Publications of the Korean Astronomical Society
30: 321 ∼ 325, 2015 September

pISSN: 1225-1534
eISSN: 2287-6936
http://dx.doi.org/10.5303/PKAS.2015.30.2.321

COSMOLOGY WITH MASSIVE NEUTRINOS: CHALLENGES TO THE STANDARD ΛCDM PARADIGM

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(Received November 30, 2014; Reviced May 31, 2015; Aaccepted June 30, 2015)

ABSTRACT

Determining the absolute neutrino mass scale and the neutrino mass hierarchy are central goals in particle physics, with important implications for the Standard Model. However, the final answer may come from cosmology, as laboratory experiments provide measurements for two of the squared mass differences and a stringent lower bound on the total neutrino mass – but the upper bound is still poorly constrained, even when considering forecasted results from future probes. Cosmological tracers are very sensitive to neutrino properties and their total mass, because massive neutrinos produce a specific redshift- and scale-dependent signature in the power spectrum of the matter and galaxy distributions. Stringent upper limits on $\sum m_\nu$ will be essential for understanding the neutrino sector, and will nicely complement particle physics results. To this end, we describe here a series of cosmological hydrodynamical simulations which include massive neutrinos, specifically designed to meet the requirements of the Baryon Acoustic Spectroscopic Survey (BOSS) and focused on the Lyman-α (Lyα) forest – also a useful theoretical ground for upcoming surveys such as SDSS-IV/eBOSS and DESI. We then briefly highlight the remarkable constraining power of the Lyα forest in terms of the total neutrino mass, when combined with other state-of-the-art cosmological probes, leading to a stringent upper bound on $\sum m_\nu$.

Key words: Methods: analytical, statistical, numerical; cosmology: theory, large-scale structure of universe, neutrinos

1. SIGNATURE OF MASSIVE NEUTRINOS IN THE LARGE SCALE STRUCTURE

The breakthrough discovery over the last decade that neutrinos are massive, from oscillation experiments, has led to intense research activity in neutrino science. However, two pressing questions remain to be answered: the determination of the absolute neutrino mass scale, and the nature of the neutrino mass hierarchy. Answering these questions would improve our understanding of the neutrino sector remarkably, with important implications for leptogenesis, baryogeneis, and eventually for explaining the origin of mass. Most likely, in the near future particle physics alone will not be able to provide a solution to the previous problems, as upper limits on the total neutrino mass from laboratory experiments are still poorly constrained – even with projects results of upcoming experiments such as KATRIN. On the other hand, the answer may come from cosmology, since stringent upper bounds on the total neutrino mass can be obtained by combining different cosmological tracers with unrelated systematics. For example, an upper limit of $\sum m_\nu < 0.1$ eV would be sufficient to exclude the inverted hierarchy scenario, in which two neutrino eigenstates are much heavier than the third one, and nearly degenerate. Upper limits on the total neutrino mass obtained from cosmological probes are now approaching this interesting level, as we discuss in Section 3.

Currently, the concordance ΛCDM model only assumes a minimal neutrino mass of 0.06 eV, and therefore it requires some extension to accommodate massive neutrinos – but their inclusion in the model cannot be neglected. In fact, massive neutrinos alter the radiation content of the Universe, resulting in a delayed matter domination (see Lesgourgues & Pastor 2006 for details); moreover, because of their free-streaming, neutrinos significantly change structure formation and impact several large-scale structure (LSS) observables. Hence, massive neutrinos can be studied through their imprints on the CMB, particularly in the polarization maps, and by using several baryonic tracers of the LSS clustering of matter such as the 3D power spectrum from galaxy surveys, the Sunyaev-Zel'dovich effect in galaxy clusters, cosmic shear through weak lensing, and the Lyman-α (Lyα) forest – the main focus of Section 2.

Cosmology is very sensitive to massive neutrinos, for essentially two reasons: (1) a combination of measurements obtained with different tracers and techniques map very different regions in parameter space, helping to break degeneracies on the total neutrino mass; (2) neutrinos have a unique redshift- and scale-dependent signature in the total matter power spectrum (up to

a 5% suppression of power, due to an absence of clustering at small scales) and in the galaxy distribution. An example is provided in Figure 1, which shows linear predictions for the total matter power spectra in the presence of massive neutrinos. The spectra $P_{\mathrm{k,M_\nu}}$ have been normalized by the baseline Planck (2013) ΛCDM model, which includes a minimal massive neutrino component with total mass $M_\nu = 0.06$ eV. Four total neutrino masses are considered in the plot, ranging from 0.1 to 0.4 eV, as indicated in the panel with different line styles; the other baseline cosmological parameters are consistent with Planck (2013) cosmology. Three redshift intervals are considered, $z = 0$ (red), $z = 1$ (black), and $z = 2$ (blue). The cyan area in the plot indicates the region where linear theory can be safely used to describe the subsequent nonlinear evolution of the neutrino component. The pale yellow area indicates the region of interest for the 1D Baryon Acoustic Spectroscopic Survey (BOSS) Lyα flux power spectrum, which would be required to resolve the nonlinear description. Note the characteristic redshift- and scale-dependent suppression of power, which cannot be mimicked by other combinations of parameters – and eventually translates into a suppression of power in the Lyα forest flux.

The outline of the paper is as follows. In Section 2, we discuss a new suite of cosmological hydrodynamical simulations which included massive neutrinos, specifically designed to meet the requirements of BOSS, and the numerical implementation of massive neutrinos: the main target is the Lyα forest at high-z. In Section 3, we briefly highlight the remarkable constraining power of the Lyα forest in terms of the total neutrino mass, when combined with other cosmological probes, leading to a stringent upper bound on $\sum m_\nu$. Finally, in Section 4, we point out how these studies represent a useful theoretical ground for upcoming large-volume surveys such as SDSS-IV/eBOSS and DESI.

2. MASSIVE NEUTRINOS: A NUMERICAL IMPLEMENTATION

Rossi et al. (2014) presented a suite of 48 cosmological hydrodynamical simulations which include massive neutrinos, in addition to the cold dark matter and baryonic components. The simulations were developed specifically to meet the requirements of BOSS (Dawson et al. 2013), in particular for Lyα forest studies. They are grouped into two categories: in the first one, the total neutrino mass is varied while cosmological and astrophysical parameters remain compatible with Planck (2013) data; in the second one, the total neutrino mass is kept fixed at 0.8 eV, and the main cosmological and astrophysical parameters are slightly perturbed with respect to the reference Planck (2013) cosmology. The latter category of simulations was developed in order to implement the technique introduced by Viel et al. (2006, 2010) based on a Taylor expansion of the Lyα flux power spectrum, which requires the numerical evaluation of cross-derivative terms.

The simulations were produced with the GADGET-3 code. Neutrinos, considered as three degenerate species,

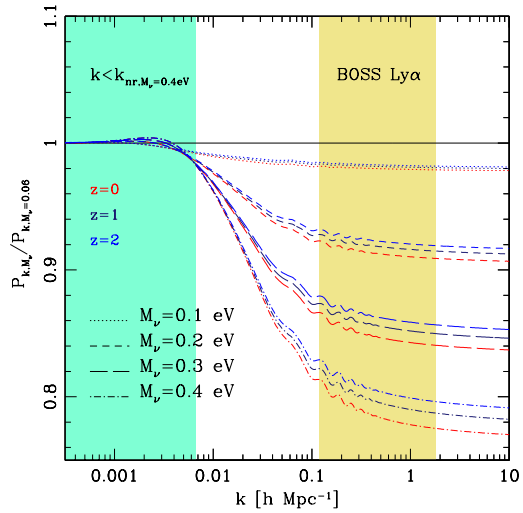

Figure 1. Total matter power spectra with massive neutrinos: linear theory predictions. All the spectra $P_{\mathrm{k,M_\nu}}$ have been normalized by the baseline Planck (2013) ΛCDM model, which includes a a massive neutrino component with total mass $M_\nu = 0.06$ eV. Four total neutrino masses are considered in the plot, ranging from 0.1 to 0.4 eV; cosmological parameters, except for $\sum m_\nu$, are compatible with a Planck (2013) cosmology. Three redshift intervals are considered: $z = 0$ (red), $z = 1$ (black), and $z = 2$ (blue). The cyan area in the plot indicates the region where linear theory can be safely used to describe the subsequent nonlinear evolution of the neutrino component. The pale yellow area is the region of interest for the 1D BOSS Lyα flux power spectrum, which requires a nonlinear description.

were implemented as an extra particle type. Several improvements upon previous studies were introduced, and in particular updated routines for intergalactic medium (IGM) radiative cooling and heating processes, and initial conditions determined at $z = 30$ by second-order Lagrangian Perturbation theory – with separate transfer functions per species obtained from CAMB. Each simulation set is composed of three runs with different box sizes (ranging from 25 to $100h^{-1}$Mpc) and resolutions (from 3×192^3 to 3×768^3 particles). A splicing technique (McDonald 2003) is used to achieve the equivalent resolution of 3×3072^3 particles in a $(100h^{-1}\mathrm{Mpc})^3$ box size, otherwise prohibitive in terms of CPU time. Snapshots were properly stored, at redshifts between $z = 4.6$ and $z = 2.2$ – in intervals of $\Delta z = 0.2$.

Figure 2 shows examples of snapshots at $z = 0$ of the gaseous component, obtained from simulations with $25h^{-1}$Mpc box size and resolution $N_\mathrm{p} = 192^3$ particles per type. The upper panels are projections of the density field in the $x - y$ direction and across z, while the bottom panels represent the internal energy of the gas. The left panels do not contain massive neutrinos, while the central and right panels have a total neutrino mass of 0.1 and 0.4 eV, respectively. The presence of massive neutrinos affects the clustering properties and the temperature of the baryonic component, with implications for galaxy formation physics.

From these simulations, 100,000 pencil beam skewers

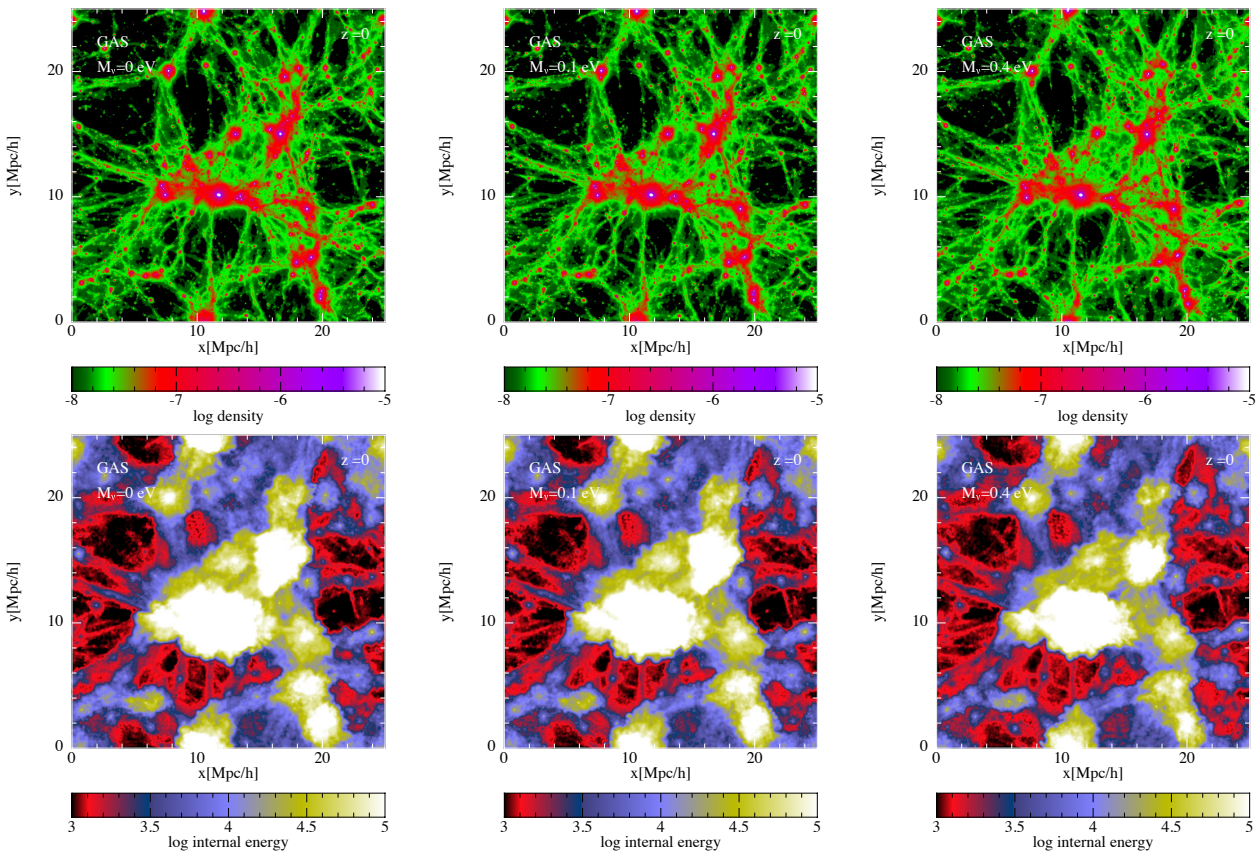

Figure 2. Snapshots at $z = 0$ of the gaseous component from simulations with $25h^{-1}$Mpc box size and resolution $N_{\rm p} = 192^3$ particles/type. Upper panels are projections of the density field in the $x - y$ direction and across z; bottom panels represent the internal energy of the gas. Massive neutrinos are not included in the left panels, while the central and right panels have a total neutrino mass of 0.1 and 0.4 eV, respectively. See the main text for more details.

were extracted, and the 1D flux power spectra computed at different redshifts and for different cosmological and astrophysical parameters, in addition to the total neutrino mass. This modeling provides the cosmological interpretation for the Lyα forest flux power spectrum measurements. In particular, the characteristic scale- and redshift-dependent suppression in the nonlinear total matter and flux power spectra is the key to constraining massive neutrinos; this feature is captured only in simulations that have separate species accounting for cold and hot dark matter – while a linear implementation of massive neutrinos would not be able to detect this effect. Figure 3 shows examples of Lyα forest flux power spectra in the presence of massive neutrinos – and proves that the effects of M_ν, σ_8, and $n_{\rm s}$ are not fully degenerate with one another. Extensive details on the numerical aspects of these simulations can be found in Rossi et al. (2014), along with details on the role of massive neutrinos in the total matter and flux power spectra.

3. TIGHT UPPER BOUNDS ON THE TOTAL NEUTRINO MASS FROM COSMOLOGY

The simulation-based Taylor-expansion model for the dependence of the Lyα flux power spectrum on cosmological and astrophysical parameters discussed previously (see also Borde et al. 2014, and Rossi 2014), combined with corresponding measurements from BOSS (Palanque-Delabrouille et al. 2013) and complemented by state-of-the-art CMB probes (i.e.,WMAP9, Planck, ACT, SPT) allows one to obtain competitive constrains on cosmological parameters, and a stringent upper bound on the total neutrino mass (Palanque-Delabrouille et al. 2014). This is done by constructing a multidimensional likelihood, modeled with three categories of parameters (cosmological, astrophysical, nuisance) which are subsequently floated in the maximization procedure. Afterwards, two independent techniques are adopted to interpret the likelihood: one method is based on the classical confidence level approach, and the other relies on a Bayesian approach. The agreement between these two independent techniques highlights the robustness of the results. In particular, Palanque-Delabrouille et al. (2014) showed that, while the constraining power of the Lyα forest with respect to the total neutrino mass is somehow weak ($\sum m_\nu < 1.1$ eV at 95% CL), the combination of Lyα forest and other cosmological data provides a strong upper bound on the total neutrino mass, $M_\nu < 0.14$ eV at 95% CL – which improves on Seljak & McDonald (2005); this is because the Lyα and CMB tracers have very different directions of degeneracy in parameter space, and in addition mas-

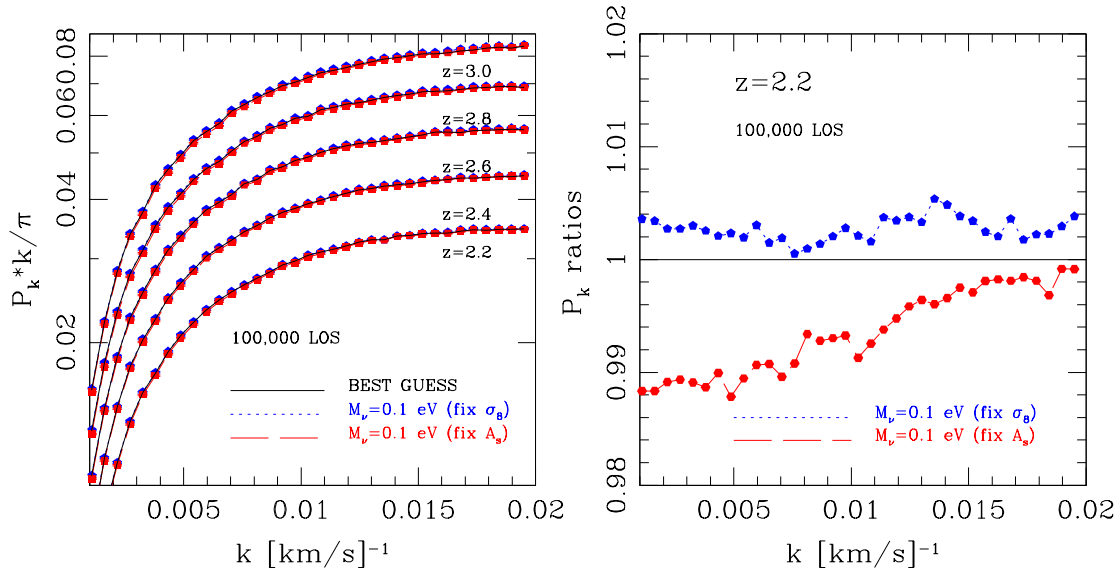

Figure 3. [Left] Simulated 1D Lyα forest flux power spectra in presence of massive neutrinos (red and blue dotted and long-dashed lines, and points), when $M_\nu = 0.1$ eV, for different redshift intervals. Power spectra are obtained from an average of 100,000 mock skewers. Solid lines represent the reference cosmological model, which does not include massive neutrinos. Dotted lines are obtained by forcing σ_8 to have the same value as in the baseline model at $z = 0$, while long-dashed lines have the same A_s values at the initial redshift – and therefore their σ_8 values differ at $z = 0$. [Right] Ratios of the flux power spectra for the massive neutrino models with respect to the baseline model without massive neutrinos, when $z = 2.2$. Massive neutrinos induce a characteristic mass- and redshift-dependent signature in the LSS clustering, so that the effects of M_ν, σ_8, and n_s are not fully degenerate with one another.

sive neutrinos produce a characteristic suppression of power at small scales in the total matter and flux power spectra, which cannot be mimicked by a combination of other parameters (see again Figure 3).

4. FUTURE DEVELOPMENTS

The stringent upper bound on the total neutrino mass obtained in Palanque-Delabrouiulle et al. (2014) does not exclude the neutrino inverted hierarchy scenario yet, but it indicates a preference for the normal hiearchy scenario. It also highlights 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 – nicely complementing particle physics results. A detailed knowledge of the neutrino sector would provide a better understanding of other issues in particle physics, such as leptogenesis and baryogenesis, and eventually shed light into a crucial aspect of the Standard Model of particle physics, namely the origin of mass.

In the very near future those two problems will be solved, and very likely the answer will come from cosmology. In fact, ongoing and future large-volume spectroscopic experiments such as SDSS-IV/eBOSS and DESI, and a new stage-IV CMB polarization experiment (CMB-S4) will provide high-significance detection of a nonzero neutrino mass. Therefore, it will be possible to clarify the controversial situation on the side of LSS with respect to the neutrino mass, where probes such as the galaxy lensing power spectrum or redshift space distortion measurements still require a sizable total neutrino mass. New datasets will also allow us to better understand the systematics that affect the overall amplitude of the measured power spectrum, and their detailed interpretation calls for a corresponding improvement in the numerical modeling of massive neutrinos.

ACKNOWLEDGMENTS

This work and the participation to the 12th Asia-Pacific Regional IAU Meeting (APRIM 2014) in Daejeon, South Korea, were supported by the faculty research fund of Sejong University in 2014, and by the National Research Foundation of Korea through SGER Grant 2014055950. Many thanks to the Scientific and Local Organizing Committees for an enjoyable and stimulating meeting.

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