WEIGHING NEUTRINOS WITH THE LARGEST PHOTOMETRIC REDSHIFT SURVEY: MEGAZ DR7

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We present a new upper limit of $\sum m_\nu \leq 0.28$ eV (95% CL) on the sum of the neutrino masses assuming a flat ΛCDM cosmology. This relaxes slightly to $\sum m_\nu \leq 0.34$ and $\sum m_\nu \leq 0.47$ when quasi non-linear scales are removed and $w \neq -1$, respectively. These bounds are derived from a new photometric redshift catalogue of over 700,000 Luminous Red Galaxies (MegaZ DR7) with a volume of 3.3 (Gpc $h^{-1})^3$, extending over the redshift range $0.45 < z < 0.65$ and up to angular scales of $\ell_{\max} = 300$. The data are combined with WMAP 5 CMB fluctuations, Baryon Acoustic Oscillations, type 1a Supernovae and an HST prior. This is the first combined constraint from a photometric redshift catalogue with other cosmological probes. The upper limit is also one of the tightest and 'cleanest' constraints on the neutrino mass from cosmology or particle physics. Furthermore, if the aforementioned bounds hold, they all predict that next generation neutrino experiments, such as KATRIN, are unlikely to obtain a detection.

1 Introduction

Studies of the neutrino have traditionally been the realm of particle physics experiments with bounds placed on the splitting *between* the neutrino mass eigenstates from solar, accelerator and atmospheric experiments[1]. However, currently both the absolute scale and the hierarchy of the masses remain hidden. KATRIN, a kinematic beta decay experiment [2], aims to provide a constraint in the future.

Cosmology not only probes the absolute mass scale of the neutrino but is a completely independent method. A cosmological constraint on the sum of the neutrino masses is primarily a constraint on the relic Big-Bang neutrino density Ω_ν. One can relate this density to the sum of the mass eigenstates $\sum m_\nu$ as given by,

$$\Omega_\nu = \frac{\sum m_\nu}{93.14\mathrm{h}^2\mathrm{eV}}. \tag{1}$$

The direct effects of the neutrinos depend on whether they are relativistic, non-relativistic and the scale under consideration. Neutrinos have a large thermal velocity as a result of their low mass and subsequently erase their own perturbations on scales smaller than the *free streaming* length. This subsequently contributes to a suppression of the statistical clustering of galaxies over small scales and can be observed in a galaxy survey. The abundance of neutrinos in the Universe can also have a *direct* effect on the primary CMB anisotropies if non-relativistic before the time of decoupling. However, one of the most clear effects at this epoch is a displacement in the time of matter-radiation equality. All these cosmological effects can be used to impose bounds on the neutrino mass.

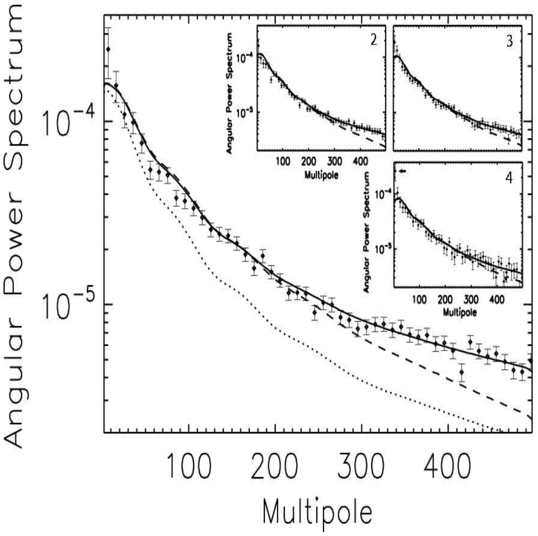

Figure 1: The best fit angular power spectra C_ℓ in the combined analysis (solid lines) are plotted over the MegaZ DR7 data. The panels relate to four redshift bins with width $\Delta z = 0.05$ from $z = 0.45$ (main panel) to $z = 0.65$ (panel 4). The fit is also plotted for linear spectra (dashed lines). The dotted line demonstrates the effect of introducing $\sum m_\nu = 1$ eV neutrinos with all parameters, except Ω_c, held fixed.

In [3] we utilise the *new* SDSS MegaZ LRG DR7 galaxy clustering data that we produce in [4] to provide the first photometric galaxy clustering constraint on the neutrino. With an almost comprehensive combination of probes this renders one of the tightest constraints on the neutrinos in cosmology and therefore physics. We assume a flat Universe with Gaussian and adiabatic fluctuations and a constant spectral index. The effective number of neutrinos are fixed to $\mathrm{N_{eff}} = 3.04$. The constant dark energy equation of state is at first set to $w = -1$ and later relaxed. Finally, we consider the neutrinos to be mass degenerate given that current inferred bounds are much greater than the splitting hierarchies.

2 Analysis

Although parameter degeneracies and a mild insensitivity to relativistic neutrinos limit the upper bound one can place on $\sum m_\nu$ with the CMB its high statistical discrimation of the remaining cosmological model facilitates a competitive combination of probes. We therefore start by using the latest 5-year WMAP data and likelihood [5] to vary seven ΛCDM parameters: $\Omega_b h^2$, $\Omega_c h^2$, Ω_Λ, n_s, τ, $\ln(10^{10} A_s)$ and A_{SZ}, in addition to $\sum m_\nu$. τ, n_s and A_s are defined at $k = 0.002$/Mpc. The contributions from the Sunyaev-Zeldovich fluctuations are included with the pre-factor A_{SZ} and is allowed to vary as $0 < A_{SZ} < 2$ [5].

Our CMB run yields $\sum m_\nu < 1.271$ eV at the 95% confidence level consistent with [6]. This bound implies the neutrinos were relativistic at decoupling and as such induces a degeneracy between the neutrino masses and Ω_m as well as h. This can be seen in Figure 2 and [6]. This degeneracy can be improved by adding supernovae data from the first year Supernova Legacy Survey and the BAO data from [7]. Our analysis for WMAP + SNe + BAO gives $\sum m_\nu < 0.695$ eV (95% CL) similar to [6] ($\sum m_\nu < 0.67$ eV).

In order to go beyond such studies we include the MegaZ LRG (DR7) *photometric* redshift survey that will be presented in [3], which we have checked to be compatible with earlier SDSS clustering and photo-z analyses[8]. This adds galaxy clustering information that is sensitive to the growth of structure suppressed by the free streaming neutrinos. The SDSS colours provide reliable photometric redshift estimates and, due to their high luminosity, probe a large region of

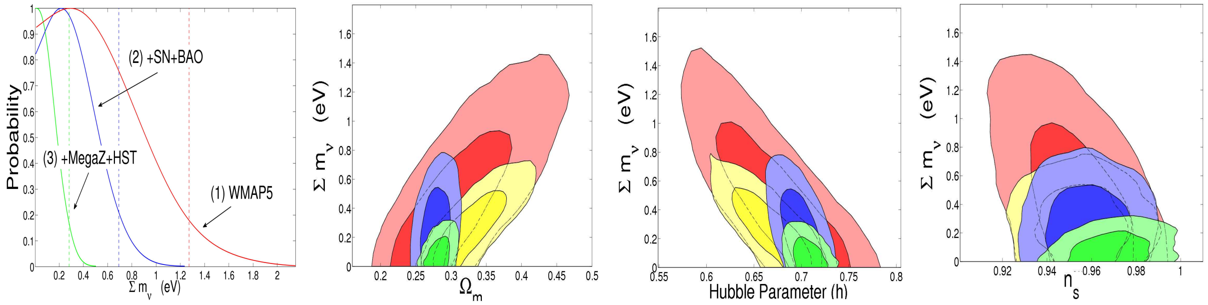

Figure 2: *Left Panel:* The marginalised 1D distribution for the neutrino from three incrementally combined analyses. The vertical dashed lines correspond to 95% CL. *Other Panels:* 68% and 95% marginalised distributions for Ω_m, h and n_s against the total neutrino masses. The contours correspond to (from bottom layer) WMAP-only (red/dark), WMAP+MegaZ (yellow/light), WMAP+SNe+BAO (blue/dark) and WMAP+SNe+BAO+MegaZ+HST (green/light).

cosmic volume. Encapsulating 7746 deg^2, we utilise 723,556 photometrically determined LRGs in four redshift bins of width $\Delta z = 0.05$ between $0.45 < z < 0.65$ in a spherical harmonic analysis of the galaxy distribution until a maximum multipole $\ell_{max} = 300$. Specifically we use the angular power spectrum defined as,

$$C_\ell \equiv < \delta^{2D}\delta^{*2D} >= 4\pi \int \Delta^2(k) W_\ell^2(k) \frac{\mathrm{d}k}{k}. \tag{2}$$

where $\Delta^2(k)$ is the dimensionless power spectrum calculated with CAMB. The matter distribution is projected onto a plane in the sky with weight $W_\ell^2(k)$ described by both $W_l(k) = \int f(z) j_l(kz)\mathrm{d}z$ and $f(z) = n(z)D(z)(\frac{\mathrm{d}z}{\mathrm{d}x})$, with the spherical Bessel function $j_l(kz)$, the linear growth factor $D(z)$ and the normalised redshift distribution $n(z)$. The effects of redshift space distortions are included. The likelihood combines the four measured redshift bins and includes the full covariance as a result of photometric errors scattering galaxies between bins and therefore correlating slices. There are four additional parameters included in the study as a result of the galaxy bias in each bin (b_1, b_2, b_3 and b_4), i.e. modestly accounting for the redshift dependence. Despite the non-linear contribution becoming significant only at scales $\ell > 300$ we use HALOFIT to model the non-linear power spectrum.

This survey is not only one of the largest to date but is one of the most competitive available. However, these power spectra provide an additional incentive for this combined measurement. This because the BAOs, which were shown to be so advantageous before, can be used in conjunction to MegaZ with no cross-covariance. The BAO data is extracted at $z = 0.2$ and $z = 0.35$, whereas MegaZ is defined at a higher redshift. They therefore constitute independent data.

By combining the MegaZ LRGs as described above with the previous CMB, SNe and BAO data we find a significantly lower bound of $\sum m_\nu < 0.325$ eV at 95% CL. Again, this is roughly a factor 2 improvement in the neutrino masses with the addition of the LRGs and is shown clearly against Ω_m, h and the 1D marginalised distribution in Figure 2.

The information on the growth of stucture is paramount to the improvement seen in this study. However, part of this information originates from the quasi-non-linear regime. We repeat the combined analysis with the smaller scales removed. By truncating the multipoles at $\ell_{\max} = 200$ this more conservative approach is seen to give a similar but slightly relaxed limit of $\sum m_\nu < 0.393$ eV. While this highlights the importance of understanding non-linearities for obtaining the most stringent constraints, it is reassuring that there is still a marked improvement on the previous study (CMB+SNe+BAO) with linear LRGs.

It is also intriguing to compare the input of the LRGs to those of the two distance measures (SNe+BAO). We therefore perform a joint analysis using just the WMAP5 and LRG data, subsequently obtaining the limit $\sum m_\nu < 0.651$ eV at 95% CL. This is comparable to the *spec-*

$\sum m_\nu$ (95% CL)	Analysis
< 1.271 eV	WMAP5
< 0.695 eV	WMAP5 + SNe + BAO
< 0.651 eV	WMAP5 + MegaZ
< 0.344 eV	WMAP5 + SNe + BAO + MegaZ$_{(\ell_{200})}$ + HST
< 0.281 eV	WMAP5 + SNe + BAO + MegaZ + HST
< 0.491 eV	WMAP5 + SNe + BAO + MegaZ$_{(\ell_{200})}$ + HST
< 0.471 eV	WMAP5 + SNe + BAO + MegaZ + HST

Table 1: A summary of the bounds placed[3] on $\sum m_\nu$. ℓ_{200} corresponds to the truncation in the maximum multipole scale. The top constraints are for $w = -1$; the bottom for $w \neq -1$, marginalised over.

troscopic DR7 galaxy clustering addition to the CMB in[9] with $\sum m_\nu < 0.62$ eV and illustrates the development of photometric surveys as a competitive tool for the future.

We conclude by further restricting the parameter space with the addition of the new HST prior[10] on h to the WMAP5 + SNe + BAO + MegaZ DR7 run. With this the final limit is reduced to $\sum m_\nu < 0.28$ eV. This is one of the tightest constraints in the literature. The angular power spectra C_ℓ corresponding to the best fit values are plotted in Figure 1 with the galaxy clustering data. An overview of all the neutrino bounds are displayed in Table 1. For $w \neq -1$ the tighter bound relaxes slightly to $\sum m_\nu < 0.47$ eV. We note that biasing *could* act to mimic the neutrino signature over smaller scale analyses. As a gauge of this effect we implement, as an example, the 'Q-model'[11]; resulting in a combined constraint (all data) of $\sum m_\nu < 0.44$ eV.

3 Conclusions

Using the biggest ever large scale structure survey we have set bounds on the neutrino masses at $\sum m_\nu < 0.28$ eV ($\ell_{\max} = 300$) and $\sum m_\nu < 0.34$ eV ($\ell_{\max} = 200$) at 95% CL, when combined with WMAP5+SNe+BAO+HST data. This is the first ever determination of neutrino masses from a photometric galaxy redshift survey. Not only have we shown that photometric redshifts can be used for this problem, but also that such a galaxy survey is competitive with all currently available geometric probes (SNe+BAO) or spectroscopic clustering when added to the CMB. Our constraint is one of the tightest current bounds available without the use of data from Lyman-α[12], which is prone to systematics. Further, all our results show that KATRIN's projected 90% sensitivity ($\sum m_\nu < 0.6$ eV) leaves an unlikely neutrino mass detection.

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