Joint Constraints on Neutrino Mass and Number of Effective Neutrino Species from Cosmology

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Abstract

We present joint constraints on the number of effective neutrino species $N_{\rm eff}$ and the sum of neutrino masses $\sum m_\nu$, using a technique based on state-of-the-art hydrodynamical simulations with massive neutrinos, which allows one to exploit the full information contained in the one-dimensional Lyman-α forest flux power spectrum complemented by additional cosmological probes. Our results provide strong evidence for the cosmic neutrino background ($N_{\rm eff} = 0$ is rejected at more than 14σ), and rule out the possibility of a sterile neutrino thermalized with active neutrinos at a significance of over 5σ – one of the strongest bounds to date.

1 Cosmological Neutrinos

From oscillation experiments we now know that neutrinos are massive, and this breakthrough discovery was awarded the Nobel Prize in Physics 2015 and the 2016 Breakthrough Prize in Fundamental Physics. Yet, despite neutrinos being the most numerous known particles in the entire cosmos, their nature is still subject of intense scrutiny. In particular, we ignore the absolute neutrino mass scale, and the nature of the neutrino mass hierarchy. Answering those questions would improve our understanding of the neutrino sector, and impact the knowledge of leptogenesis, baryogeneis, and the origin of mass.

At the present time, cosmology may be in a better position than particle physics in answering the above questions, since it is possible to obtain stringent upper bounds on the total neutrino mass $\sum m_\nu$ by combining several different cosmological tracers with unrelated systematics. If $\sum m_\nu < 0.1$ eV, a value within reach with planned near-term cosmological surveys such as eBOSS or DESI [1, 2], one could in principle exclude the inverted hierarchy scenario, in which two neutrino eigenstates are much heavier than the third one, and nearly degenerate. As we show here, cosmological observations are approaching this stringent upper value for $\sum m_\nu$, and will be able to close the loop on these fundamental issues. On the contrary, particle physics experiments such as KATRIN cannot reach an equivalent sensitivity, but they will be complementary to cosmology and offer interesting synergies.

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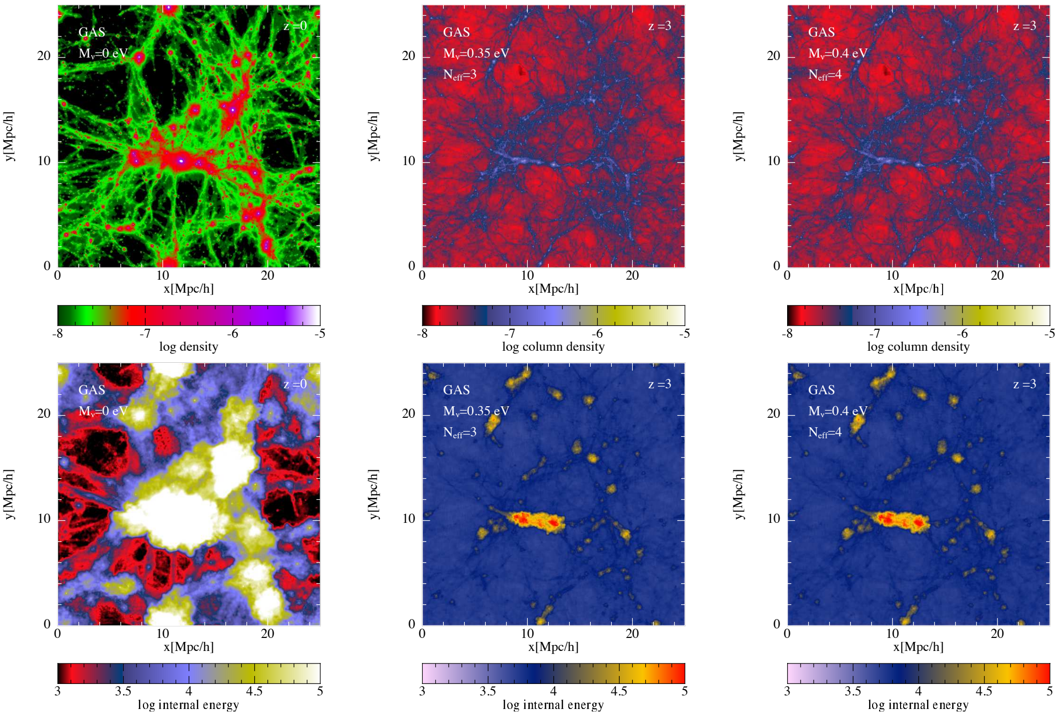

Figure 1: Snapshots at $z = 0$ and $z = 3$ of the gas, from simulations with $25h^{-1}$Mpc box size and resolution $N_{\rm p} = 192^3$ particles/type. Upper panels are projections of the density field in the $x - y$ direction; bottom panels represent the internal energy. Both standard ($N_{\rm eff} = 3$) and non-standard ($N_{\rm eff} = 4$) cosmologies are considered, as specified in the panels, for different values of $\sum m_\nu$. The two cosmologies are related by our analytic remapping. When present, an additional sterile neutrino is assumed to be massless and thermalized with the three-active neutrinos. Plots from [4, 5, 6].

The fact that neutrinos are massive implies that our current concordance ΛCDM cosmological model needs to be extended, since in its present formulation it only assumes a minimal neutrino mass of 0.06 eV – derived from oscillation experiments. Not only massive neutrinos alter the radiation content of the Universe, resulting in a delayed matter domination [3], but they also play a key role in structure formation. Because of their high thermal velocities, they free-stream and do not cluster at small scales, hence impacting several large-scale structure (LSS) observables such as the three-dimensional power spectrum from galaxy surveys, the cosmic shear through weak lensing, or the flux observed in the Lyman-α (Lyα) forest via the one-dimensional power spectrum.

Ultimately, the high-sensitivity of cosmology in determining neutrino properties relies on the fact that neutrinos cast a unique redshift- and scale-dependent signature in the total matter power spectrum (up to a 5% suppression of power, due to absence of clustering at small scales) and in the galaxy distribution, and when combining different cosmological tracers with independent systematics the parameter space is significantly constrained – so that several parameter degeneracies can be lifted.

2 Techniques

By developing new cosmological hydrodynamical simulations with massive neutrinos, in addition to the cold dark matter and baryonic components [4], we studied how neutrinos impact the main LSS observables – especially considering the Lyα forest as a cosmological tracer. In particular, from these simulations 100,000 pencil beam skewers were extracted, and the one-dimensional flux power spectra computed at different redshifts and for different cosmological and astrophysical parameters. We also considered alternative cosmologies, where the number of effective species $N_{\rm eff}$ is different from the canonical value of 3.046 expected in the standard three-neutrino framework [5, 6]. In Figure 1 we show some examples of snapshots from those simulations, for the gaseous component.

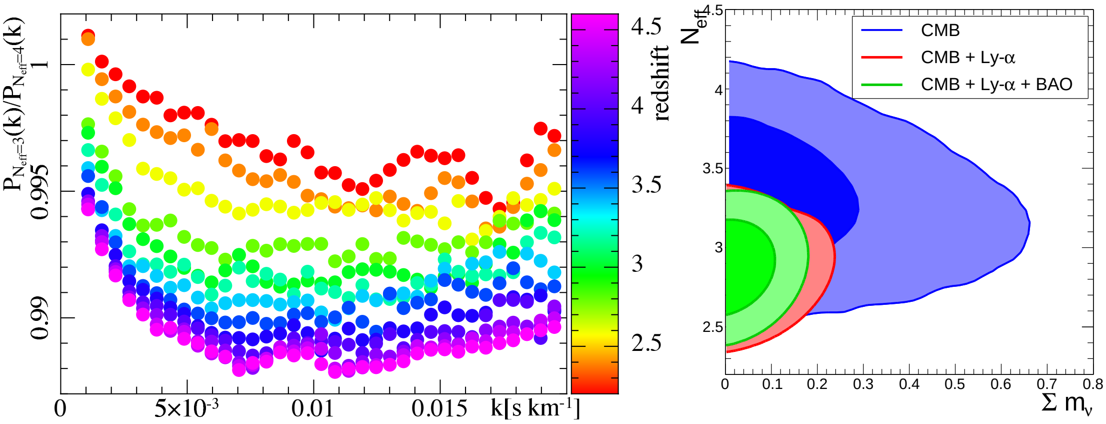

Figure 2: [Left] Testing the validity of our remapping procedure in the nonlinear regime, for the Lyα flux power spectra extracted from a canonical model and from a model where $N_{\rm eff} = 4$ characterized by a massless sterile neutrino and three active degenerate neutrinos. For all the z-ranges considered, our approximation works within 1% error. [Right] Joint constraints on $N_{\rm eff}$ and $\sum m_\nu$ from cosmological probes, as specified in the panel with different colors. Our results exclude the possibility of a sterile neutrino – thermalized with active neutrinos – at a significance of over 5 σ, and provide strong evidence for the CNB from $N_{\rm eff} \sim 3$ – as $N_{\rm eff} = 0$ is rejected at more than 14 σ. Plots from [5].

We then adopted a sophisticated technique to construct the Lyα forest likelihood, based on a second-order Taylor-expansion model for the dependence of the Lyα flux power spectrum on cosmological and astrophysical parameters (see [5, 7, 8] for a detailed description of the method), complemented by an analytical approximation [3] to include non-standard dark radiation models. The left panel of Figure 2 shows that our approximation works within 1%, validating the analytic remapping in the nonlinear regime [5]. In the numerical model, we used a splicing method introduced by [9].

3 Main Results

We finally interpreted the likelihood obtained by combining our simulation-based Taylor-expansion model with data from the BOSS Lyα forest, the BOSS galaxy clustering BAO measurements, and state-of-the-art CMB probes (i.e.,WMAP9, ACT, SPT) in the context of the frequentist approach. The main results of this analysis are shown in the right panel of Figure 2: red contours are for the combination CMB+Lyα, green contours are obtained by further adding BAO information. Specifically, $N_{\rm eff} = 2.91^{+0.21}_{-0.22}$ (95% CL) and $\sum m_\nu < 0.15$ eV (95% CL) in the first case, and $N_{\rm eff} = 2.88 \pm 0.20$ (95% CL) and $\sum m_\nu < 0.14$ eV (95% CL) in the second [5].

There are several important implications of our results in particle physics and cosmology, and for a detailed discussion see [5]. Here we just stress two major conclusions of our analysis: we find that (1) a sterile neutrino thermalized with active neutrinos – or more generally of any decoupled relativistic relic with $\Delta N_{\rm eff} \simeq 1$ – is ruled out at a significance of over 5 σ; (2) in addition, our constraints provide strong evidence for the CNB from $N_{\rm eff} \sim 3$ by rejecting $N_{\rm eff} = 0$ at more than 14 σ. Hence, according to our results, the minimal ΛCDM model is strongly favored over extensions with non-standard neutrino properties or with extra-light degrees of freedom. There are also interesting complementarity with future particle physics direct measurements of the effective electron neutrino mass, and with recent findings from Planck (2015).

Our results also highlight the fact that cosmological probes are now reaching the sensitivity required to solve two of the most fundamental problems in neutrino science: the determination of their individual mass, and the nature of their mass hierarchy. This is within reach with ongoing and future large-volume cosmological experiments such as eBOSS and DESI, and with a new stage-IV CMB polarization experiment that will provide a high-significance detection of a nonzero neutrino mass.

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