Highlights on Spanish Astrophysics IX, Proceedings of the XII Scientific Meeting of the Spanish Astronomical Society held on July 18 – 22, 2016, in Bilbao, Spain. S. Arribas, A. Alonso-Herrero, F. Figueras, C. Hernández-Monteagudo, A. Sánchez-Lavega, S. Pérez-Hoyos (eds.)

Constraints on Neutrino Mass from Galaxy Surveys

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Abstract

Modern large-scale galaxy surveys, combined with measurements of the cosmic microwave background, have managed to constrain the sum of neutrino masses to an order of magnitude below the limit placed by laboratory experiments. We discuss the signature of massive neutrinos in the distribution of galaxies and the current state of the art of neutrino mass constraints, focusing on parameter degeneracies that reveal how we can improve current constraints with next-generation galaxy surveys. We also comment on how the near future cosmology experiments are an opportunity for the first measurement of the value of the sum of neutrino masses, or alternatively, to find profound implications for neutrino physics extensions beyond the Standard Model.

1 Introduction

The discovery of neutrino oscillations, which imply that neutrinos have mass (awarded the Nobel Prize in Physics 2015) has triggered a search for the neutrino mass signal in the particle physics community, but also in the astrophysics community. Interestingly, cosmological bounds on neutrino masses have become an order of magnitude stronger than laboratory experiments (this can be seen for instance comparing the limits derived from the BOSS Lyman-α flux power spectrum [15] to the results of the Mainz Experiment [12]), making cosmology an attractive source of information to cast light on this subject.

Neutrino oscillations have their origin in the fact that flavor states (electron neutrino, muon neutrino, tau neutrino) and mass states do not coincide, hence definite flavor states have non-definite mass as they propagate. Experimentally, the measured mass differences are $\Delta m_{12}^2 = 7.53 \times 10^{-5}$ eV^2 (from solar neutrinos) and $|\Delta m_{32}^2| = 2.44 \times 10^{-3}$ eV^2 (from atmospheric neutrinos). These differences imply that for the *normal* ordering (1 heavy neutrino, i.e. $m_1 < m_2 < m_3$) the minimum total mass is 0.058eV, whereas for the *inverted* ordering (2 heavy neutrinos, i.e. $m_3 < m_1 < m_2$) the minimum total mass is 0.098eV, remarkably larger than the minimum value for the normal ordering (see e.g. [11]).

Although commonly referred to as *ghost particles*, neutrinos actually play a role in shaping the visible structures in the Universe, as they influence the formation and the distribution of galaxies. The main signature of massive neutrinos on the clustering of galaxies is a suppression of the density fluctuations at small scales due to neutrino free-streaming (see e.g. [14]). In fact, in linear theory an expected suppression of $\Delta P/P \simeq -8f_\nu = -8\Omega_\nu/\Omega_m = -8M_\nu/(93.14\Omega_m h^2 \text{ eV}) \simeq -(2/3)M_\nu[\text{eV}]$ is expected[1]. Fortunately, this signature is not fully degenerate with the one from a scale-independent galaxy bias. Measurements of the full shape of the galaxy power spectrum in cosmology are therefore of great importance for neutrino physics, since they are able to put tight constraints on the sum of neutrino masses.

2 Results

As our base dataset, we will assume the temperature and polarization power spectrum of the Cosmic Microwave Background (hereafter CMB) as measured by the *Planck* satellite [16]. Massive neutrinos can alter the measured CMB fluctuations through two main effects: the amount of matter in the form of neutrinos affects the clustering of the large scale structure of the Universe, altering the deflections of CMB photon trajectories through intervening matter along their propagation from recombination to their detection at redshift $z = 0$, which is measured by CMB lensing; and also, massive neutrinos affect the evolution of gravitational potentials, which is detected by the Integrated Sachs-Wolfe (ISW) effect in the CMB.

Using our base dataset, we find three main degeneracies (correlations) with the neutrino mass parameter in a ΛCDM cosmology: an anti-correlation with the current expansion rate of the Universe (the Hubble constant H_0), an anti-correlation with the r.m.s. of the matter density fluctuations in spheres of $8h^{-1}$Mpc evolved using linear theory to redshift $z = 0$ (the parameter σ_8), and a positive correlation with the optical depth to reionization τ_{reio}.

A qualitative description of these degeneracies can be explained as follows: first, massive neutrinos behave as relativistic particles by the epoch of recombination, but are non-relativistic at low redshift. This change in their equation of state can be interpreted as a transfer of energy density in the form of radiation at high redshift to energy density in the form of matter at low redshift. Since both ingredients enter the Friedmann equation, the expansion history of the Universe will be affected. Hence the uncertainty in the total mass in the form of neutrinos translates into an uncertainty in the present expansion rate, unless additional datasets are used to break this degeneracy. We refer to this degeneracy as geomet-

[1] Hereafter we will refer to the sum of neutrino masses $\sum m_\nu$ as M_ν.

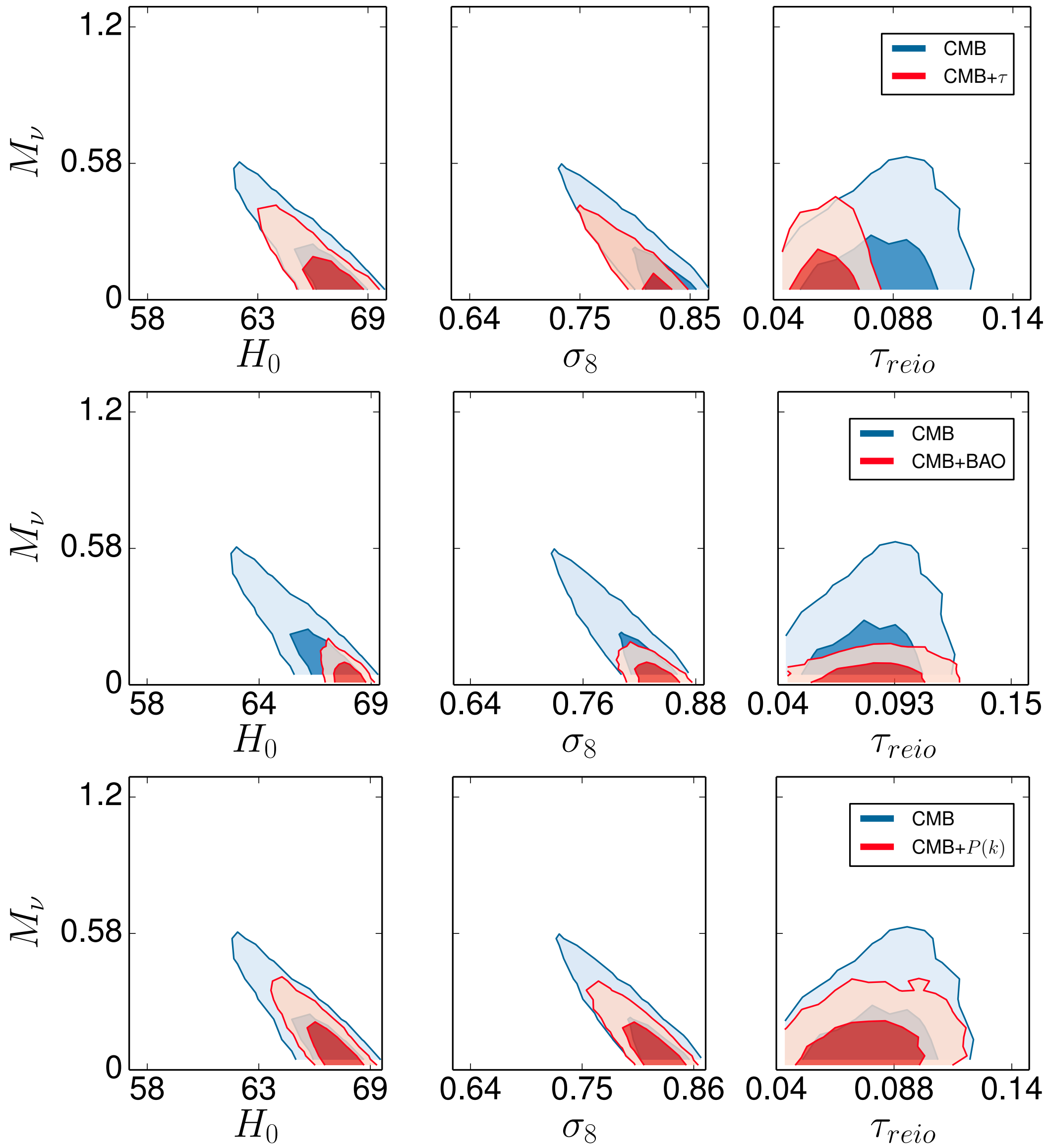

Figure 1: Main degeneracies in neutrino mass constraints from current *Planck* CMB data, compared to those including an extra dataset that current and future surveys can help better constrain. The main degeneracies are with the Hubble constant H_0, which influences distance measurements, and the normalization of the matter power spectrum σ_8, which contains information about structure growth. There is also a weaker (but relevant) degeneracy with the optical depth to reionization $\tau_{\rm reio}$. We show in blue contours the 1-sigma and 2-sigma bounds from CMB only (identical in all three rows), compared to those in red which show the limits from the addition of a prior on $\tau_{\rm reio}$ (CMB+τ, top panel), baryon acoustic oscillations (CMB+BAO, middle panel), and galaxy power spectrum (CMB+$P(k)$, bottom panel).

rical, since the well-measured angular size of CMB fluctuations translates the uncertainty in neutrino mass to an uncertainty in the angular diameter distance to recombination.

Second, massive neutrinos affect the growth of large scale structures in the Universe, especially by suppressing structure formation at small scales, and hence the matter power spectrum is modified. The cosmological parameter σ_8, being just a convolution of the matter power spectrum with a top-hat filter at a fixed scale of $8h^{-1}$Mpc, will be affected as well. Since the CMB observable is actually measuring a combination of the amplitude of the primordial power spectrum at large scales and the optical depth to reionization $A_s \exp(-2\tau)$, the uncertainty in A_s combined with those in the rest of parameters determining the matter power spectrum, can be interpreted as a potential signature for non-zero neutrino mass. Moreover, since $\tau_{\rm reio}$ is not very well constrained itself, its uncertainty also translates into a partial degeneracy with neutrino mass. Note that contrary to the geometrical degeneracy which affects the evolution of the Universe at the background level, these two degeneracies are instead related to the evolution of cosmological perturbations.

We will now show constraints from the combination of CMB and low redshift datasets, in the same spirit as in [6] and [10]. The first dataset combination that we use to derive neutrino mass constraints is actually CMB + a prior on $\tau_{\rm reio}$ motivated by the recent *Planck* 2016 revision of their large scale polarization measurements, resulting in a constraint on the reionization optical depth of $\tau_{\rm reio} = 0.055 \pm 0.009$ [17]. This can be seen in the top row of Fig. 1 (red contours), compared to the constraints with our base dataset, which does not include such a prior (blue contours). Even though this constraint is not derived from a galaxy survey, it highlights the importance of having a good determination of the parameter $\tau_{\rm reio}$, which future large-scale surveys of neutral hydrogen at high redshift can help constrain [2].

Another way to further constrain neutrino masses is to combine CMB data with expansion history measurements so that the degeneracy with H_0 is broken. Ideally, one could use direct (local) measurements of the Hubble constant in order to break this degeneracy. However, the values of H_0 derived from CMB data and from local measurements are somewhat in tension [18] and hence the resulting neutrino constraints derived from this combination might be just a reflection of this tension rather than actual physical constraints. It is for this reason that we explore the combination of CMB data with Baryon Acoustic Oscillation (BAO) measurements from the Data Release 11 of the BOSS survey (combined with lower redshift BAO measurements from the Main Galaxy Sample of SDSS and from the 6dFGS survey), which constrain H_0 through the so-called *inverse distance ladder* [3]. These geometrical measurements greatly reduce the allowed parameter space for neutrino masses, leaving room only for a total mass well below 0.20eV (e.g. [1]). This can be seen by comparing in the middle row of Fig. 1 the red contours (CMB+BAO) and the blue contours (CMB only).

Finally, we make use of information at the perturbation level. Quoting [5], we use the constraints from the combination of two galaxy surveys (SDSS and WiggleZ) targeting very different types of galaxies, although the constraints from each survey individually are very similar given that the effective volume they probe is approximately the same. Since this is a direct measurement of both the amplitude and the shape of the power spectrum[2],

[2]The clustering bias of the galaxies is somewhat poorly constrained, so when we relate the galaxy power spectrum to the matter power spectrum, galaxy bias is marginalized over analytically.

it breaks degeneracies present in CMB data. However, although the small-scale suppression due to massive neutrinos is not apparent given the current error bars (otherwise we would have a detection of non-zero mass), this dataset has the power to constrain σ_8 and hence M_ν. The resulting constrains are shown in the bottom row of Fig. 1, with the red contours showing CMB+$P(k)$ on top of our reference dataset CMB only, shown with blue contours. To summarize, in Table 1 we quote the 95% confidence level upper limits from the marginalized distribution of M_ν for all the dataset combinations discussed here.

Table 1: Upper limits (at 95% confidence level) on the sum of neutrino masses after marginalizing over the remaining cosmological parameters, for different dataset combinations. We include the result from CMB+H_0 for comparison only, albeit it might be spurious (see text).

	CMB only	CMB+$\tau_{\rm reio}$	CMB+$P(k)$	CMB+BAO	CMB+H_0 (*)
	[16]	[17]	[5]	[1]	[10]
M_ν (eV)	< 0.49	< 0.34	< 0.30	< 0.16	< 0.13

3 Conclusions

We have explored the degeneracies present in current CMB data when a non-zero neutrino mass is allowed in the ΛCDM model. Interestingly, galaxy surveys have a large potential in breaking these degeneracies, by constraining geometrical quantities related to the expansion history (by measuring baryon acoustic oscillations) and structure growth observables related to structure formation (by measuring the galaxy power spectrum). These in turn reduce the allowed parameter space for the parameters H_0 and σ_8, which turn out to be the major degeneracies of the neutrino mass parameter M_ν present in CMB data. A residual correlation is also found in CMB data with the parameter $\tau_{\rm reio}$, but this is being reduced with cleaner measurements of large-scale CMB polarization power spectrum and might not even relevant in future galaxy surveys as this correlation is weak in any case.

A more worrisome issue is the neutrino mass constraints derived when local measurements of the Hubble constant are combined with CMB data, which might be reflecting a tension between datasets or unaccounted systematics (e.g. [4]) rather than signaling a competitive upper limit. Hence, such constraints must be taken with caution, especially since they might be already ruling out the entire parameter space for the inverted mass ordering with high confidence (more than 2-sigma for CMB+BAO+H_0 and a prior on $\tau_{\rm reio}$), so these claims should be backed up with tested consistency between datasets. Furthermore, to avoid model-dependent claims one should venture beyond the minimal ΛCDM+M_ν model [7].

Future next-generation galaxy surveys will be able to further constrain the sum of neutrino masses, to the extent that forecasted upper limits by surveys like EUCLID [13] or DESI [9] are actually quoted as error bars (rather than upper limits) in the case of an eventual detection of the minimum mass of the neutrino normal ordering. Even if no detection is made, such result will be very interesting since extensions beyond the Standard Model of particle physics including neutrino masses will have to accommodate such puzzling result. On the other hand, laboratory-based tritium beta decay experiments like KATRIN [8] will catch up with current upper limits from cosmology, checking the consistency between such different information sources. In any case, the quest for the first measurement of neutrino masses is bound to return interesting results for both particle physics and cosmology in the very next decade.

Acknowledgments

AJC is supported by the European Research Council under the European Community's Seventh Framework Programme FP7-IDEAS-Phys.LSS 240117. Funding for this work was partially provided by the Spanish MINECO under projects AYA2014-58747-P and MDM-2014-0369 of ICCUB (Unidad de Excelencia 'María de Maeztu').

Based on observations obtained with Planck (http://www.esa.int/Planck), an ESA science mission with instruments and contributions directly funded by ESA Member States, NASA, and Canada.

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III web site is http://www.sdss3.org/.

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