Neutrino masses with Lyman-α forest power spectrum

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Abstract

We present constraints on neutrino masses in the case of the ΛCDMν and ΛWDM models, using the one-dimensional Lyα-forest power spectrum measured the Baryon Oscillation Spectroscopic Survey (BOSS) of the Sloan Digital Sky Survey (SDSS-III), complemented by Planck 2015 Cosmic Microwave Background (CMB) data.

Fitting Lyα data alone leads to cosmological parameters in excellent agreement with the values derived independently from CMB data, except for a weak tension on the scalar index n_s. Combining BOSS Lyα with Planck CMB constrains the sum of neutrino masses to $\sum m_\nu < 0.12$ eV (95% C.L.) including all identified systematic uncertainties.

In the case of ΛWDM model, we issue the tightest bounds to date on pure dark matter particles: $m_X \gtrsim 4.35$ keV (95% C.L.) for early decoupled thermal relics and its corresponding bound for a non-resonantly produced right-handed neutrino $m_s \gtrsim 26.4$ keV (95% C.L.).

1 Introduction

The flux power spectrum of the Lyman-α (Lyα) forest in quasar absorption spectra is a powerful tool to study clustering in the Universe, at redshifts $\sim 2-4$. Compared to a model derived from a set of dedicated hydrodynamical simulations, the Lyα-flux power spectrum can provide valuable information on the formation of structures and their evolution. Furthermore, by probing scales down to a few Mpc, the 1D flux power spectrum is also sensitive to neutrino masses through the suppression of power on small scales that neutrinos induce because they become non-relativistic at small redshift and they therefore free-stream during most of the history of structure formation. We here use the 1D Lyα flux power spectrum measured by [1] with the DR9 release of BOSS quasar data , and a grid of 36 hydrodynamical simulations having a resolution equivalent to 3×3072^3 particles in a $(100\ h^{-1}\ \mathrm{Mpc})^3$ box [2, 3], to constrain both cosmology and the sum of the neutrino masses $\sum m_\nu$.

Cosmic Microwave Background (CMB) can also constrain $\sum m_\nu$. In the standard thermal history of the Universe, massless neutrinos have a temperature corresponding to ~ 0.17 eV at the epoch of last scattering. This temperature sets the range of masses for which neutrinos start to have an appreciable effect on the CMB power spectrum to $\sum m_\nu > 3 \times 0.17 = 0.51$ eV. Below this mass, the neutrinos are still relativistic at recombination and have no impact on the primary CMB anisotropies. The latest limit on $\sum m_\nu$ from CMB data alone is at the level of 0.7 eV [4].

Lyα data alone have sensitivity to $\sum m_\nu$ at the level of about 1 eV due to the fact that the scales probed by Lyα forests are in the region where the ratio of the power spectra for massive to massless neutrinos is quite flat. However, a tight constraint on $\sum m_\nu$ can be obtained by combining CMB data, which probe the initial power spectrum unaffected by $\sum m_\nu$, and Lyα data, which probe the suppressed power spectrum. Thus, Lyα measures the power spectrum level, defined by σ_8 and Ω_m, CMB provides the correlations between these parameters and $\sum m_\nu$, and the joint use of these two probes significantly improves the constraint on $\sum m_\nu$ compared to what either probe alone can achieve.

In the case of ΛWDM models, when traveling, massive particles can interfere with the gravitational collapse of structures. This manifests in a step-like suppression in the matter power spectrum at scales above $\sim 0.01(\mathrm{km/s})^{-1}$ for particles of a few keV. These particles have a free-streaming scale which falls below the Mpc range and within the region probed by the Lyα forests of distant high redshift quasars. Lyα forest data therefore provide again an ideal tool to study keV-range WDM and give constraints on the lower-bound mass of early decoupled thermal relics.

2 Data, Simulations and Methodology

As our large-scale structure probe, we use the 1D Lyα-flux power spectrum measurement [1] from the first release of BOSS quasar data. The data consist of a sample of 13 821 spectra selected from the larger sample of about 60 000 quasar spectra of the SDSS-III/BOSS DR9 [5, 6] on the basis of their high quality, high signal-to-noise ratio and good spectral resolution ($< 85\,\mathrm{km\ s^{-1}}$ on average over a quasar forest). We use 12 redshift bins, spanning the range $2.1 < z < 4.5$, as shown on Fig. 1. We do the analysis on 420 Lyα data points, consisting of 12 redshift bins and 35 k bins.

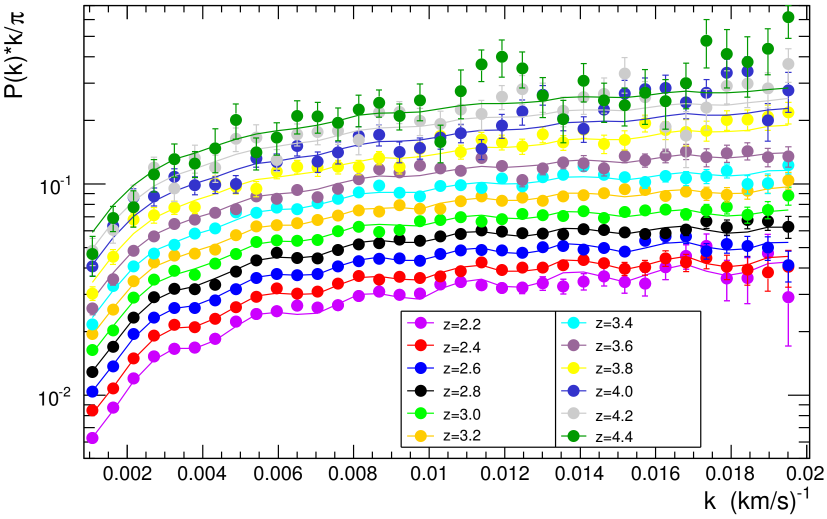

Figure 1: *1D Lyα forest power spectrum from the SDSS-III/BOSS DR9 data. The solid curves show the best-fit model when considering Lyα data alone. The oscillations arise from Lyα-Si III correlations, which occur at a wavelength separation $\Delta\lambda = 9.2\AA$.*

The cosmic microwave background (CMB) data and results we use, are described in the 2015 Planck cosmological parameters paper [4]. In our analysis [7], we consider several subsets of Planck data and we obtain very similar results for the different configurations. Therefore, in this proceeding, we focus on the base configuration, denoted 'TT+lowP' as in [4] which uses the TT spectra at low and high multipoles and the polarization information up to multipoles $\ell = 29$ ('lowP').

The cosmological interpretation of the Lyα power spectrum measurement is obtained by comparison to a set of full hydrodynamical cosmological simulations that were produced specifically for that purpose. The methodology and technical framework for these simulations are presented in [2], while all issues concerning the inclusion of neutrinos in the pipeline and their impact on the power spectrum are described in detail in [3]. The neutrinos, considered as three degenerate species, are globally introduced as a third particle type, in addition to cold dark matter and baryons. The simulations were run using `CAMB` to compute the transfer functions and linear power spectra at $z = 30$, then `2LPT` (second-order Lagrangian Perturbation Theory) to compute the initial displacement of the particles, and finally `GADGET-3` [8] for the hydrodynamical processing. Using a splicing technique [2], we infer the flux power spectrum of an equivalent ($L = 100\,h^{-1}$ Mpc, $N = 3072$) simulation from a combination of three lesser ones: a scaled-down (25, 768) to provide high resolution on small scales, a large-box low-resolution (100, 768) for large scales, and a small-box low-resolution (25, 192) which bridges the preceding two at intermediate scales.

The ΛWDM analysis described in [9] shares a similar strategy. We just use two particle types, baryons and dark matter instead of three types. We explore two pure ΛWDM models with $m_X = 2.5$ and 5 keV thermal relics implemented using the neutrino mass degeneracy parameters in `CAMB` to encode $\Delta N_{\rm eff} \propto (T/T_\nu)^4$, which models the impact of any massive particle with temperature T coupled to photons prior to standard neutrino decoupling.

By varying the input parameters (cosmological and astrophysical parameters, total neutrino mass or inverse of thermal relic mass) around a central model chosen to be in agreement with the latest Planck results [4], the simulations were used to derive a second-order Taylor expansion, including cross-terms, around the central model. Finally, we minimize a likelihood built around three categories of parameters which are floated. The first category describes the cosmological model assuming a flat Universe. The second category models the astrophysics within the IGM, and the relationship between the gas temperature and its density. The purpose of the third category (nuisance parameters) is to describe the imperfections of our measurement of the 1D power spectrum. This likelihood allows us to compare the measurement to the power spectrum predicted from the hydrodynamical simulations described above.

3 Results for ΛCDMν

The maximization of the likelihood with the Lyα data, imposing a Gaussian constraint $H_0 = 67.4 \pm 1.4$ gives a best-fit value of $\sum m_\nu$, the sum of the neutrino masses equal to 0.41 eV and compatible with 0 at about 1σ as described in[7]. The upper bound on $\sum m_\nu$ is thus 1.1 eV (95% C.L.). The cosmological parameters $\sigma_8 = 0.830 \pm 0.032$ and $\Omega_m = 0.293 \pm 0.013$ are in excellent agreement with the values derived independently from CMB data [4]. We observe a weak tension at the 2.3 σ level on the scalar index, $n_s = 0.939 \pm 0.010$. The fitted values of the astrophysical and nuisance parameters are all well within the expected range. The 2D constraints in the $n_s - \sigma_8$, $\sum m_\nu - \Omega_m$ and $\sum m_\nu - \sigma_8$ planes are shown as the red contours in Fig. 2.

Then we combine the Lyα likelihood (imposing no constraint on H_0) with the likelihood of Planck 2015 data. We constrain $\sum m_\nu$ to be less than 0.12 eV (at 95% C.L.) from Lyα and Planck TT+lowP, closer to to the inverted-hierarchy lower bound of 0.10 eV than current CMB-based limits. For comparison, Planck (TT+lowP) alone constrains the sum of the neutrino masses to $\sum m_\nu < 0.72\ eV$ and Planck (TT+lowP) with BAO measurements to $\sum m_\nu < 0.21$ eV.

In addition, when we release the effective number of neutrino species, N_{eff}, as described in a similar analysis[10] , we obtain $N_{eff} = 2.91 \pm 0.22$ (95% C.L.). This result rules out the possibility of a sterile neutrino thermalized with active neutrinos (i.e., $N_{eff} = 4$) at a significance of 5σ.

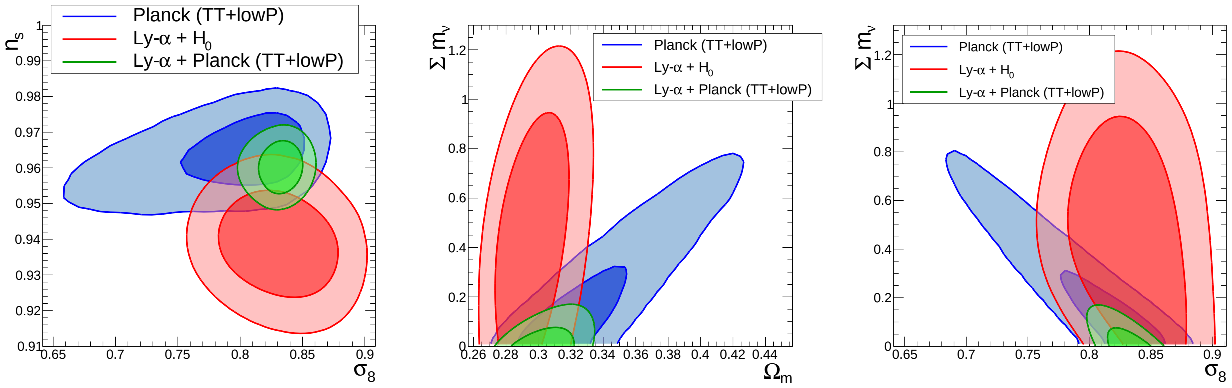

Figure 2: *2D confidence level contours for the* (σ_8, n_s) , $(\Omega_m, \sum m_\nu)$ *and* $(\sigma_8, \sum m_\nu)$ *cosmological parameters. The 68% and 95% confidence contours are obtained for the BOSS Ly*α *data with a Gaussian constraint* $H_0 = 67.4 \pm 1.4$ km s^{-1} Mpc^{-1}, *for the Planck 2015 data (TT+lowP) and for the combination of BOSS Ly*α *and Planck 2015.*

4 Results for ΛWDM cosmology

The likelihood used in the case of ΛWDM cosmology is quite similar to the likelihood used in the previous section (see the full description in [9]). Its maximization gives the most stringent lower limit on WDM mass to date, set at $m_X > 4.35\,\mathrm{keV}$ (95% CL) for thermal relics. Using the Dodelson-Widrow [11] framework, in which the sterile neutrinos are produced by oscillations with the active neutrinos in a seesaw mechanism in the early Universe ($T \sim 100\,\mathrm{MeV}$ for keV masses), we can derive a limit on non-resonantly-produced sterile neutrinos $m_s \gtrsim 26.4\,\mathrm{keV}$ (95% C.L.) as shown on Fig. 3. Our work distinguishes itself from those of our predecessors [12, 13, 14] mainly in the usage of a significantly larger sample of medium-resolution quasar spectra (SDSS-III) than previously (SDSS-I) and in a sharpened understanding of the systematics related to our numerical simulations.

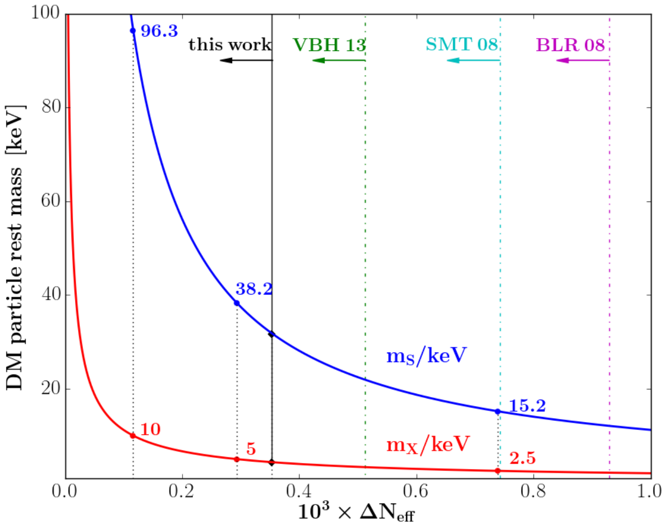

Figure 3: Relation between $\Delta N_{\mathrm{eff}} \propto (T/T_\nu)^4$ and dark matter particle mass in the thermal relic (magenta) and Dodelson-Widrow [11] sterile neutrino (blue) cases. The dark matter lower-bound mass obtained by our analysis [9] and previous works are illustrated by the solid black vertical lines: BLR09 [14], SMT06 [13] and VBH08 [12].

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