Neutrino Signatures on the High Transmission Regions of the Lyman-α Forest

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We quantify the influence of massive neutrinos on the statistics of low density regions in the intergalactic medium as probed by the Lyman-α forest at redshifts $z = 2.2-4$. Based on mock quasar spectra from hydrodynamic simulations with cold dark matter, baryons and neutrinos, we find that the probability distribution of weak Lyman-α absorption features, as sampled by Lyman-α flux regions at high transmissivity, is strongly affected by the presence of massive neutrinos, when the amplitude of the matter power spectrum is fixed on large scales from measurements of the microwave background anisotropies. The application of the derived statistic to observed quasar spectra would provide a new sensitive measure of neutrino masses.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Linear power spectra for different neutrino masses at $z = 0$ (upper lines) and $z = 3$ (bottom lines). The inner panel shows the linear (solid lines) and non-linear (dotted lines) power spectrum at $z=3$ normalized to the case without neutrinos. On scales $k < 0.03$ h Mpc$^{-1}$ changes in the non-linear power spectra are driven by the differences in the linear power spectra.}
\end{figure}

\textit{Introduction.} Neutrino oscillation experiments revealed that neutrinos are not massless particles. Since then a major effort has been dedicated to measure or constrain neutrino masses. Current laboratory bounds constrain the electron neutrino mass to $m_{\nu_e} < 2.05$ eV \cite{1, 2}. Cosmological bounds for the sum of all neutrino masses are still significantly stronger: constraints from WMAP7 alone yield $\Sigma_i m_{\nu_i} < 1.3$ eV \cite{8, 9}. The tightest $2\sigma$ upper limit of $\Sigma_i m_{\nu_i} < 0.17$ eV, is obtained by combining cosmic microwave background (CMB) results, LSS and Lyman-α forest \cite{8} data sets (see \cite{8} for a summary of current and future neutrino mass constrains). Among all the different observables the Lyman-α forest is particularly constraining since it probes structures over a wide range of redshift, in a mildly non-linear regime and on small scales where the neutrino signature is present \cite{10, 11, 12}.

The dynamics of cosmological neutrinos is very different from that of the dominant cold dark matter (CDM) component. The large velocity dispersion of neutrinos suppresses their power spectrum of density fluctuations on small scales, making the shape of the total power spectrum a potential probe of neutrino masses.

Previous studies have addressed the role of neutrinos in dark matter halos \cite{13, 15}, LSS \cite{16, 21} and the intracluster medium \cite{22}, using both linear theory and N-body/hydrodynamic techniques for the non-linear regime. It has been shown that on scales of 1-10 h$^{-1}$Mpc the non-linear suppression is redshift and mass dependent in a way that is different from a naive extrapolation of linear theory.

In this Letter we study the effect of massive neutrinos on the properties of low density regions or \textit{voids} in the intergalactic medium (IGM). Naturally, neutrinos have only a mild effect on dark matter halos \cite{13, 15}, since their large velocity dispersion prevents their clustering on small scales. In contrast, we find that the impact of neutrinos on void properties is much stronger. Voids are relatively empty regions with $\delta = \rho_m/\rho_m - 1$ ranging from almost $-1$ in their cores to $\sim -0.7$ at radii $10 - 20$ Mpc at $z = 0$ \cite{23}. By solving the dynamical equations for an isolated spherical top-hat underdense perturbation, we find that neutrinos modify the evolution of underdense regions by making them smaller and denser. Neutrinos contribute to the interior mass of the underdense region delaying the rate at which CDM is being evacuated from its interior and slowing down the velocity of the shell surrounding it. We find that the linearly extrapolated density contrast when the underdense region enters into its non-linear phase decreases by $\sim 10\%$ for neutrinos with $\Sigma_i m_{\nu_i} \sim 1$ eV. Using the analytic model presented in \cite{24} we find that the statistics of voids depend on both $\sigma_8$ and $\Sigma_i m_{\nu_i}$. Lyman-α voids and their dependence on other cosmological parameters have been studied in \cite{25}. Here we study the dependence of void properties on the
sum of the neutrino masses. We focus our attention on the Lyman-α signature of low density regions, and introduce a new and simple statistical tool that samples most of the IGM volume and appears highly sensitive to neutrino masses.

Numerical Method. Our mock quasar spectra are based on cosmological simulations run with the TreePM-SPH code GADGET-3 [26]. The code has been extended to include neutrinos either by solving their potential on the mesh or by representing them as discrete particles [21]. Here, we use primarily the first implementation and refer the reader to [17, 18, 21] for a critical comparison of the two methods. Our simulations consist of 2 × 512^3 CDM plus gas particles sampling a periodic box of 512 h^{-1}Mpc. We adopt a flat ΛCDM background with cosmological parameters Ω_{CDM} + Ω_{ν} = 0.25, Ω_{Λ} = 0.7, Ω_{b} = 0.05, h = 0.7 and n_s = 1. We consider three degenerates neutrino species with a total mass of Σm_{ν} = 0.0, 0.3 and 0.6 eV. The initial power spectra of most of our simulations, produced with CAMB[1], are normalized for all neutrino masses at a wavenumber 2 × 10^{-4}h \text{ Mpc}^{-1}, corresponding to the scale constrained by CMB data. This produces different values of σ_8 = 0.877, 0.806 and 0.732 at z = 0 for the models with Σm_{ν} = 0.0, 0.3 and 0.6 eV, respectively (see Fig. 1). Our initial conditions are generated at z = 49.

For each simulation we consider snapshots at redshifts z = 2.2 and z = 4 that bracket the range of interest for the observed Lyman-α forest in quasar spectra from ground-based telescopes. For each snapshot we sample 4500 random line of sights (RLOSs) uniformly distributed along each x, y or z direction. For each RLOS we extract the baryon density contrast ρ_b(r)/ρ_b and the peculiar velocity V_p(r) along the line of sight and then compute the transmitted flux e^{-τ(u)} in redshift space (with u in km s^{-1}), where τ is the Lyman-α optical depth, by using the Fluctuating Gunn Peterson Approximation:

\[\tau(u) = A \int_{-\infty}^{+\infty} dx \delta[u - x - V_p(x)] \left(\frac{\rho_b(x)}{\rho_b}\right)^{1.6},\]

with z = H(z)r/(1 + z) the redshift space coordinate and A is a factor that depends on the global thermal history of the IGM [27],

\[A = 0.433 \left(\frac{1 + z}{3.5}\right)^6 \left(\frac{Ω_b h^2}{0.02}\right)^2 \left(\frac{0.65}{h}\right) \left(\frac{3.68 H_0}{H(z)}\right) \times \left(\frac{1.5 \times 10^{-12} \text{s}^{-1}}{\Gamma_{HI}}\right) \left(\frac{6000 K}{T_0}\right)^{0.7}\]

where \(\rho_b/\rho_b\) is the hydrogen photoionization rate. The power-law index in the scaling with \(\rho_b/\rho_b\) arises from the equation of state for the IGM temperature, \(T = T_0(\rho_b/\rho_b)^{\alpha}\) [28], with \(\alpha \approx 0.6\). In all our calculations we adopt \(T_0 = 10^4K\) and choose \(\Gamma_{HI}\) such that the mean flux over the whole set of RLOS reproduce the observed mean flux at redshift z [29] \(F = e^{-\tau(z)}\) with \(\tau_{eff}(z) = 0.0023(1 + z)^{2.65}[30]\). We neglect effects of thermal broadening. Finally, we smooth the flux over a scale of 1 h^{-1}Mpc which is larger than the Jeans length to avoid sensitivity to substructure below the Jeans scale which is affected by numerical resolution and astrophysical processes (e.g. feedback from galactic winds).

Figure 2 shows the baryon density contrast, ρ_b/ρ_b, and peculiar velocity, V_p, extracted along a RLOS as a function of the comoving coordinate r together with the corresponding transmitted flux F = e^{-τ} in redshift space, plotted in terms of the mean flux at redshift z.

Analysis of the simulations. We focus our analysis on the statistical properties of low density regions that produce weak absorption features. A region is a continuous domain in the transmitted flux profile which remains above a given threshold. The higher the threshold, the lower the absorption in that region. For each RLOS we extract the transmitted flux from ρ_b/ρ_b and V_p and count the number of regions above the selected threshold. This results in a statistical estimate of the low absorption contribution to the Lyman-α signal, and allows us to quantify the impact of neutrinos on those regions.

In Fig. 3 we plot the probability distribution function (PDF) for the number of regions per path length of 100 h^{-1}Mpc\(^2\) above a threshold \(F/F < 1.14\) at redshift \(z = 2.2\) (top) and at redshift \(z = 4.0\) for a threshold \(F/F = 1.70\) (bottom) for three different neutrino masses, \(Σm_{νi} = 0.0, 0.3, 0.6\) eV. We have verified that these PDFs do not change if we increase the number of

\[\text{http://camb.info/}\]

\[\text{2 Non-integer numbers are due to the path length normalization.}\]
PDFs have long tails with a very low probability that extend up to 10-12. The $\sigma_8 - \Omega_\nu$ degeneracy is not perfect and can be broken by studying the spectra at different redshifts.

RLOS, i.e. our statistical sample of RLOS is large enough to reliably measure the PDF. Figure 3 shows that the neutrino mass has a significant impact on the mean of the distributions. In Fig. 4 we plot the mean of the distributions, i.e. the average number of regions per path length of 100 $h^{-1}$Mpc above a given threshold, as a function of the threshold for the three different neutrino masses ($\Sigma_i m_{\nu_i} = 0.0, 0.3, 0.6$ eV) at redshift $z = 2.2$ (top) and $z = 4.0$ (bottom). This shows clearly that the higher the threshold, the larger are the differences between the various neutrino cosmologies. This is the expected neutrino signature as we discuss below.

$\sigma_8 - \Omega_\nu$ degeneracy. In order to investigate the degeneracy between $\sigma_8$ and $\Omega_\nu$, we run one simulation with $\Sigma_i m_{\nu_i} = 0.6$ eV and the same $\sigma_8 = 0.877$ as the $\Sigma_i m_{\nu_i} = 0.0$ eV model. This mimics the case for which $\sigma_8$ is measured independently and one would like to constrain $\Omega_\nu$. We find that the PDF for the number of regions above a threshold of 1.14 at $z = 2.2$ is close to the one with $\Sigma_i m_{\nu_i} = 0.0$ eV (see Fig. 3), but not identical. Larger differences between these two models show up at $z = 4.0$ (see Fig. 4). Given that neutrinos affect the growth factor, we conclude that the degeneracy between $\sigma_8$ and $\Omega_\nu$ can be broken by examining the redshift evolution of the PDFs.

Numerical convergence. We explicitly checked that relative differences between our neutrino models are numerically converged against mass and spatial resolution. Furthermore, we used the neutrino particle implementation and found the same trends in the neutrino signature as with the grid method, although relative differences between the different models are even slightly larger when we use the particle implementation. This is due to the fact that non-linear neutrino effects, such as phase mixing, are only captured properly by using the particle implementation. We note however that the grid implementation in the mildly non-linear Lyman-$\alpha$ regime is fully justified since non-linear neutrinos effects should not be particularly important at those redshifts and at $k < 1$ $h$ Mpc$^{-1}$.

Discussion and Conclusions. We have presented a novel and simple method to measure neutrino masses by studying the properties of low density regions in the Lyman-$\alpha$ forest of quasar spectra. Those regions correspond to the inner parts of non-linear voids. We find that the number of regions above a given threshold in the flux is strongly affected by neutrinos, especially once the amplitude of the matter power spectrum is fixed at large scales (i.e. normalized by the CMB anisotropies). The changes between different models are due to two factors: the change in amplitude and slope in the linear power spectrum driven by neutrinos and non-linear effects associated with CDM and neutrinos (note that neutrinos modify the non-linear evolution of the CDM distribution). The inner panel of Fig. 4 shows the linear (solid lines) and non-linear (dotted lines) versions of the power spectrum at $z = 3$ normalized to the case without neutrinos. Whereas the modification on large scales ($k < 0.03$ $h$ Mpc$^{-1}$) is driven by the linear power spectrum, we find that on smaller spatial scales the non-linear effects dominate. We have also shown that the $\sigma_8 - \Omega_\nu$ degeneracy can be broken by studying the redshift evolution of low density regions in the Lyman-$\alpha$ forest flux.

Our method can be used to constrain neutrino masses by measuring the average number of regions as a function of threshold. In the subplot of Fig. 4 we show the average number of regions per path length of 100 $h^{-1}$Mpc as a function of the threshold at $z = 2.2$ normalized to the neutrinoless model. The black error bars show the 90% (interior tick marks) and 99% (exterior tick marks) confidence intervals for a mock catalog consisting of 200 RLOS taken from the simulation with ($\Sigma_i m_{\nu_i} = 0.0$ eV, $\sigma_8 = 0.877$). We find that with a catalog consisting of 200 RLOS we can rule out models ($\Sigma_i m_{\nu_i} = 0.3$ eV, $\sigma_8 = 0.806$) and ($\Sigma_i m_{\nu_i} = 0.6$ eV, $\sigma_8 = 0.732$) with a high significance. The best way to distinguish models with the same $\sigma_8$ would be by adding more quasar spectra and combining results at different redshifts. Although regions at high transmissivity are prone to systematic errors (such as the continuum fitting procedure.
FIG. 4. Average number of regions per path length of 100 h\(^{-1}\)Mpc as a function of flux threshold at redshift \(z = 2.2\) (top) and \(z = 4\) (bottom) for different neutrino masses and \(\sigma_8\). The subplot in the upper panel shows the ratio between model with \(\Sigma m_{\nu} \neq 0.0\) and the model with \(\Sigma m_{\nu} = 0.0\). The black error bars indicate the 90% (interior tick marks) and 99% (exterior tick marks) confident intervals for a mock catalog consisting of 200 RLOS taken from the simulation with \((\Sigma m_{\nu} = 0.0 \text{ eV}, \sigma_8 = 0.877)\). Models with \(\Sigma m_{\nu} = 0.3, 0.6\) and \(\sigma_8 = 0.806, 0.732\) respectively can be ruled out with a high significance by using a catalog of 200 QSO spectra.

which provides the main systematic uncertainty in calibrating the flux at weak absorption levels), we believe that statistics of large-scale voids such as the one presented here could be important for upcoming and present spectroscopic surveys of quasars (e.g. [31]). Variations in the thermal and ionization histories of the IGM are expected to impact on the Lyman-\(\alpha\) properties of large size voids [22] and the neutrino signatures should be seeked by marginalizing over all the other relevant parameters. However, the generic redshift evolution and threshold (scale) dependence of the neutrino effects can be used to separate them from the redshift evolution of the IGM properties. Independent constraints on thermal evolution obtained by different techniques and data sets can be put as priors in the analysis performed.

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