

Improved limit on the neutrino mass with CMB and redshift-dependent halo bias-mass relations from SDSS, DEEP2, and Lyman-break galaxies

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We use measurements of luminosity-dependent galaxy bias at several different redshifts, SDSS at $z = 0.05$, DEEP2 at $z = 1$, and LBGs at $z = 3.8$, combined with WMAP 5-year cosmic microwave background anisotropy data and SDSS Red Luminous Galaxy survey three-dimensional clustering power spectrum to put constraints on cosmological parameters. Fitting this combined dataset, we show that the luminosity-dependent bias data that probe the relation between halo bias and halo mass and its redshift evolution are very sensitive to sum of the neutrino masses: in particular, we obtain the upper limit of $\sum m_\nu < 0.28$ eV at the 95% confidence level for a Λ CDM + m_ν model, with a σ_8 equal to $\sigma_8 = 0.759 \pm 0.025$ (1σ). When we allow the dark energy equation-of-state parameter w to vary, we find $w = -1.30 \pm 0.19$ for a general w CDM + m_ν model with the 95% confidence level upper limit on the neutrino masses at $\sum m_\nu < 0.59$ eV. The constraint on the dark energy equation of state further improves to $w = -1.125 \pm 0.092$ when using also ACBAR and supernovae Union data, in addition to above, with a prior on the Hubble constant from the Hubble Space Telescope.

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I. INTRODUCTION

Galaxy clustering at large physical or angular scales corresponding to the linear regime is a well-known probe of the cosmological parameters. The combination of cosmic microwave background (CMB) anisotropy data and the galaxy clustering spectrum, when combined with additional probes such as distance measurements with Type Ia supernovae or baryon acoustic oscillations, are known to break various degeneracies between cosmological parameters that exist when using either CMB data or galaxy clustering data alone [1,2].

While cosmological parameters are generally derived from the shape of the galaxy power spectrum by marginalizing over the overall uncertainty associated with galaxy bias that relates clustering of dark matter to galaxies at the linear scales, the galaxy bias b_g itself contains certain cosmological information that is generally ignored. The relation between galaxy bias and cosmology is evident in the context of the halo model for galaxy clustering, which provides a simple way to relate the galaxy distribution to that of the dark matter halo distribution. The cosmological information is present in the relation between dark matter halo distribution and the linear density field and is captured by the dark matter halo bias as a function of the halo mass $b_h(M)$ [3]. The dark matter halo bias contains shape information of the power spectrum through rms fluctuations of mass $\sigma(M)$.

In the halo model, either expressed in terms of a halo occupation distribution [4–12] or a conditional luminosity function (CLF) [13–15], one can relate the clustering bias of galaxies measured as a function of the galaxy property, such as the luminosity $b_g(L)$, to the bias of dark matter

haloes as a function of the halo mass. To derive the relation between $b_g(L)$ and $b_h(M)$, it is necessary to have a proper understanding of the relation between an observable quantity such as the galaxy luminosity L and a more fundamental quantity, the halo mass M [15–18]. This relation can be achieved through modeling of certain galaxy observables, such as the luminosity function, nonlinear or 1-halo part of the galaxy clustering spectrum, and relations related to galaxy-mass observables from galaxy-galaxy weak lensing measurements [19–21]. In the context of cosmological measurements, the $b_g(L)$ relation as measured by the SDSS survey at low redshifts has been used to constrain cosmological parameters, including the neutrino mass [22,23]. When combined with Wilkinson Microwave Anisotropy Probe (WMAP) 1-year data, SDSS power spectrum shape, and the SDSS $b_g(L)$ relation results in a 95% confidence limit on the sum of the neutrino masses of ~ 0.54 eV.

Beyond SDSS, several galaxy surveys that target galaxy populations at higher redshifts either through spectroscopic measurements or through Lyman dropout techniques have provided measurements related to the galaxy luminosity functions and galaxy clustering power spectra or correlation functions, as a function of the galaxy luminosity. Among these surveys are the DEEP2 [24] at $z \sim 1$ and Lyman-break galaxy surveys at $z \sim 3$ to 4 [25,26]. These clustering and luminosity function measurements can be interpreted in terms of a common CLF model [13,15,16] with which one can derive the appropriate relation to connect galaxy luminosity L to halo mass M at a given redshift z [19–21] terms of a conditional probability distribution function $P(M|L, z)$ [16,17,27].

Given that clustering measurements at large linear scales lead to estimates of $b_g(L)$ at a redshift different from SDSS and we also have a mechanism to connect $b_g(L)$ to $b_h(M)$ through a statistical description, this raises the possibility of further constraining the cosmological parameters than using SDSS galaxy power spectrum and SDSS galaxy bias-luminosity relation alone. In addition to the shape information captured by $b_g(L)$ at each redshift, the overall evolution of $b_g(L)$ as a function of redshift is further sensitive to the linear growth function of dark matter fluctuations. Since the growth function depends strongly on properties of the dark energy, such as the equation-of-state (EOS) relating the ratio of dark energy pressure to density, the combination of $b_g(L)$ measurements at several redshifts raises the possibility of constraining the EOS, in addition to cosmological parameters that probe the shape of the dark matter power spectrum.

The paper is organized as follows. In Sec. II, we provide a brief summary on how cosmological information can be extracted from $b_g(L, z)$ measurements by making use of the relations between galaxy luminosity and halo mass, captured by the probability distribution of a galaxy with a luminosity L to appear in a halo mass of mass M at a redshift z , $P(L|M, z)$, from CLF modeling described in Refs. [16,27]. In Sec. III, we describe the analysis of all data. In addition to $b_g(L)$ measurements at three different redshifts, we also make use of WMAP 5-year data [28] (by updating WMAP first-year data used in the analysis of [22]) and shape of the SDSS Luminous Red Galaxy (LRG) power spectrum [29] at low redshifts. § IV presents our results and we concluded with a summary of important constraints on cosmological parameters in § V.

II. MODELLING THE BIAS

The clustering of bound virialized objects is biased with respect to that of underlying dark matter distribution and with the decreasing number density of the objects, the bias factor is known to increase [3]. Thus, bright galaxies that are in rare massive halos are expected to be more biased than less luminous and abundant galaxies. Here, we model the relation between galaxy bias and halo bias following an approach similar to that of Ref. [22], but using the improved halo bias relation from Ref. [30] corresponding to the ellipsoidal collapse model instead of the fitting function for bias [31]. We also generalize this relation to higher redshifts (see, Appendix A of Ref. [32]):

$$b_h(\nu(z)) = 1 + \frac{1}{\sqrt{a}\delta_c} \left[\sqrt{a}(\nu^2) + \sqrt{ab}(\nu^2)^{1-c} - \frac{(a\nu^2)^c}{(a\nu^2)^c + b(1-c)(1-c/2)} \right], \quad (1)$$

in this expression $\delta_c = 1.686$ is the threshold over-density required for collapse of an over-density region and $\nu(z) = \delta_c/\sigma(M, z)$. The parameters a , b and c are constants and

we use the values suggested in Ref. [30] with $a = 0.707$, $b = 0.5$, and $c = 0.6$. The quantity $\sigma(M, z)$ is the rms mass fluctuation in spheres with radius $r = (3M/4\pi\rho)^{1/3}$, where M is the halo mass and ρ the mean matter density at redshift z . $\sigma(M, z)$ can be calculated through the relation:

$$\sigma^2(M, z) = \frac{1}{2\pi^2} \int P(k, z) W^2(k) k^2 dk \quad (2)$$

where $W(k)$ is the Fourier transform of top-hat window function. To compute Eq. (2) we use the linear matter power spectrum $P(k, z)$ generated by CAMB at redshift z for a given set of cosmological parameters. The dependence of bias on cosmological parameters is contained in the quantity $\nu(z) = \delta_c/\sigma(M, z)$ through information from the linear matter power spectrum from $\sigma(M, z)$.

As shown in several works involving measurements with data galaxy bias, as measured from the galaxy power spectrum at large physical scales corresponding to linear regime of clustering depends on luminosity, with brighter galaxies more strongly clustered than fainter ones [33,34]. In the halo model, galaxies are expected to populate dark matter halos and these halos are already biased with respect to the density field $b_h(M, z)$, where M is the mass of a halo at a redshift z . This is the quantity that is directly linked to cosmology, while bias measurements directly from data are a function of luminosity. We can relate the two through the probability distribution $P(M; L, z)$ [16,18,35] that a galaxy of luminosity L resides in a halo of mass M .

If we know the $P(M; L, z)$ then the bias at a fixed luminosity is given by:

$$b(L, z) = \int P(M; L, z) b_h(M, z) dM \quad (3)$$

For SDSS galaxies, the conditional probability $P(M; L, z)$ at low redshifts was derived based on a combination of SDSS galaxy luminosity function [36] and luminosity-dependent galaxy correlation functions [37] that probe the nonlinear, 1-halo term of the halo model [5]. The luminosity function is a strong probe of the $L_c(M)$ relation relating the luminosity of central galaxies to their host dark matter halo mass, as well as an average scatter in that relation [15], while the nonlinear (1-halo) part of the galaxy clustering, either the correlation function or the power spectrum, establishes information related to the CLF of satellite galaxies. The large, linear scale clustering provides necessary information related to $b_g(L)$. The degeneracies in the model parameters related to the CLF parameterization is broken with additional data such as the of galaxy-mass correlation function from SDSS galaxy-galaxy lensing measurements, similar to the analysis in Ref. [22], and we make use of results from publicly available SDSS galaxy-mass correlation functions [35, 36] in Ref. [16]. In the case of DEEP2 and higher redshift LBG data, we again use galaxy clustering (DEEP2: Ref. [24];

Subaru LBG: Ref. [26] and luminosity functions measurements (DEEP2: Ref. [38]; LBG: Ref. [25]) from the literature [27].

These conditional probability distributions are plotted in Fig. 1 as a function of redshift and luminosity. The distribution functions account for both central galaxies and the satellite galaxies, following the conditional luminosity function approach of Refs. [16,27]. Because of scatter in the relation between luminosity of central galaxies and the halo mass, the distributions have a scatter even for the central galaxy peak at the low-mass end. The previous analysis in Ref. [22] ignored this scatter and described the relation between central galaxy luminosity and halo mass with a delta function and assumed simple model description with one free parameter to describe the same relation for satellites. The distributions shown in Fig. 1 have additional uncertainties due to limitations in constructing CLFs and when fitting to data, we allow for this uncertainty in two ways: to account for an overall systematic error, we marginalize over a nuisance parameter b_* that scales the bias values by an overall factor and we include an additional error in bias measurements.

III. ANALYSIS

To fit bias measurements together with CMB and SDSS we performed a Monte Carlo Markov Chain analysis using a modified version of the publicly available code cosmoMC [39], with a convergence diagnostic based on the Gelman and Rubin statistic [40] (also known as ‘‘R-1’’ statistic, where R is defined as the parameter R is defined as the ratio between the variance of chain means and the mean of variances). Our cosmoMC runs consist of 2–3 chains typically with 15000–20000 points and we have for our chains $R - 1 < 0.01$, ignoring first 50% of the chains.

For each cosmological model we repeated the procedure described in the previous Section to calculate the theoretic

cal $b_g(L)$ relation and implemented, at each redshift, a relation similar to that used in Ref. [22] to compare with data

$$\chi^2 = \sum_i \frac{(b_{th,i} - b_*(b_{data}/b_*)_i)^2}{b_*^2 \sigma_{b/b_*}^2 + \sigma_{sys}^2} \quad (4)$$

where $b_{th,i}$ is the predicted bias at given luminosity for a given cosmological model, b_{data}/b_* is the observed bias at the same luminosity with error σ_{b/b_*} , and $\sigma_{sys} = 0.03$ is a systematic uncertainty in the modeling of bias [31]. The sum is over the number of bias data points at each redshift. $b_*(z)$ is the bias parameter, as a function of redshift, that accounts for an overall uncertainty in the bias measurements or modeling of bias based on CLFs. We treat it as a free parameter and marginalize over it when quoting cosmological parameter errors. This parameter shifts the model (or data) by a constant factor while keeping the shape the same. Thus, cosmology is measured through the shape of the $b_g(L)$ relation and not from its exact amplitude.

We included Eq. (4) into the likelihood for the 5-year WMAP data [28] and SDSS LRG power spectrum [29]. We sample first the following simple seven-parameters cosmological model assuming flat priors on parameters and treating the dark energy component as a cosmological constant: the physical baryon and cold dark matter densities, $\Omega_b h^2$ and $\Omega_c h^2$, the ratio of sound horizon to the angular diameter distance at decoupling θ_s , the overall normalization of the spectrum at $k = 0.002 \text{ h Mpc}^{-1}$, A_s , the amplitude of SZ spectrum A_{SZ} , the optical depth to reionization τ , and the scalar spectral index n_s . In our analysis we always assume spatial flatness ($\Omega_k = 0$). The bias parameter depends on redshift, so when using all redshift data set we introduce three free bias parameters for b_* in our analysis

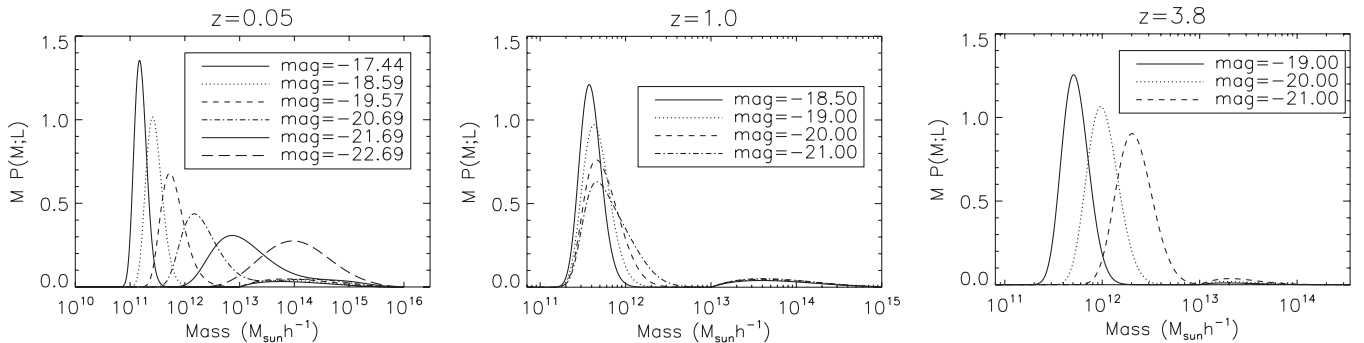


FIG. 1. The conditional probability distribution $P(M; L, z)$ relating the galaxy luminosity L and halo mass M , at different redshifts, as calculated in Refs. [16,27] for SDSS at $z \sim 0.05$, DEEP2 at $z \sim 1$, and LBGs at $z \sim 4$. The probabilities to find a galaxy at a given luminosity in a halo of mass M at redshift z is plotted as a function of the halo mass for luminosity values for which we have galaxy bias data. In each of the distributions, the peak at low halo masses is related to galaxies of the given luminosity that appear as central galaxies, while the tail extending to higher masses is for galaxies that appear as satellites in more massive halos. The width of the central peak is related to the scatter in the relation between luminosity of central galaxies and halo mass and cannot simply be described by a delta function relating a one-to-one correspondence between mass and luminosity [19–21].

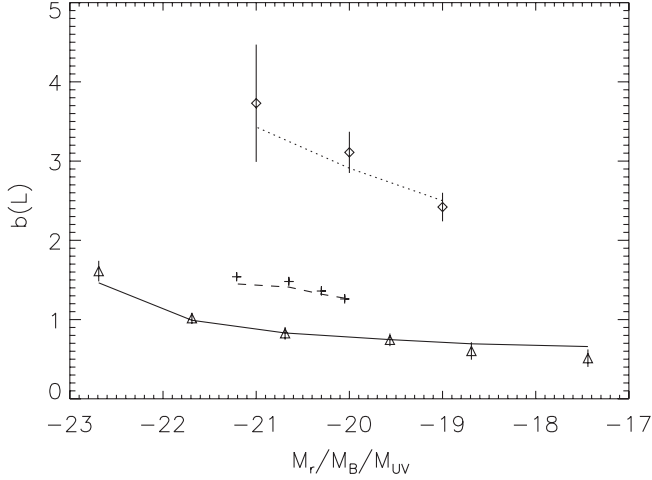


FIG. 2. The galaxy bias-luminosity data set used in our analysis for the three average redshifts of SDSS ($z \sim 0.05$), DEEP2 ($z \sim 1$), and LBG ($z \sim 3.8$) in comparison with the bias prediction calculated for the best fit Λ CDM model. The x-axis magnitude values plotted are M_r for SDSS, M_B for DEEP2, and M_{UV} for LBGs at $z \sim 3.8$.

in addition to the cosmological parameters listed above, for a total of 10 free parameters.

We also explored a larger set of parameters, introducing the sum of neutrino masses $\sum m_\nu$ and the dark energy equation-of-state w . When including both neutrino masses and w , we performed an analysis combining bias data with WMAP and LRG only and one also using Arcminute Cosmology Bolometer Array Receiver (ACBAR) data [41] and luminosity distance SN-Ia data (SNe) [42,43] assuming the prior from Hubble Space Telescope (HST) on the value of Hubble constant $h = 0.72 \pm 0.07$ [44].

We use galaxy bias data at three different redshifts: from Sloan Digital Sky Survey [34], six points between redshift 0.05 and 0.1, from DEEP2 redshift survey [24] four points

at $z \sim 0.8$ to $z \sim 1.1$, and from clustering of Lyman-break galaxies in the Subaru Deep Field [26,27] with three points at $z = 3.8$. These data points are shown in Fig. 2 with the best fit model.

IV. RESULTS

The constraints on cosmological parameters are shown in the Tables I, II, and IV with a comparison to constraints from WMAP 5-year data [28] alone both for a simple Λ CDM model (Table II) and for a model with a nonzero mass for neutrinos (Λ CDM + m_ν) (Table I), and with a dark energy equation-of-state different from the cosmological constant value of -1 in addition to neutrino mass (Λ CDM + m_ν + w) (Table IV). In addition to WMAP data, we also consider the combination of WMAP data and SDSS LRG power spectrum shape with $b_g(L)$ relation from SDSS, and finally the same data complemented with high-redshift $b_g(L)$ relations from DEEP2 and Subaru LBGs.

As we have discussed in the introduction, galaxy bias depends on rms fluctuation $\sigma(M)$ in spheres that contains a mass M . Galaxy bias measurements, as a function of luminosity, are therefore able to constrain all cosmological parameters that affect this quantity, mainly the amplitude of matter fluctuations σ_8 , power spectrum spectral index or tilt n_s , and neutrino mass, that affect the growth of density perturbations. As presented in Ref. [22], bias data at low redshifts from SDSS are already strongly sensitive to neutrino masses: with WMAP first-year data combined with SDSS galaxy power, spectrum shape and SDSS $b_g(L)$ data lead to $\sum m_\nu < 0.54$ eV at the 95% confidence level (see Table III for recent results on neutrino masses).

With WMAP 5-year data and SDSS LRG power spectrum complemented by galaxy bias data at $z \sim 0.05, 1$, and 3.8 , we are able to improve constraints on the sum of neutrino mass by a factor ~ 2 with respect to the result of

TABLE I. Mean values and 1σ constraints on cosmological parameters from WMAP + SDSS + bias data at all redshifts in comparison with constraints from WMAP alone, for models with dark energy equation of state allowed to vary.

	Λ CDM + w		Λ CDM + w + m_ν	
	WMAP5	+SDSS + all z 's	WMAP5	+SDSS + all z 's
$\Omega_b h^2$	0.02273 ± 0.00065	0.02248 ± 0.00060	0.02222 ± 0.00063	0.02234 ± 0.00060
$\Omega_c h^2$	0.1102 ± 0.0065	0.1160 ± 0.0041	0.1119 ± 0.0064	0.1223 ± 0.0065
τ	0.086 ± 0.017	0.087 ± 0.017	0.083 ± 0.016	0.083 ± 0.016
n_s	0.963 ± 0.016	0.965 ± 0.014	0.948 ± 0.017	0.954 ± 0.014
w	-1.06 ± 0.41	-1.12 ± 0.10	-1.23 ± 0.55	-1.30 ± 0.19
$\ln(10^{10} A_s)$	3.18 ± 0.05	3.22 ± 0.04	3.22 ± 0.06	3.24 ± 0.05
Ω_m	0.27 ± 0.10	0.259 ± 0.020	0.31 ± 0.13	0.267 ± 0.027
σ_8	0.81 ± 0.14	0.802 ± 0.037	0.71 ± 0.14	0.775 ± 0.045
$\sum m_\nu$	-	-	< 1.5 eV (95% CL)	< 0.59 eV (95% CL)
b_1^*	-	1.01 ± 0.03	-	1.03 ± 0.04
b_2^*	-	1.18 ± 0.06	-	1.21 ± 0.07
b_3^*	-	3.44 ± 0.35	-	3.44 ± 0.35

TABLE II. Mean values and 1σ constraints on cosmological parameters from WMAP + SDSS + bias data at all redshifts in comparison with constraints from WMAP alone, for Λ CDM and Λ CDM + m_ν models.

	Λ CDM		Λ CDM + m_ν	
	WMAP5	+SDSS + all z 's	WMAP5	+SDSS + all z 's
$\Omega_b h^2$	0.02273 ± 0.00062	0.02266 ± 0.00057	0.02226 ± 0.00063	0.02267 ± 0.00058
$\Omega_c h^2$	0.1099 ± 0.0062	0.1131 ± 0.0034	0.1110 ± 0.0062	0.1141 ± 0.0038
τ	0.087 ± 0.017	0.092 ± 0.017	0.084 ± 0.016	0.094 ± 0.016
n_s	0.963 ± 0.014	0.964 ± 0.013	0.950 ± 0.017	0.964 ± 0.013
$\ln(10^{10} A_s)$	3.18 ± 0.05	3.20 ± 0.04	3.21 ± 0.05	3.21 ± 0.04
Ω_m	0.258 ± 0.030	0.273 ± 0.017	0.331 ± 0.066	0.282 ± 0.023
σ_8	0.796 ± 0.036	0.807 ± 0.021	0.675 ± 0.084	0.759 ± 0.025
Σm_ν	-	-	<1.3 eV (95% CL)	<0.28 eV (95% CL)
b_1^*	-	1.01 ± 0.03	-	1.03 ± 0.03
b_2^*	-	1.21 ± 0.06	-	1.24 ± 0.06
b_3^*	-	3.44 ± 0.34	-	3.41 ± 0.33

TABLE III. Summary of the constraints at 95% confidence level on the sum of neutrino masses from various data sets in the literature. CMB means the collection of CMB data sets listed, respectively, in [45–47]. LSS means combination of SDSS and 2dF data sets. SNLS is the Supernova Legacy Survey, CMF is the cluster mass function, and Ly- α are the clustering measurements of the Lyman- α forest. We refer the reader to individual references given in the table for additional details related to datasets used and how constraints were derived.

Kahniashvili <i>et al.</i> (2005) [48]	Cluster Number Density	$\Sigma m_\nu < 2.4$ eV
Komatsu <i>et al.</i> (2008) [28]	WMAP5	$\Sigma m_\nu < 1.3$ eV
Tegmark <i>et al.</i> (2006) [29]	SDSS + WMAP3	$\Sigma m_\nu < 0.9$ eV
Komatsu <i>et al.</i> (2008) [28]	WMAP5 + BAO + SNe	$\Sigma m_\nu < 0.61$ eV
Kristiansen <i>et al.</i> (2007) [49]	WMAP3 + SDSS + SNLS + BAO + CMF	$\Sigma m_\nu < 0.56$ eV
Seljak <i>et al.</i> (2005) [22]	WMAP1 + SDSS + SDSS $b_g(L)$	$\Sigma m_\nu < 0.54$ eV
Mac Tavish <i>et al.</i> (2005) [47]	CMB + LSS	$\Sigma m_\nu < 0.48$ eV
Seljak <i>et al.</i> (2004) [23]	WMAP1 + SDSS + Ly α	$\Sigma m_\nu < 0.42$ eV
Kristiansen <i>et al.</i> (2007) [49]	WMAP3 + SDSS + SNLS + BAO + HST	$\Sigma m_\nu < 0.40$ eV
Fogli <i>et al.</i> (2008) [45]	CMB + HST + SNe + BAO + Ly- α	$\Sigma m_\nu < 0.19$ eV
Seljak <i>et al.</i> (2006) [46]	CMB + SDSS + 2dF + SNe + Ly- α	$\Sigma m_\nu < 0.17$ eV
This paper	WMAP5 + SDSS LRG + SDSS, DEEP2, LBG $b_g(L)$	$\Sigma m_\nu < 0.28$ eV

Ref. [22] obtaining $\Sigma m_\nu < 0.28$ eV at the 95% confidence level. We get a similar result if we only keep to $z \sim 0.05$ SDSS $b_g(L)$ data and the LRG power spectrum shape with WMAP 5-year data, since by adding additional bias data at higher redshifts we are also introducing to the analysis two more unknown parameters, i.e. the nuisance bias normalization parameters for redshifts $z = 1$ and $z = 3.8$, which are marginalized over when quoting parameter errors. The relative increase of a factor of ~ 2 in the neutrino mass limit compared with Ref. [22] is partly due to the improvement in both the CMB (WMAP 1-year to WMAP 5-year) and galaxy power spectrum shape data (SDSS DR2 power spectrum with $\sim 200\,000$ galaxies to SDSS DR4 LRG power spectrum with $\sim 400\,000$ galaxies) and partly due to the improvement in the CLF modeling of the $P(M|L, z)$ relation for SDSS galaxies. While the combination of all bias data at the three redshifts does not improve the limit on the sum of neutrino masses compared with the case with bias measurements from SDSS only, we

TABLE IV. Mean values and 1σ constraints on cosmological parameters from WMAP combined with ACBAR experiment, SNe-Ia data, HST prior and all bias data sets.

	WMAP5 + SDSS + ACBAR + HST + SNe + all z 's
$\Omega_b h^2$	0.02264 ± 0.00054
$\Omega_c h^2$	0.1203 ± 0.0055
τ	0.088 ± 0.016
n_s	0.961 ± 0.13
w	-1.125 ± 0.092
$\ln(10^{10} A_s)$	3.22 ± 0.05
Ω_m	0.285 ± 0.023
σ_8	0.778 ± 0.037
Σm_ν	<0.56 eV (95% CL)
b_1^*	1.03 ± 0.02
b_2^*	1.22 ± 0.07
b_3^*	3.41 ± 0.33

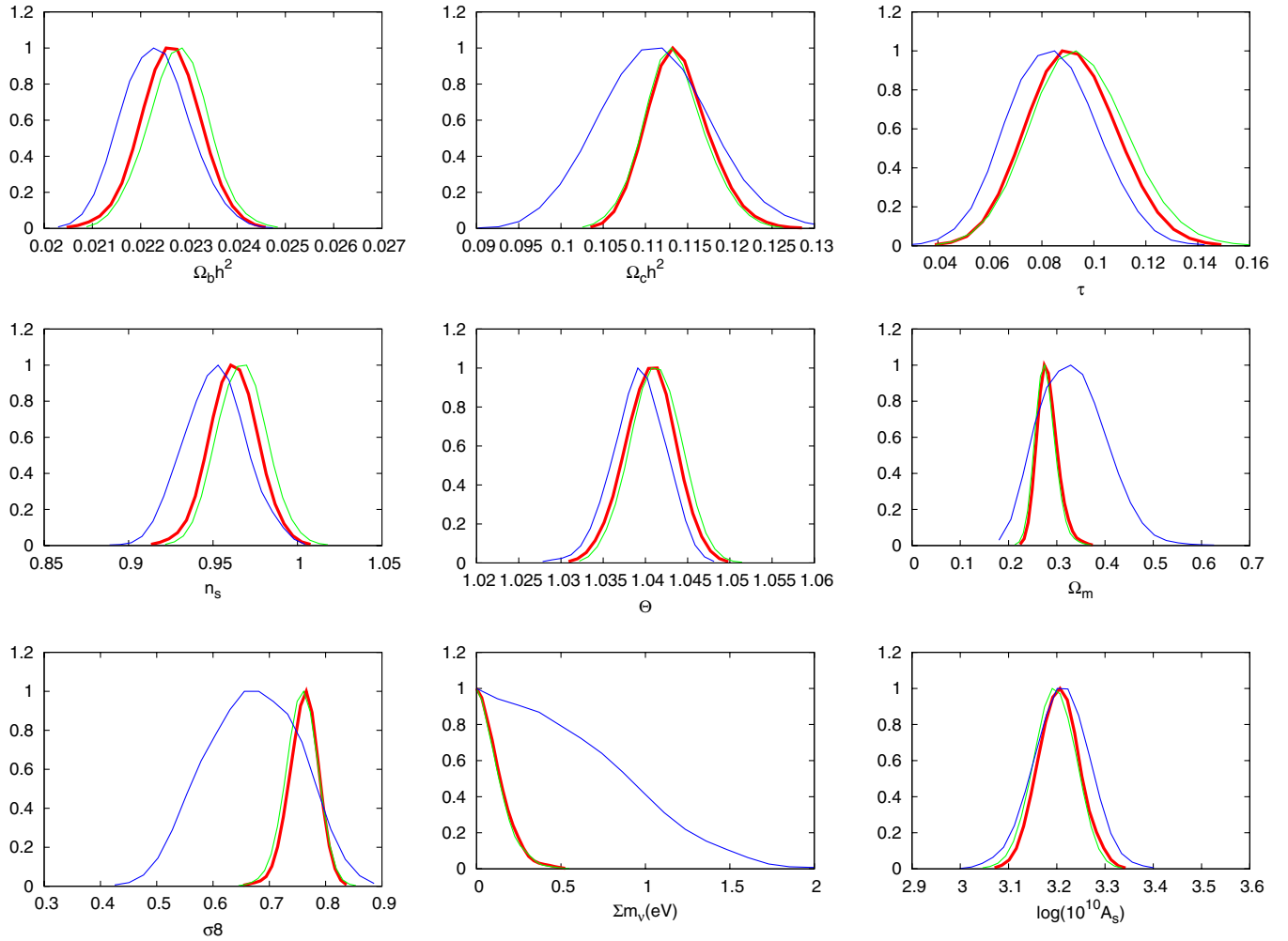


FIG. 3 (color online). Constraints on the parameters of the Λ CDM + m_ν model from WMAP alone (thin dark line), WMAP + LRG + bias data set at $z = 0.05$ (thin light line) and WMAP + LRG + all bias data sets (bold line).

do find small improvements in the uncertainties of the other parameters, as shown in Fig. 3 for the case of the Λ CDM model with a nonzero mass for neutrinos. We plot also probability contours in the σ_8 - n_s plane and in the Σm_ν - σ_8 plane in Figs. 4 and 5.

As the growth of structure depends also on the dark energy density and equation of state, we explored a more general parameter space, relaxing the assumption of a cosmological constant for dark energy and constraining the equation of state of dark energy w both in the case of neutrino mass fixed to zero and allowed to vary (Table I). We find that $w = -1.06 \pm 0.41$ with WMAP 5-year data alone and -1.12 ± 0.10 with WMAP 5-year + SDSS LRG power spectrum shape and all $b_g(L)$ data. For comparison, the WMAP 5-year data combined with Baryon Acoustic Oscillation (BAO) data [50] gives $w = -1.15 \pm 0.21$.

Our constraints on σ_8 are $\sigma_8 = 0.759 \pm 0.025$ in the case of Λ CDM + m_ν , while WMAP combined BAOs [50], and SNe data gives $\sigma_8 = 0.732 \pm 0.062$. The analysis of

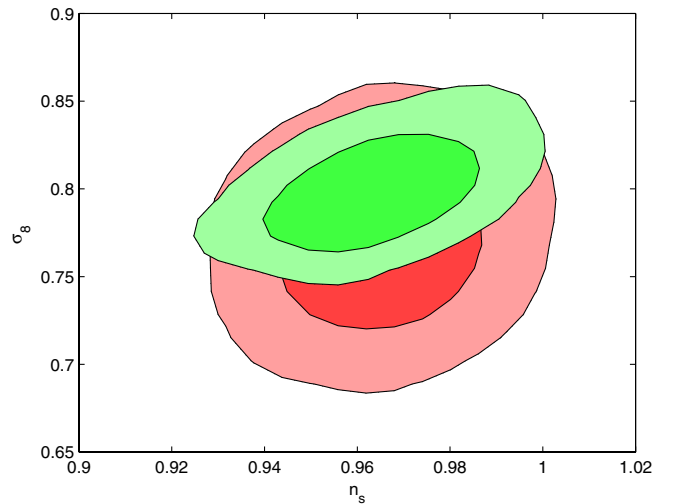


FIG. 4 (color online). Joint two-dimensional posterior probability contour plot in the σ_8 - n_s plane showing 68% and 95% contours from WMAP alone (contours behind) and WMAP + LRG + bias data at all redshifts (front contours).

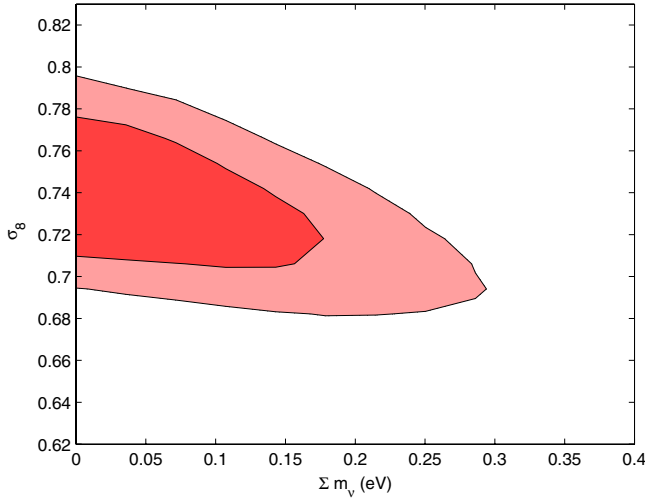


FIG. 5 (color online). Joint two-dimensional posterior probability contour plot in the σ_8 - $\sum m_\nu$ plane showing 68% and 95% contours from WMAP + LRG + bias data at all redshifts.

bias data combined with CMB and SDSS showed in [22] gives 0.854 ± 0.062 .

For the most general parameter space explored in our analysis, with both sum of the neutrino masses and dark energy equation of state allowed to vary, we improve constraints on equation of state with respect to WMAP alone ($w = -1.23 \pm 0.54$), obtaining $w = -1.30 \pm 0.19$. When w is allowed to vary, constraints on neutrino masses are weakened to $\sum m_\nu < 0.59$ eV at the 95% confidence level, but are still improved with respect to $\sum m_\nu < 0.66$ eV at the same 95% confidence level with WMAP + BAO + SNe, for the same model. We then performed the same analysis combining WMAP, LRG, and all bias data set with ACBAR and SNe data, assuming the prior from HST on the value of Hubble constant, and we improve the last constraints on neutrino masses and w , obtaining $\sum m_\nu < 0.56$ eV at the 95% confidence level and $w = -1.125 \pm 0.092$. These results are shown in Table IV. In Fig. 6, we plot the probability contours for w and $\sum m_\nu$ from WMAP combined with LRG and bias data sets and the same combined also with ACBAR and SNe, with the prior from HST. In the last case, the inclusions of SNe and ACBAR data and of the prior on h slightly improves the constraints on $\sum m_\nu$, but above all improves constraints on w (see also Tables I, II, III, and IV).

It is interesting to note that these limits on the sum of neutrino masses are almost the strongest cosmological constraints available in literature (as we can see from Table III). Compared with the results we present with a combination of WMAP 5-year data, SDSS LRG power spectrum shape, and $b_g(L)$ data at three redshifts, better constraints on the sum of neutrino masses have been published with cosmological analyses that also make use of clustering measurements of the Lyman- α forest [45,46]. There is some possibility that Ly- α statistics may be more

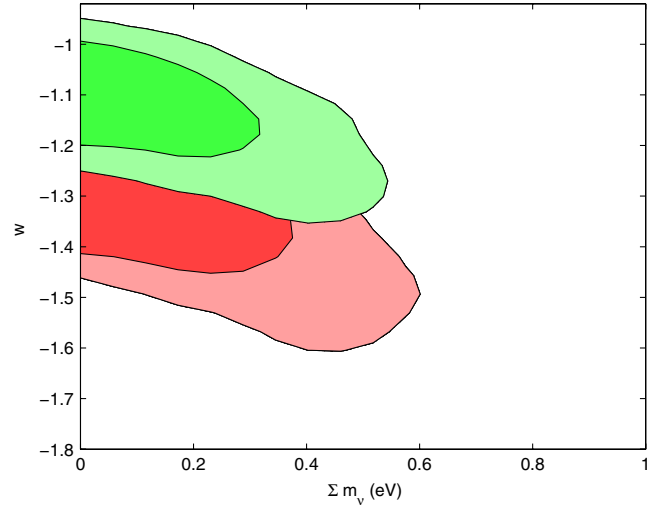


FIG. 6 (color online). Joint two-dimensional posterior probability contour plot in the $\sum m_\nu$ - w plane showing 68% and 95% contours from WMAP + LRG and bias data at all redshifts (contours behind) and WMAP + ACBAR + SNe + LRG + HST and bias data at all redshifts (front contours).

subject to uncertainties in both the measurement and the modeling from the theory side.

The strong limit imposed with Ly- α measurements, combined with other cosmological data, that lead to $\sum m_\nu < 0.17$ eV [46], is in tension with the evidence for a nonzero neutrino mass claimed in Ref. [51], where the combination of CMB data with the 2° Field Galaxy Redshift Survey [52] data, x-ray luminosity function observations and baryonic gas mass fraction measurements led to the constrain $\sum m_\nu = 0.32^{+0.29}_{-0.15}$ eV. Independent of Ly- α data, with a 95% confidence level limit on the sum of neutrino masses of 0.28 eV, we can also conclusively state that this suggested detection of neutrino masses limit is not compatible with a different set of cosmological data involving galaxy clustering and clustering bias, combined with CMB. The origin of the result in Ref. [51] was due to the inclusion of x-ray measurements that favored low values of matter amplitude fluctuations, $\sigma_8 = 0.70 \pm 0.04$, and the use of the first-year WMAP data that favored an higher value of $\sigma_8 \sim 0.9$. Because of the degeneracy between $\sum m_\nu$ and σ_8 from CMB data the inclusion of x-ray luminosity function data in the analysis led therefore to the evidence for a nonzero neutrino mass, that can be ruled out when considering increased uncertainties in the x-ray data. We also refer the reader to Refs. [51,53] for further discussions about this result.

In the near future, cosmological data could reach the sensitivity level of ~ 0.1 eV to begin to distinguish between the normal and the inverted neutrino mass hierarchy. For example, inverted hierarchy could be ruled out if we can exclude that $\sum m_\nu > 2\sqrt{(\Delta m_{23}^2)}$, where $\Delta m_{23}^2 \sim 2.4 \cdot 10^{-3}$ eV² is the squared mass difference between neutrino mass eigenstates [54]. We also note that the current limit on

the sum of neutrino masses from cosmological observations could be quite important for ongoing and future experiments, which aim to measure neutrino masses: for example, there is a tension between our results and the limits of $0.16 < m_{\beta\beta} < 0.52(2\sigma)$ on the neutrino mass coming from the analysis of part of the Heidelberg-Moscow experiment on neutrinoless double beta decay [55]: moreover, the next-generation tritium β -decay experiment KATRIN [56] would not be able to measure the absolute value of neutrino mass because its detectability threshold is at ~ 0.2 eV.

V. CONCLUSIONS

Here, we have used galaxy bias measurements as a function of luminosity to put constraints on cosmological parameters, mainly σ_8 , $\sum m_\nu$, and the dark energy equation-of-state w . We used three galaxy bias-luminosity data sets at three different redshifts and improved by roughly a factor of 2 previous constraints obtained with an analogous set of data, finding the sum of neutrino masses to be $\sum m_\nu < 0.28$ eV at the 95% confidence level for a Λ CDM + m_ν model, with $\sigma_8 = 0.759 \pm 0.025$. We also have shown that redshift evolution of the bias information can constrain the equation-of-state of dark energy, and we obtained the constraints $w = -1.12 \pm 0.10$ for a Λ CDM + w model and $w = -1.30 \pm 0.19$ for a Λ CDM + m_ν + w model.

In the case of dark energy equation of state allowed to vary the constraints on the sum of neutrino masses are weakened to $\sum m_\nu < 0.59$ eV at the 95% confidence level, but this still improves previous constraints from WMAP combined with BAO and SNe data only ($\sum m_\nu < 0.66$ eV). While the inclusion of Ly- α data have led to stronger constraints on the sum of neutrino masses, our constraint with a minimal set of data is still competitive and only uses clustering information of galaxies and the primordial fluctuations as probed by the CMB. In the future, methods such as the one we use could further improve constraint on neutrino masses independent of Ly- α data and achieve the sensitivity necessary to distinguish between the normal and the inverted neutrino mass hierarchies.

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