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Weighing neutrinos using high redshift galaxy luminosity functions

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Abstract. We have proposed a novel way to constrain the neutrino mass using UV luminosity function (LF) of high-z Lyman break galaxies. Combining the constraints from the Wilkinson Microwave Anisotropy Probe 7 year (WMAP-7) data with the LF data at $z \sim 4$, we have got a limit on the sum of the masses of 3 degenerate neutrinos at the 95 % CL. The additional constraint of using the prior on Hubble constant strengthens this limit to at 95 % CL. As different astronomical measurements may suffer from different set of biases, the method presented here provides a complementary probe of sum of neutrino masses.

1. Introduction

A cosmic background of neutrinos is one of the key predictions of standard big bang cosmology. The absolute mass scale of neutrinos could be inferred from various β-decay experiments [1]. However, at present, stronger constraints on neutrino mass are obtained from cosmological observations [2]). The recent WMAP-7 data by itself sets an upper limit to sum of neutrino masses, $\Sigma m_\nu < 1.3$ eV [3]. It is well known that the presence of massive neutrinos leads to the suppression of density perturbations below a time dependent scale known as the free streaming scale [2, 4]. This suppression results in a decrease in the formation of dark matter halos below a characteristic mass scale. Thus, observations related to large scale structure formation in the universe can be used to probe the absolute mass scale of neutrinos. In this work, we have explored the possibility of using the luminosity functions (LF) of Lyman break galaxies (LBG) for constraining Σm_ν.

The basic idea is as follows: The reduction in the matter power spectrum in models with $m_\nu > 0$, compared to models with $m_\nu = 0$ implies a reduced abundance of galactic scale dark matter halos at high redshifts. In order to account for the observed LF of these galaxies, the light to mass ratio of each galactic halo has to be systematically higher in the models with $m_\nu > 0$. However, changing the light to mass ratio is degenerate with the unknown extinction correction, one applies to the observed LF. Nevertheless, this degeneracy can be lifted if one has a feature in the LF at some characteristic mass scale, introduced by various feedback processes, like the radiative feedback after reionization. In such cases, the shape of the predicted galaxy LF depends on the neutrino mass. We have used this idea to constrain neutrino masses. We have explained our basic model in Sections 2 and 3, presented our limits on Σm_ν in Section 3.1 and concluded in Section 4.

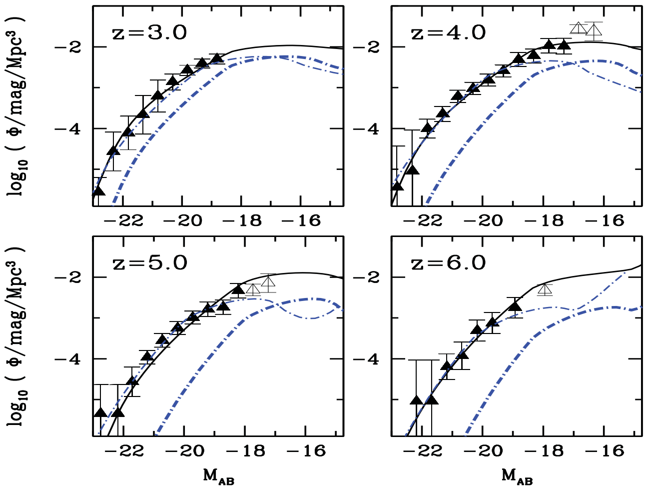

Figure 1. UV LF of LBGs at redshifts $3, 4, 5$ and 6. The solid (black) line shows the predicted best fit LF for our model with $\Sigma m_\nu = 0$. The thick dashed-dotted (blue) curve shows our model predictions with $\Sigma m_\nu = 1$ eV and using the same best fit f_*/η as the $\Sigma m_\nu = 0$ eV model. This is to illustrate the suppression due to massive neutrinos. The thin dashed-dotted (blue) curves are best fits for the models with $\Sigma m_\nu = 1$ eV. The data points (filled and open triangles) for $z = 3$ are taken from [5] and for $z = 4 - 6$ are from [6].

2. High redshift galaxy luminosity functions

We have modelled high redshift galaxy LF using the semi-analytical treatment in [7], and the models are successful in explaining the observed UV LF of high redshift galaxies at $3 \leq z \leq 8$ (see also [8]). The crucial ingredient of their model is the star formation rate (SFR) of an individual dark matter halo of mass M collapsed at redshift z_c and observed at redshift z. This is assumed to rise linearly after the collapse of the halo, and decay exponentially in a dynamical time scale. A key component of the SFR is f_*, the fraction of the total baryonic mass that is converted into stars over the entire lifetime of the galaxy. The assumed star formation rate of a galaxy can be converted to a luminosity (See Eq. (6) and Figure 1 of [7]). Only a fraction $(1/\eta)$ of the total light produced by the stars comes out of the galaxy due to the absorption by dust. The LF, $\Phi(L)dL$ can be obtained by counting all galaxies collapsed at any redshift z_c, which can produce a luminosity L at the redshift of observation. To calculate the LF, one requires the formation rate of dark matter halos of mass M. The authors of [7] have modelled this formation rate as the time derivative of Sheth and Tormen (ST) mass function [9] (see also [10]).

Star formation in a given halo also depends on various feedback processes. The ionization of the IGM by UV photons increases the temperature of the gas, thereby increasing the Jean's mass for collapse. In ionized regions, we have incorporated this feedback by a complete suppression of star formation for halos with circular velocity $v_c \leq 35$ km s^{-1}, and no suppression with $v_c \geq 95$ km s^{-1} [11]. For intermediate circular velocities, a linear fit from 1 to 0 is adopted as the suppression factor [11, 7]. This is called the *radiative feedback*. (The details of other feedback mechanisms can be found [7].)

3. Effect of neutrino mass on high redshift LF

We have shown in Figure 1 that our model predictions of LF at different redshifts $z = 3 - 6$, along with the observational data. The solid line shows the predicted best fit LF at various redshifts for the fiducial cosmology and with $\Sigma m_\nu = 0$. In order to fit the observed data points, we have adjusted the free parameter f_*/η in our models, using χ^2 minimization. The flattening of the predicted LF as seen in Figure 1 at the faint end is due to the radiative feedback. The thick dashed-dotted (blue) curves show the predicted LF if we use the same f_*/η for a model with $\Sigma m_\nu = 1.0$ eV. It is clear that there is an order of magnitude suppression in the number density of galaxies at a given luminosity. This is because the presence of neutrinos suppresses the formation rate of halos at the mass and redshift scales of our interest. We can make our model predictions match with the observed data by increasing f_*/η (i.e., shifting this curve

Data	$10^2\Omega_b h^2$	$10\Omega_{DM} h^2$	τ	n_s	σ_8	H_0	Σm_ν(eV)
WMAP-7	$2.223^{+0.060}_{-0.058}$	$1.172^{+0.070}_{-0.068}$	$0.087^{+0.014}_{-0.014}$	$0.962^{+0.016}_{-0.015}$	$0.717^{+0.071}_{-0.072}$	$66.1^{+4.1}_{-4.9}$	< 1.08
WMAP-7+LF	$2.229^{+0.055}_{-0.056}$	$1.228^{+0.065}_{-0.064}$	$0.090^{+0.013}_{-0.014}$	$0.961^{+0.015}_{-0.014}$	$0.820^{+0.051}_{-0.052}$	$65.5^{+2.8}_{-2.8}$	< 0.52
WMAP-7+H_0	$2.263^{+0.050}_{-0.056}$	$1.107^{+0.051}_{-0.050}$	$0.091^{+0.015}_{-0.015}$	$0.973^{+0.013}_{-0.013}$	$0.756^{+0.049}_{-0.047}$	$70.3^{+2.5}_{-2.5}$	< 0.54
WMAP-7+H_0+LF	$2.259^{+0.054}_{-0.054}$	$1.169^{+0.056}_{-0.058}$	$0.095^{+0.015}_{-0.014}$	$0.969^{+0.014}_{-0.016}$	$0.821^{+0.042}_{-0.041}$	$68.7^{+2.1}_{-2.2}$	< 0.29

Table 1. Results of our MCMC analysis to constrain Σm_ν. The first column lists the various data used for our analysis. The last column gives limits on Σm_ν, at the 95% CL. For all other parameters, their mean values and 1σ range are given.

along the luminosity axis). These best fit LF, obtained with the new f_*/η (thin dashed-dotted curves), have a very different shape compared to the zero neutrino mass case. In particular, the predicted LF in models with $\Sigma m_\nu = 1$ eV, are suppressed at the low luminosity end compared to the zero mass case. This is basically because increasing f_*/η increases the light to mass ratio, which brings even small mass galaxies whose star formation has been suppressed due to radiative feedback, into the observable luminosity range. Therefore, strong constraints on the neutrino mass can in principle be obtained by comparing the shape of the predicted LF with observations.

3.1. Limits on neutrino mass

In order to obtain quantitative upper limits by exploring the full range of cosmological parameters consistent with both the WMAP-7 data and the observed LF of LBGs, we have performed a Markov Chain Monte Carlo (MCMC) analysis using the publically available CosmoMC code [12]. In particular, we have concentrated on the LF of LBGs at $z = 4$. We have given the constraints on Σm_ν obtained from the MCMC analysis in Table 1 and Figure 2. The constraints on neutrino mass from WMAP-7 data alone [3] is $\Sigma m_\nu < 1.08$ eV at the 95% CL. Combining the UV luminosity function data at $z = 4$ with the WMAP-7 data, significantly lowers this limit to $\Sigma m_\nu \leq 0.52$. Further, addition of the constraints from the H_0 determination of the HST SHOES (Supernova H_0 for the Equation of State) programme [13] (which we refer to as H_0) leads to a lower limit of $\Sigma m_\nu \leq 0.29$ eV.

All the above neutrino mass limits along with the other cosmological and astrophysical parameters are summarized in Table 1. The corresponding 1D marginalized distribution for Σm_ν, from various MCMC analysis, is shown in the top left panel of Figure 2. The figure also clearly shows that adding the constraint from the $z = 4$ UV luminosity function significantly improves the constraint on neutrino masses. These results are not very much sensitive to various feedback mechanisms. (For a detailed discussion, interested reader may refer to the original paper [10].)

4. Conclusions

We have proposed here a novel probe of neutrino mass using the high redshift UV LF of Lyman break galaxies. In particular, our model constructed in the framework of ΛCDM cosmology with massive neutrinos, shows that the observed shape of the UV LF of high redshift LBGs can be used to constrain the mass of the neutrinos. We have carried out an MCMC analysis to obtain quantitative upper limits on Σm_ν, by combining observed LF data with other data, and exploring the full range of cosmological parameters. Our results are summarized in Table 1 and Figure 2. We have noticed that our best limit on neutrino mass is almost a factor ~ 4 improvement compared to the limit obtained using the WMAP-7 data alone.

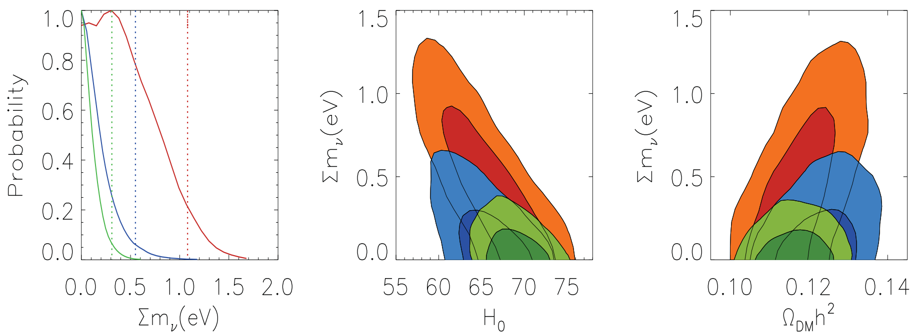

Figure 2. The 1D and 2D marginalized distributions of Σm_ν from our analysis. The left panel gives the marginalized 1D distribution for Σm_ν. The vertical dashed lines correspond to 95% confidence levels. The other two panels show the regions of 68% (dark color) and 95% (light color) confidence levels for H_0 and $\Omega_{DM}h^2$ against m_ν. The various contours corresponds to constraints obtained using WMAP-7 only (red), WMAP-7+LF (blue) and WMAP-7+HST+LF (green) data.

Some of the current limits on Σm_ν from various cosmological probes are given by [14, 15, 16, 17, 18, 19, 20]. The constraints on Σm_ν obtained here adding in the $z \sim 4$ UV LF data to the WMAP-7 and HST data, are comparable (or better in several cases) to the above limits. Our work is mainly a demonstrative first step, where we have suggested the utility of the LF of high redshift galaxies to constrain Σm_ν. Improvements in the LF data, especially at the faint end, and at higher redshifts together with a better understanding of the astrophysics of galaxy formation, will allow us to place more stringent constraints on Σm_ν.

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