The Signature of Neutrinos on the Lyman-α Forest

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We quantify the impact that massive neutrinos have on the distribution of low density and high redshift regions of the Intergalactc Medium as probed by the Lyman-α forest. We run hydrodynamic simulations that include dark matter, baryons and neutrino particles and extract mock quasar (QSO) spectra. We find that the distribution of the low baryon density regions is strongly affected by the Ω_ν value, once the amplitude of the matter power spectrum is fixed at large scales. Based on our findings, we propose a new sensitive method to measure neutrino masses by using QSO spectra.

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Introduction. Neutrino oscillation experiments pointed out that neutrinos are not massless particles. Since then a huge effort has been made to measure and constraint neutrino masses over the last years.

Current experimental bounds constraint the electron neutrino mass to be below $m_\nu < 2.05-2.3$ eV [1, 2], while cosmology bounds for the sum of all neutrino masses are still significantly stronger. Constraints from WMAP7 alone yield to $m_\nu < 1.3$ eV [3], while combinations of these results with LSS studies put limits on $m_\nu < 0.3$ eV [4, 5, 6, 7]. The current tightest constraint in the form of a 2σ upper limit is $m_\nu < 0.17$ eV, comes by combining CMB, Large Scale Structure (LSS) and the Lyman-α[8]. 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 at small scales, where the neutrino signature is present [9].

As an additional mass contribution neutrinos play an important role for structure formation. Their large velocity dispersion make them behave in a very different way from the common cold dark matter (CDM) particles like neutralinos. These velocities produce a suppression in the small scale matter power spectrum, making the shape of the total mass power spectrum a potential probe for neutrino masses. On scales much smaller than the free-streaming length of neutrinos, the relative suppression is given by [9] $\left|\frac{\Delta P(k)}{P(k)}\right| \simeq 8\frac{\Omega_\nu}{\Omega_m}$, where $\Omega_\nu h^2 = (\Sigma m_\nu)/(93.14 \text{ eV})$.

Some previous works have studied the role of neutrinos in dark matter halos [10, 11, 12], cosmology [13, 14, 15] and intracluster medium [16], using both linear approaches and N-body/hydrodynamic techniques, to properly model the non-linear regime. Indeed it has been shown that at scales 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. At these scales also baryons are expected to impact significantly on the matter power spectrum and thereby this regime has to be addressed with simulations that do include baryonic physics.

In this paper we study the effect that neutrinos produce in hydrogen low density regions, that we label as *voids*. The impact that neutrinos have in dark matter halos is not large, as previous studies have demonstrated [10, 11, 12]. The reason is that large neutrino thermal velocities prevent them to cluster significantly in halos, making their contribution there very small. In contrast, the impact of neutrinos in void properties can be expected to be stronger. In this paper we define voids as under dense regions with overdensities $\delta = \rho_m/\bar{\rho}_m - 1 < 0$ and sizes ranging from few to ~ 30 Mpc/h [17].

Here we aim to study the effect of neutrinos on the low density hydrogen gas populating the voids. We probe this regime by looking at the Lyman-α forest. The Lyman-α forest is a powerful tool used to constraint cosmological parameters and probe the nature of dark matter among others (for a Lyα review see [18, 24]). Lyman-α voids and their dependence on cosmological parameters have been studied in [19]. In this paper, we focus on the dependence of void properties on the sum neutrino masses. By introducing a new and simple statistical tool, we restrict ourself to the study of low density regions, that sample most of the IGM volume, and demonstrate that neutrino masses have a significant impact on the Lyman-α signature of these regions.

Numerical Method. We run cosmological simulations using the Tree-SPH code GADGET-3 [20], which has been extended to include neutrinos in two different ways: either by solving their potential on the mesh or by representing them as discrete particles [15]. Here, we use the first implementation and we refer to [13, 14, 15] 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 use the flat ΛCDM model with cosmological parameters $\Omega_{CDM} + \Omega_\nu = 0.25$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.05$, $h = 0.7$ and $n_s = 1$. We consider three degenerates neutrino species with total mass $\Sigma m_\nu = 0.0$ eV, $\Sigma m_\nu = 0.3$ eV and $\Sigma m_\nu = 0.6$ eV.

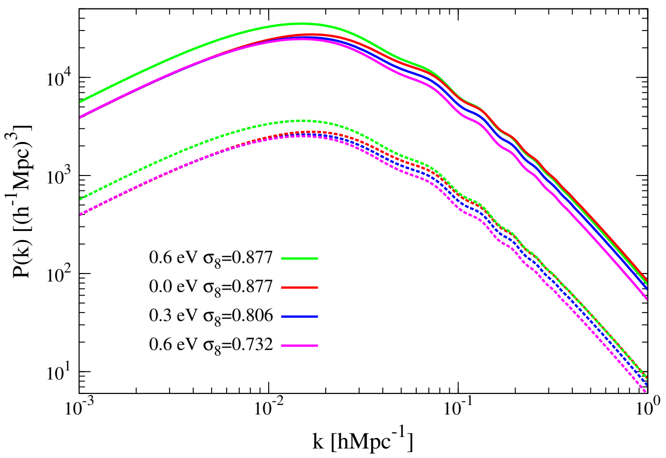

FIG. 1: Power spectrum for the different neutrino masses and σ_8 at $z = 0$ (upper lines) and $z = 3$ (bottom lines).

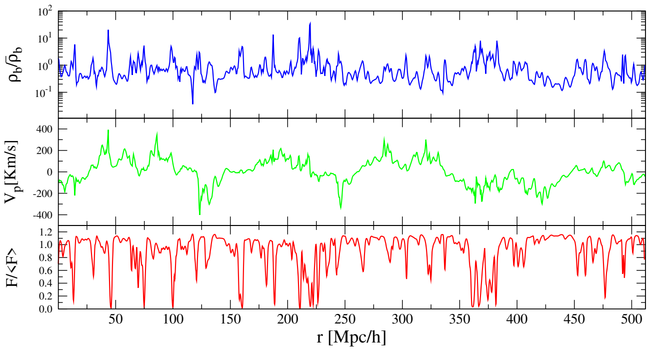

FIG. 2: In the top and middle panels we plot, in real space, the baryon overdensity $\rho_b/\overline{\rho}_b$ and the peculiar velocity along a RLOS. In the bottom panel we plot the flux suppression $e^{-\tau}$, in units of the mean flux $< F >$, in redshift space.

The power spectrum is produced using the code CAMB[1] and for the main set of simulations normalized at 0.002 h/Mpc, the power at the CMB scale is the same for all neutrino masses. This produces different values for $\sigma_8 = 0.877,\ 0.806,\ 0.732$ at $z = 0$ for the models with $\Sigma m_\nu = 0.0,\ 0.3,\ 0.6\ eV$ respectively. In the initial conditions at $z = 99$ the different particles species get their power spectrum as read from the outputs of CAMB. **FV I would say the redshift at which these simulations star (z=49??)**

For each simulation we consider the snapshots at $z = 2.2$ and $z = 4$ that bracket the Lyman-α forest range of QSO observed spectra. For each snapshot we take 4500 random line of sight (RLOS) uniformly distributed in each direction, i.e. 1500 RLOS in each x, y, z direction. For each RLOS we extract the baryon overdensity $\rho_b(r)/\overline{\rho}_b$ and the peculiar velocity $V_p(r)$ along the line of sight and then compute the flux decrement $e^{-\tau(u)}$ in redshift space (u in km/s), where τ is the optical depth, by using the *Fluctuating Gunn Peterson Approximation*:

$$\tau(u) = A \int_{-\infty}^{+\infty} dx\ \delta[u - x - V_p(x)] \left(\frac{\rho_b(x)}{\overline{\rho}_b}\right)^{1.6}, \quad (1)$$

being $x = H(z)r/(1 + z)$ the redshift space coordinate and A is a factor that depend on the universe thermal history [21]:

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

with Γ_{HI} the hydrogen photoionization rate. In all our calculations we use $\Gamma_{HI} = 10^{-12}\ s^{-1}$ and $T_0 = 10^4$ K. The exponent in $\rho_b/\overline{\rho}_b$ arises by making use of the IGM equation of state $T = T_0(\rho_b/\overline{\rho}_b)^\alpha$ [22] with $\alpha \sim 0.6$. We neglect both effects of thermal broadening and time dependence of Γ_{HI} and T_0, since we are only interested in the relative differences between different neutrino and neutrinoless simulations that do share the same thermal history. 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).

In Figure 2 we show the baryon overdensity $\rho_b/\overline{\rho}_b$ and the peculiar velocity V_p extracted along a RLOS as a function of the comoving coordinate r together with the corresponding flux decrement $e^{-\tau}$, computed as described above, in units of the mean flux at redshift z ($< F >= 0.0023(1 + z)^{3.65}$ [23]) in redshift space (i.e. including peculiar velocities).

Analysis of the simulations. We focus our analysis on regions at low baryon density, because we expect neutrinos to have the largest effect there. For this purpose, we study the properties of low absorption regions. By region we mean a continuous domain in the transmitted flux profile which remains always above a given threshold. The higher the threshold, the lower the absorption in that region. For each RLOS we extract the transmitted flux from $\rho_b/\overline{\rho}_b$ and V_p and count the number of

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[1] `http://camb.info/`

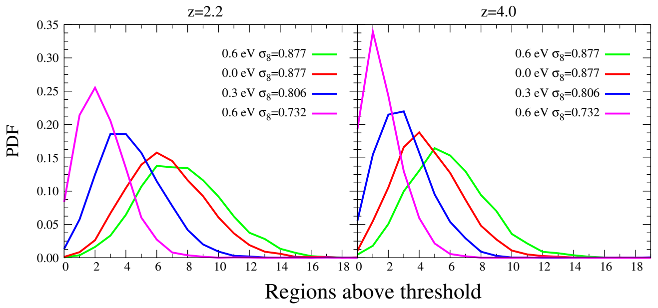

FIG. 3: Number of regions above threshold PDF (*probability distribution function*) as a function Ω_ν and σ_8 for $z = 2.2$ (left) and $z = 4$ (right) for a threshold $e^{-\tau}/ < F >= 1.12$, where $< F >= 0.0023(1 + z)^{3.65}$. The PDFs have long tails with a very low probability that extend until around 50.

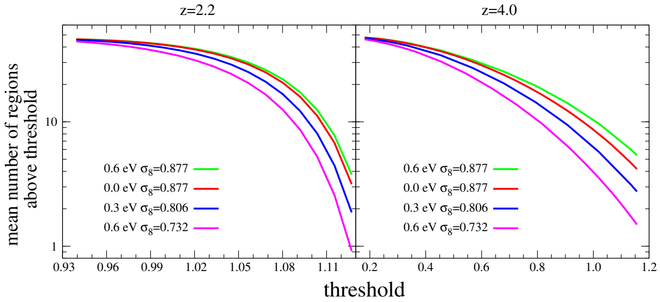

FIG. 4: Average number of regions as a function of threshold at redshift $z = 2.2$ (left) and $z = 4$ (right) for three different neutrino masses.

regions above a 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 such low density regions.

In Figure 3 we plot the probability distribution function (*PDF*) for the number of regions above a threshold of $e^{-\tau}/ < F >= 1.12$ for three different neutrino masses ($\Sigma m_\nu = 0.0,\ 0.3,\ 0.6\ eV$) at redshifts $z = 2.2$ (left) and $z = 4.0$ (right). The PDFs typically have a long tail that extends up to $\sim 50-60$ with a negligible probability (not shown in the figure). We have checked that these PDF do not change if we increase the number of RLOS, i.e. our statistical sample of RLOS is large enough. Fig. 3 shows that the neutrino mass has a significant impact on the mean of the distributions.

In Figure 4 we plot this mean, i.e. the average number of regions above a given threshold, as a function of the threshold for three different neutrino masses ($\Sigma m_\nu = 0.0,\ 0.3,\ 0.6\ eV$) at redshift $z = 2.2$ (left) and $z = 4.0$ (right). This shows clearly that the higher the threshold, the larger the differences between neutrino cosmologies: larger differences are thus expected in the low density IGM.

σ_8-Ω_ν degeneracy. In order to investigate the degeneracy between σ_8 and Ω_ν we run a simulation with $\Sigma m_\nu = 0.6\ eV$ and $\sigma_8 = 0.877$ (i.e. the same σ_8 as the previous simulation with $\Sigma m_\nu = 0.0\ eV$). This would mimick the case for which σ_8 is measured independently and one would like to constrain Ω_ν. We find that the PDF for the number of regions above a threshold equals to 1.12, at $z = 2.2$ is close to the one with $\Sigma m_\nu = 0.0\ eV$ (see Fig. 3), but not identical. Larger differences between these two models take place by comparing the PDFs at $z = 4.0$. At this redshift, relatives differences are of the same order of those from $\Sigma m_\nu = 0.0$ eV: $\sigma_8 = 0.877$ and $\Sigma m_\nu = 0.3$ eV $\sigma_8 = 0.806$. **I want to say that relative difference between models (0.0eV, 0.877) and (0.6eV, 0.877) is similar to the one for models (0.0eV, 0.877) and (0.3eV, 0.806). Eliminate that sentence if it is still confusing**

Given that neutrinos affect the growth factor, we conclude that the degeneracy between σ_8 and Ω_ν can be broken by looking at the different models PDFs at different redshifts.

Convergence. We explicitly checked the convergence of our results by changing the number of dark matter and SPH particles. We run simulations with $\Sigma m_\nu = 0.0, 0.6\ eV$ and $\sigma_8 = 0.877, 0.732$ respectively but half number of gas and CDM particles than our fiducial simulations. Relative differences between the different neutrino cosmologies are converged at our fiducial resolution, although individual PDFs are not yet converged.

Discussion and Conclusion. We have presented a novel and simple method to measure neutrino masses by studying the properties of low density regions in Lyman-α forest QSO spectra. We find that the number of regions above a given threshold in the flux is strongly affected by neutrinos, especially once the amplitude of matter power is fixed at large (CMB) scales.

We have also shown that we can break the $\sigma_8 - \Omega_\nu$ degeneracy by looking at the redshift evolution of low density regions in the Lyman-α forest flux.

Our method can be used to constraint neutrino masses by measuring the average number of regions as a function of threshold. We demonstrate this in Fig. 5, where we we plot the average number of regions as a function of the threshold at $z = 2.2$ for three cosmological models with $\Sigma m_\nu = 0.0,\ 0.3,\ 0.6\ eV$ and $\sigma_8 = 0.877,\ 0.806,\ 0.732$ respectively. From the simulation with $\Sigma m_\nu = 0.0\ eV$ and $\sigma_8 = 0.877$, we create a mock catalog of 20 RLOS. The black dashed line in Figure 5 shows the mean number of regions above the threshold from the mock catalog. We find that with 20 RLOS the statistical error is small enough to distinguish between different neutrino masses. We point out that with this number of RLOS the error is not small enough to distinguish models with $\Sigma m_\nu = 0.0$ eV-$\sigma_8 = 0.877$ and $\Sigma m_\nu = 0.6$ eV-$\sigma_8 = 0.877$. The best way to distinguish between these two models would be to

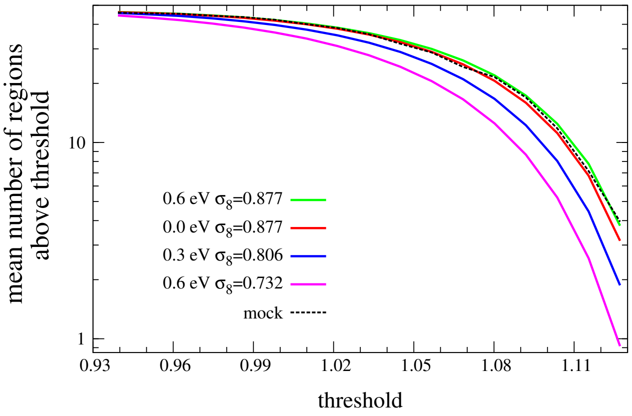

FIG. 5: Mean number of regions as a function of threshold at redshift $z = 2.2$ for three neutrino masses. The black dashed line shows the results from a mock catalog of 20 RLOS taken from the simulation with $\Sigma m_\nu = 0.0\ eV$ and $\sigma_8 = 0.877$.

add more QSO spectra and to combine results at different redshifts.

Although regions at high transmissivity are prone to systematic errors (such as for example the continuum fitting procedure which is one of the main uncertainty/systematic effect in measuring the flux around one), we believe that statistics of large-scale voids such as the one presented here could be important for coming and on-going QSO spectroscopic surveys [25]. Furthermore, the physics of the IGM could impact on the void properties and different thermal/ionization history would affect flux statistics and thus the distribution of voids. However, we do not expect that properties of large voids like the one considered here can be affected strongly [19]. The neutrino signature should however not be correlated with the redshift evolution of IGM physical properties.

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