.5$ (long-dashed line), and $m_\nu = 3$ eV (dot-dashed line). The other parameters are fixed at $\Omega_m = 0.3$, $\Omega_b = 0.04$, $h = 0.7$. The vertical bars are the 2dFGRS power spectrum data points. Bottom Figure: CMB power spectra for $m_\nu = 0$ (full line), $m_\nu = 0.1$ (dotted line), $m_\nu = 0.3$ (dashed line), $m_\nu = 0.5$ (long-dashed line), and $m_\nu = 3$ eV (dot-dashed line). The other parameters are fixed at $\Omega_m = 0.3$, $\Omega_b = 0.04$, $h = 0.7$. The vertical bars are the WMAP power spectrum data points.
trinos [23]. For slightly larger masses, there is an enhancement of the acoustic peaks with respect to the massless case, as shown in Figure 3 (bottom). While there is some sensitivity to the neutrino mass, note that all other parameters have been fixed in Figure 3 (bottom). Analytic considerations by [24] provide insight into the effect of the neutrinos on the CMB. There are severe degeneracies between $m_\nu$ and other parameters like $n$ and $\Omega_\Lambda h^2$. The full analysis of the WMAP data alone in [20] gave no upper limit on $m_\nu$. On the other hand [21] have claimed an upper limit of 2.2 eV from CMB alone, in contrast with the conclusions of [21] and [20]. The differences might be due to the assumed priors and the marginalisation procedures over other cosmological parameters.

Future CMB missions like Planck will provide high-resolution maps of the CMB temperature and polarization anisotropies. Gravitational lensing of these maps causes distortions, and Kaplinghat, Knox & Song [25] have shown that this effect can be used to obtain very stringent limits on neutrino masses from the CMB alone. For Planck, they predict a sensitivity down to 0.15 eV, whereas a future experiment with higher resolution and sensitivity can possibly reach the lower bound $\sim 0.06$ eV set by the neutrino oscillation experiments.

4. RECENT COSMOLOGICAL NEUTRINO MASS LIMITS

The connection between neutrino masses and cosmic structure formation was realized early, but for a long time cosmologists were mostly interested in neutrino masses in the $\sim 10$ eV range, since then they would be massive enough to make up all of the dark matter. The downfall of the top-down scenario of structure formation, and the fact that no evidence for neutrino masses existed before Super-Kamiokande detected oscillations of atmospheric neutrinos in 1998, makes it understandable that there was very little continuous interest in this sub-field. However, the detection of neutrino oscillations showed that neutrinos indeed have a mass. In an important paper Hu, Eisenstein & Tegmark [27] showed that one could obtain useful upper limits on neutrino masses from a galaxy redshift survey of the size and quality of the Sloan Digital Sky Survey (SDSS).

Going down Table 4 one notes a marked improvement in the constraints after the 2dFGRS power spectrum became available. After WMAP, there is a further tendency towards stronger upper limits, reflecting the dual role of the CMB and large-scale structure in constraining neutrino masses: the matter power spectrum is most sensitive to neutrino masses, but one needs good constraints on the other relevant cosmological parameters to break degeneracies in order to obtain low upper limits. The limit will depend on the datasets and priors used in the analysis, but it seems like we are now converging to the precision envisaged in [27]. The latest limit from [37] uses galaxy-galaxy lensing to extract information about the linear bias parameter in the SDSS, making a direct association between the galaxy and matter power spectra, and hence get a stronger constraint on the neutrino mass than would have been possible using just the shape of the galaxy power spectrum.

Direct probes of the total matter distribution avoid the issue of bias and are therefore ideally suited for providing limits on the neutrino masses. Several ideas for how this can be done exist. In [20] the normalization of the matter power spectrum on large scales derived from COBE was combined with constraints on $\sigma_8$ (defined as the rms mass fluctuation in $8h^{-1}$Mpc radius sphere), they obtained a 95% confidence) from cluster abundances and a constraint $m_{\nu,\text{tot}} < 2.7$ eV obtained, although with a fairly restricted parameter space. However, $\sigma_8$ is probably one of the most debated numbers in cosmology at the moment [35], and a better understanding of systematic uncertainties connected with the various methods for extracting it from observations is needed before this method can provide useful constraints. The potential of this method to push the value of the mass limit down also depends on the actual value of $\sigma_8$: the higher $\sigma_8$ turns out to be, the less room there will be for massive neutrinos. As an illustration we show in Figure 4 the value of $\sigma_8$ as a function of varying $\Omega_\nu$ with the remaining cosmological parameters fixed at their ‘concordance’ values. For a given value of $m_{\nu}$,
one fits the corresponding CMB power spectrum to the data. This in turn leads to a best-fit amplitude and a prediction for $\sigma_8$ for the given value of $m_\nu$. If one then has an independent measurement of $\sigma_8$, one can infer the value of $m_\nu$. In Figure 4 the amplitude of the power spectrum has been fixed by fitting to the WMAP data. The claimed detection of a non-zero neutrino mass in [30] can be seen to be due to the use of the cluster X-ray luminosity function to constrain $\sigma_8$, giving $\sigma_8 = 0.69 \pm 0.04$ for $\Omega_m = 0.3$ [39]. If a value of $\sigma_8$ at the higher end of the results reported in the literature is used instead, e.g. $\sigma_8 = 0.9$ for $\Omega_m = 0.3$ from [40], one gets a very tight upper limit on $m_\nu$, but no detection of $m_\nu > 0$. It is clearly important that systematic issues related to the various methods of obtaining $\sigma_8$ are settled. The evolution of cluster abundance with redshift may provide further constraints on neutrino masses [41].

Direct probes of the mass distribution such as peculiar velocities and gravitational lensing are also potentially important for setting constraints on the neutrino mass. Deep and wide weak lensing surveys will in the future make it possible to

| Reference | CMB       | LSS       | Other data                              | $m_{\nu, \text{tot}}$ limit |
|-----------|-----------|-----------|----------------------------------------|-------------------------------|
| [28]      | —         | Ly$\alpha$ | COBE norm., $h = 0.72 \pm 0.08$, $\sigma_8 = 0.56\Omega_m^{0.47}$ | 5.5 eV                       |
| [29]      | —         | $\sigma_8$ | $\Omega_m < 0.4$, $\Omega_b h^2 = 0.015$, $h < 0.8$, $n = 1.0$ | 2.7 eV                       |
| [31]      | pre-WMAP  | PSCz, Ly$\alpha$ | —                                          | 4.2 eV                       |
| [32]      | None      | 2dFGRS    | BBN, SNIa, HST, $n = 1.0 \pm 0.1$ | 2.2 eV                       |
| [33]      | pre-WMAP  | 2dFGRS    | —                                          | 2.5 eV                       |
| [34]      | pre-WMAP  | 2dFGRS    | SNIa, BBN                                  | 0.9 eV                       |
| [1]       | WMAP+CBI+ACBAR | 2dFGRS   | Ly$\alpha$                                | 0.71 eV                       |
| [15]      | WMAP+Wang comp. | 2dFGRS | HST, SNIa                                | 1.01 eV                       |
| [30]      | WMAP+CBI+ACBAR | 2dFGRS | X-ray                                     | 0.56$^{+0.30}_{-0.26}$ eV    |
| [26]      | WMAP      | SDSS      | —                                          | 1.7 eV                       |
| [36]      | WMAP      | 2dFGRS+SDSS | —                                          | 0.75 eV                       |
| [23]      | WMAP+ACBAR | 2dFGRS+SDSS | —                                          | 1.0 eV                       |
| [37]      | WMAP      | SDSS      | bias                                       | 0.54 eV                       |

Figure 4. The clustering amplitude $\sigma_8$ as a function of $\Omega_\nu$ for models with amplitude fitted to the WMAP data.
do weak lensing tomography of the matter density field \cite{42,43}. By binning the galaxies in a deep and wide survey in redshift, one can probe the evolution of the gravitational potential. However, because massive neutrinos and dark energy have similar effects on this evolution, complementary information is required in order to break this degeneracy. Several studies of the potential of lensing tomography to constrain cosmological parameters, in particular dark energy and neutrino masses, have been carried out, see e.g. \cite{44} for an overview. Even when taking the uncertainties in the properties of dark energy into account, the combination of weak lensing tomography and high-precision CMB experiments may be sensitive to neutrino masses below to lower bound of 0.06 eV on the sum of the neutrino masses set by the current oscillation data \cite{44}.

5. DISCUSSION

The dramatic increase in amount and quality of CMB and large-scale structure data we have seen in cosmology in the last few years have made it possible to derive fairly stringent limits on the neutrino mass scale. With the WMAP and SDSS data, the upper limit has been pushed down to $\sim 1$ eV for the total mass, assuming three massive neutrino species.

One point to bear in mind is that all these limits assume the ‘concordance’ $\Lambda$CDM model with adiabatic, scale-free primordial fluctuations. While the wealth of cosmological data strongly indicate that this is the correct basic picture, one should keep in mind that cosmological neutrino mass limits are model-dependent, and that there might still be surprises. As the suppression of the power spectrum depends on the ratio $\Omega_\nu/\Omega_m$, \cite{33} found that the out-of-fashion Mixed Dark Matter (MDM) model, with $\Omega_\nu = 0.2$, $\Omega_m = 1$ and no cosmological constant, fits the 2dFGRS power spectrum well, but only for a Hubble constant $H_0 < 50$ km s$^{-1}$ Mpc$^{-1}$. A similar conclusion was reached in \cite{45}, and they also found that the CMB power spectrum could be fitted well by the same MDM model if one allows features in the primordial power spectrum. Another consequence of this is that excluding low values of the Hubble constant, e.g. with the HST Key Project, is important in order to get a strong upper limit on the neutrino masses.

If the future observations live up to their promise, the prospects for pushing the cosmological neutrino mass limit down towards 0.1 eV are good. Then, as pointed out in \cite{46}, one may even start to see effects of the different mass hierarchies (normal or inverted), and thus one should take this into account when calculating CMB and matter power spectra. For example, with a non-degenerate mass hierarchy one will get more than one free-streaming scale, and this will leave an imprint on the matter power spectrum. The coming years will see further comparison between the effective neutrino mass in Tritum beta decay, the effective Majorana neutrino mass in neutrinoless double beta decay and the sum of neutrino mass from Cosmology (\cite{47}). It would be a great triumph for cosmology if the neutrino mass hierarchy were finally revealed by the distribution of large-scale structures in the Universe.

Acknowledgements

OE acknowledges support from the Research Council of Norway through grant number 159637/V30 and OL thanks PPARC for a Senior Research Fellowship.

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