Forecasting neutrino masses from galaxy clustering in the Dark Energy Survey combined with the Planck measurements

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ABSTRACT

We study the prospects for detecting neutrino masses from the galaxy angular power spectrum in photometric redshift shells of the Dark Energy Survey (DES) over a volume of \( \sim 20 \, h^{-3} \, \text{Gpc}^3 \), combined with the cosmic microwave background (CMB) angular fluctuations expected to be measured from the Planck satellite. We find that for a \( \Lambda \) cold dark matter concordance model with seven free parameters in addition to a fiducial neutrino mass of \( M_\nu = 0.24 \, \text{eV} \), we recover from DES and Planck the correct value with uncertainty of \( \pm 0.12 \, \text{eV} \) (95 per cent confidence level; CL), assuming perfect knowledge of the galaxy biasing. If the fiducial total mass is close to zero, then the upper limit is 0.11 eV (95 per cent CL). This upper limit from DES and Planck is over three times tighter than using Planck alone, as DES breaks the parameter degeneracies in a CMB-only analysis. The analysis utilizes spherical harmonics up to 300, averaged in bin of 10 to mimic the DES sky coverage. The results are similar if we supplement DES bands (grizY) with the Visible and Infra-Red Survey Telescope for Astronomy Hemisphere Survey (VHS) near-infrared band (JHK). The result is robust to uncertainties in non-linear fluctuations and redshift distortions. However, the result is sensitive to the assumed galaxy biasing schemes and it requires accurate prior knowledge of the biasing. To summarize, if the total neutrino mass in nature is greater than 0.1 eV, we should be able to detect it with DES and Planck, a result with great importance to fundamental physics.

Key words: surveys – cosmological parameters – large-scale structure of Universe.

1 INTRODUCTION

Neutrinos are so far the only dark matter candidates that we actually know exist. It is now established from solar, atmospheric, reactor and accelerator neutrino experiments that neutrinos have non-zero mass, but their absolute masses are still unknown. Cosmology could provide an upper limit on the sum of neutrino masses (for review see e.g. Elgarøy & Lahav 2005; Lesgourgues & Pastor 2006). The growth of Fourier modes with comoving wavenumber \( k > k_{uw} \) will be suppressed because of neutrino free-streaming, where

\[
k_{uw} = 0.026 \left( \frac{m_\nu}{1 \, \text{eV}} \right)^{1/2} \Omega_m^{1/2} h \, \text{Mpc}^{-1}
\]

for three equal-mass neutrinos, each with mass \( m_\nu \).

A current mass upper limit, obtained using cosmic microwave background (CMB) Wilkinson Microwave Anisotropy Probe 5 (WMAP5) data, SN Ia and the baryonic acoustic oscillations (BAO) from Two-degree Field Galaxy Redshift Survey (2dFGRS) and Sloan Digital Sky Survey (SDSS), is \( M_\nu \equiv \sum m_\nu < 0.61 \, \text{eV} \) at 95 per cent confidence level (CL; Komatsu et al. 2009). Other recent results from samples of SDSS luminous red galaxies (LRGs) combined with WMAP5 and other probes derived an upper limit of 0.3 eV (Thomas, Abdalla & Lahav 2009; Ried et al. 2010), and a similar result was obtained from X-ray clusters (Mantz, Allen & Rapetti 2009). The challenge now is to bring down reliably the upper limits to the 0.1 eV level or even detect the neutrino mass. In this way, cosmology could resolve the mass scale of neutrinos. The new generation of deep wide surveys can play a key role in setting a tight upper limit on the neutrino mass, and possibly detect it if the true neutrino mass is sufficiently high. This is due to the order of magnitude increase in volume of the new surveys.

Here, we study specifically the ability to set an upper limit on the neutrino mass from the galaxy clustering expected in the photometric redshift survey Dark Energy Survey (DES), combined with Planck CMB measurements. The reason why a survey like DES would be effective is its large volume, \( \sim 20 \, h^{-3} \, \text{Gpc}^3 \), and large number of galaxies, \( \sim 300 \) million.

Crudely, for a spectroscopic survey, where accurate redshifts are known, the error on the power spectrum scales with the survey effective volume \( V_{\text{eff}} \) as

\[
\Delta P(k)/P(k) \propto 1/\sqrt{V_{\text{eff}}}.\tag{2}
\]
On the other hand, the suppression is proportional in the linear regime to $f_s = \Omega_c/\Omega_m$ (Hu, Eisenstein & Tegmark 1998; Kiakotou, Elgarøy & Lahav 2008), where

$$\Omega_c = \frac{\sum m_i}{93.14 \, h^2 \, eV^2}. \tag{3}$$

We expect therefore (when all other cosmological parameters are fixed) that the determination of the upper limit on the neutrino mass would be inversely proportional to $\sqrt{\Omega_c}$. From the 2dF Galaxy spectroscopic redshift survey, covering a volume of roughly 0.2 ($h^{-1}$ Gpc)$^3$, the upper limit on the sum of neutrino mass is about 2 eV at 95 per cent CL (Elgarøy et al. 2002). Had DES been a spectroscopic survey with volume of about 20 ($h^{-1}$ Gpc)$^3$, i.e. 100 times larger, we would expect an upper limit of 0.2 eV on the sum of neutrino mass. Our detailed calculation below yields an upper limit of 0.1 eV for DES and Planck. This is tighter than the above back-of-the-envelope calculation, probably as Planck priors are incorporated, and the effective volumes above are only given crudely.

However, DES is a photometric redshift survey, so the radial component of distance to galaxies is significantly degraded, resulting in a poorer estimate of the power spectrum (e.g. Blake & Bridle 2005). Therefore, we prefer in this analysis to quantify the galaxy clustering as angular (spherical harmonic) $C_\ell$ power spectrum derived in photometric redshift shells which are wide enough relative to the photometric redshift errors, and to derive the resulting upper limits more carefully and quantitatively. We defer the comparison of $P(k)$ and $C_\ell$ approaches to future studies. The utility of photometric redshifts is now well established, with many successful techniques being employed (e.g. Collister & Lahav 2004; Abdalla, Blake & Rawlings 2010). The cosmological parameter constraints resulting from future photometric redshift imaging surveys have been simulated by several authors (e.g. Seo & Eisenstein 2003; Dolney, Jain & Takada 2004; Zhan et al. 2006). Application to data such as the SDSS LRG samples were given by Blake et al. (2007) and Padmanabhan et al. (2007). These studies mainly emphasized the detection of baryon acoustic oscillations in the galaxy clustering pattern. Apart from the specific application to DES, the present paper illustrates more generally the determination of neutrino mass from photo-z surveys, to our knowledge for the first time.

This paper is organized as follows. In Sections 2, we summarize the DES and VHS surveys and Planck; in Section 3 we present the photometric redshifts for DES and DES and the Visible and Infrared Red Survey Telescope for Astronomy (VISTA) Hemisphere Survey (VHS) combined filters. Section 4 gives the formalism for the galaxy angular power spectrum and the associated joint likelihood with Planck. Section 5 presents the results for the basic observational and theoretical scenarios, while Section 6 provides extensions of the analysis. An overall discussion is given in Section 7.

# 2 THE GALAXY SURVEYS

## 2.1 The Dark Energy Survey

The DES (www.darkenergysurvey.org) is a ground-based photometric survey that will image 5000 deg$^2$ of the South Galactic Cap in the optical griz bands as well as the Y band. The survey will be carried out using the Blanco 4-m telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. The main objectives of the survey are to extract information on the nature and density of dark energy and dark matter using galaxy clusters, galaxy power spectrum measurements, weak lensing studies and a supernova survey. This will be achieved by measuring redshifts of some 300 million galaxies in the redshift range $0 < z < 2$, tens of thousands of clusters in the redshift range $0 < z < 1.1$ and about 2000 Type Ia supernovae out to redshift $z \approx 1$. Observations will be carried out over 525 nights spread over 5 yr between 2011 and 2016. The DES volume is estimated to be 23.7 $h^{-3}$ Gpc$^3$ in the range $0 < z < 2$ assuming a 10σ AB magnitude limit $r < 24$ (Banerji et al. 2008).

The DES survey area overlaps with that of several other important current and future surveys, for example, the southern equatorial strip of the SDSS and the South Pole Telescope Sunyaev–Zeldovich effect (SZE) cluster survey.

## 2.2 The VISTA Hemisphere Survey

The entire DES region will also be imaged in the near-infrared (NIR) bands on two public surveys being conducted on the VISTA at European Southern Observatory’s (ESO) Cerro Paranal Observatory in Chile. In particular, the VHS (www.vista.ac.uk) will image the entire southern sky ($\sim$20,000 deg$^2$) in the NIR Y J H K$\_s$ bands when combined with other public surveys. About 40 per cent of the total VHS time has been dedicated to VHS-DES, a 4500 deg$^2$ survey being carried out in the DES region over 125 nights in order to complement the DES optical data with NIR data. The initial proposal is for the survey to image in the JHK$\_s$ bands with 120 s exposure time in each band reaching 10σ magnitude limits of $J = 20.4$, $H = 20.0$ and $K_s = 19.4$. A second pass may then be obtained with 240 s exposures in each of the three NIR filters in order to reach the full-depth required by DES. The VHS-DES survey assumes that Y-band photometry will come from the DES.

## 2.3 Planck

The recently launched European Space Agency Planck satellite will map the CMB with better resolution, sensitivity and frequency (in nine bands from one centimetre to one third of a millimetre) than previous CMB experiments.¹

We have obtained forecasts from the Planck satellite by using the technique described in Abdalla & Rawlings (2007). We have assumed conservative values for the sensitivity by taking only one usable science channel with eight detectors, a noise effective telescope angular resolution of 10 arcmin and 65 per cent sky coverage in a 1 yr survey. The input fiducial masses are taken as $\Omega_c = 0.001$ and 0.005 and the other cosmological parameters considered as listed in Table 1. For simplicity, gravitational lensing of the CMB is not included in our analysis. However, as the lensing effect depends on neutrino mass, incorporating CMB data can potentially significantly improve results for neutrino mass (Perotto et al. 2006; Bernardis et al. 2009).

| $\Omega_\nu$ | $\Omega_c$ | $\Omega_b$ | $h$ | $\sigma_8$ | $n_s$ | $\tau$ | $N_v$ |
|--------------|------------|------------|-----|-------------|-----|-------|------|
| 0.005        | 0.255      | 0.04       | 0.72| 0.9         | 1   | 0.166 | 2.0  |
| 0.001        | 0.259      | 0.04       | 0.72| 0.9         | 1   | 0.166 | 2.0  |

¹ http://www.esa.int/SPECIALS/Planck
angular power spectrum $C_{\ell}$ (see e.g. Peebles 1973; Scharf et al. 1992; Wright et al. 1994; Wandelt, Hivon & Górscki 2001):

$$\langle |a_{\ell,m}|^2 \rangle = C_{\ell}. \quad (4)$$

The angular power spectrum $C_{\ell}$ is a projection of the spatial power spectrum of fluctuations at different redshifts $z$, $P(k, z)$, where $k$ is a comoving wavenumber. When the sky coverage is incomplete, the prediction for observed angular power spectrum can be estimated through convolution, as explained later in the paper.

We follow here the notation of Blake et al. (2007). The equation for the projection is

$$C_{\ell} = \frac{2 b^2}{\pi} \int P_0(k) g_\ell(k)^2 \, dk, \quad (5)$$

where we assume $P(k, z) = P_0(k) D(z)^2$, with $D(z)$ the linear growth factor at redshift $z$, and $g_\ell(k)$ contains $D(z)$ as defined below.

We note that this decomposition of $P(k, z)$ is strictly only valid in linear theory and its application at smaller scales is an approximation. Moreover, in the presence of massive neutrinos $P(k, z)$ cannot be decomposed even in linear theory. However, we find that over the redshift $z < 2$ and $k$-range of interest $P(k, z) \approx P_0(k) D(z)^2$ to within 0.5 per cent (cf. Lesgourgues & Pastor 2006; Kiakotou et al. 2008). We have also assumed in the above equation a scale-independent and epoch-independent bias factor $b$. Later we allow the biasing to vary with redshift.

Fig. 2 shows the expected spherical harmonic $C_{\ell}$ (ignoring shot noise) for three values of assumed neutrino mass, illustrating that the suppression effect can be measured. Fig. 3 shows the expected $C_{\ell}$ for three photo-z shells.

Similarly, $C_{\ell}^{i,j}$ is the cross-angular power spectrum between the two redshift slices $i$ and $j$, with a kernel $g_{\ell}(k)$ for a redshift slice $i$:

$$C_{\ell}^{i,j} = \frac{2 b_i b_j}{\pi} \int P_0(k) g_{\ell}(k)^2 \, dk, \quad (6)$$

where $b_i$ and $b_j$ are the linear bias factors for the slices. The kernel $g_{\ell}(k)$ is given by

$$g_{\ell}(k) = \int_0^\infty j_{\ell}(u) f(u/k) \, du. \quad (7)$$

**3 Photometric Redshifts**

We determined photometric redshift estimates as described in Banerji et al. (2008) using mock samples of DES and VHS and the photo-z software package ‘ANNZ’ (Collister & Lahav 2004). In brief, artificial neural networks are applied to parametrize a non-linear relation between the galaxy redshift and the galaxy multiband photometry. The neural network is ‘trained’ using a set of galaxies with known true redshifts by minimizing the sum of the squared differences between the photometric and true redshifts. For comparison of $ANNZ$ with five other photo-z codes, see Abdalla et al. (2010).

Fig. 1 shows the distribution of true redshifts in the evaluation set with known true redshifts by minimizing the sum of the squared

| True Redshift |
|---------------|
| 0.0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 |
| p(z) | 0.211 | 0.405 | 0.125 | 0.412 | 0.145 |
| 0.5 | 0.337 | 0.582 | 0.125 | 0.598 | 0.129 |
| 0.7 | 0.215 | 0.789 | 0.123 | 0.805 | 0.113 |
| 0.9 | 0.128 | 0.975 | 0.125 | 0.984 | 0.116 |
| 1.1 | 0.098 | 1.203 | 0.220 | 1.193 | 0.142 |
| 1.3 | 0.081 | 1.393 | 0.260 | 1.393 | 0.147 |
| 1.5 | 0.027 | 1.673 | 0.291 | 1.593 | 0.149 |

**4 The Angular Power Spectrum in Photo-z Shells**

4.1 Spherical harmonic formalism

It is common to expand the distribution of galaxies in spherical harmonic coefficients $a_{\ell,m}$, which are then averaged to form the angular power spectrum $C_{\ell}$ (see e.g. Peebles 1973; Scharf et al. 1992; Wright et al. 1994; Wandelt, Hivon & Górscki 2001):

$$\langle |a_{\ell,m}|^2 \rangle = C_{\ell}. \quad (4)$$

The angular power spectrum $C_{\ell}$ is a projection of the spatial power spectrum of fluctuations at different redshifts $z$, $P(k, z)$, where $k$ is a comoving wavenumber. When the sky coverage is incomplete, the prediction for observed angular power spectrum can be estimated through convolution, as explained later in the paper.

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Fig. 2 shows the expected spherical harmonic $C_{\ell}$ (ignoring shot noise) for three values of assumed neutrino mass, illustrating that the suppression effect can be measured. Fig. 3 shows the expected $C_{\ell}$ for three photo-z shells.

Similarly, $C_{\ell}^{i,j}$ is the cross-angular power spectrum between the two redshift slices $i$ and $j$, with a kernel $g_{\ell}(k)$ for a redshift slice $i$:

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where $b_i$ and $b_j$ are the linear bias factors for the slices. The kernel $g_{\ell}(k)$ is given by

$$g_{\ell}(k) = \int_0^\infty j_{\ell}(u) f(u/k) \, du. \quad (7)$$

**Figure 1.** Gaussian fits to the true redshift distribution of each of seven photometric redshift slices analysed in this study. The best-fitting Gaussian parameters $\mu$ and $\sigma$ are indicated, where $p(z) \propto \exp \left\{ -\|z - \mu\|^2 / 2\sigma^2 \right\}$.

**Table 2.** The best-fitting Gaussian parameters $\mu$ and $\sigma$, in true redshift $z$, where $p(z) \propto \exp \left\{ -\|z - \mu\|^2 / 2\sigma^2 \right\}$ for photo-z shells derived from DES alone (five filters) and DES and VHS (eight filters).

| Photo-z shell | Galaxy fraction | DES | DES and VHS |
|---------------|----------------|-----|--------------|
| $0.3 < z_{ph} < 0.5$ | 0.211 | 0.405 | 0.125 | 0.412 | 0.145 |
| $0.5 < z_{ph} < 0.7$ | 0.337 | 0.582 | 0.125 | 0.598 | 0.129 |
| $0.7 < z_{ph} < 0.9$ | 0.215 | 0.789 | 0.123 | 0.805 | 0.113 |
| $0.9 < z_{ph} < 1.1$ | 0.128 | 0.975 | 0.125 | 0.984 | 0.116 |
| $1.1 < z_{ph} < 1.3$ | 0.098 | 1.203 | 0.220 | 1.193 | 0.142 |
| $1.3 < z_{ph} < 1.5$ | 0.081 | 1.393 | 0.260 | 1.393 | 0.147 |
| $1.5 < z_{ph} < 1.7$ | 0.027 | 1.673 | 0.291 | 1.593 | 0.149 |
Here, $j_l(x)$ is the spherical Bessel function and $f(x)$ depends on the radial distribution of the sources as

$$f(z(x)) = p(z) D(z) \left( \frac{dx}{dz} \right)^{-1},$$

where $x(z)$ is the comoving radial coordinate at redshift $z$ and $p(z)$ is the redshift probability distribution of the sources, normalized such that $\int p(z) dz = 1$. A good approximation for equation (5) which is valid for moderately large $\ell \gtrsim 30$ is

$$C_\ell = b^2 \int P_\ell(k = \ell/x) D^2(z(x)) x(z)^2 p(z)^2 \left( \frac{dx}{dz} \right)^{-1} dz.$$

The above formalism neglects redshift distortions, which we examine later.

The cosmological parameters enter the matter power spectrum of fluctuations $P_\ell(k)$, the growth factor $D(z)$ and the comoving distance $x(z)$ in the above equations. For the redshift distribution of the sources $p(z)$, we used the Gaussian functions fitted to the training set data (see Fig. 1). We derived model spatial power spectra using the ‘CAMB’ software package (Lewis, Challinor & Lasenby 2000). For more technical details of these calculations see Blake et al. (2007).

### 4.2 Spherical harmonic likelihood

In this work, we forecast the measurements, without any data, so we use the following relation to express the ratio of (log) probabilities between a selected model in the parameter space B and the assumed fiducial model A. The model describes all the power spectra produced from random Gaussian fields with a certain degree of cross-correlation (Bucher, Moodley & Turok 2002; Abdalla & Rawlings 2007):

$$\log \left( \frac{p_B}{p_A} \right) = \log \left[ \frac{p(a_{ln} | B)}{p(a_{ln} | A)} \right] = \frac{f_{\Delta\Omega}}{2} \sum_l (2l+1) \left\{ \text{Tr} (I - M_A M_B^{-1}) + \log \left[ \text{Det} (M_A M_B^{-1}) \right] \right\},$$

where $I$ is the identity matrix and the matrices $M_A$ and $M_B$ are given by the values of the individual power spectra and their cross-correlations at a given mode $l$. As in our case, we have seven shells, each of them is a $7 \times 7$ matrix. The diagonal terms are

$$\text{diag}(M_l) = C_l + \sigma_l^2,$$

where $\sigma_l^2 = \frac{1}{N/\Delta\Omega}$ where $N/\Delta\Omega$ is the average source density and $f_{\Delta\Omega} = \Delta\Omega/(4\pi)$ denotes the fraction of sky covered by the survey. There is no shot noise in the off-diagonal terms.

To get insight into this likelihood ratio, we note the special case of equation (10) for a shell’s autocorrelation (cf. Fisher, Scharf & Lahav 1994):

$$\log \left( \frac{p_B}{p_A} \right) = \log \left[ \frac{p(a_{lm} | B)}{p(a_{lm} | A)} \right] = \frac{f_{\Delta\Omega}}{2} \sum_l (2l+1) \left[ 1 - \frac{C_{l,A} + \sigma_l^2}{C_{l,B} + \sigma_l^2} \right].$$

### 5 ANALYSIS AND RESULTS

#### 5.1 Implementation of MCMC for DES and Planck

The joint likelihood is implemented as follows. The Markov Chain Monte Carlo (MCMC) chains for Planck were derived by us, using the methods described in Abdalla & Rawlings (2007). We then used the approach of ‘importance sampling’ (e.g. Lewis & Bridle 2002) to evaluate the joint likelihood for DES and Planck. In more detail, the Planck MCMC chain in eight-dimensional space is centred at one of the two fiducial models given in Table 1. The DES likelihood is evaluated using equation (10), with label A corresponding to the fiducial model and label B to another point of the Planck chain. By evaluating the DES likelihood at the Planck chain points, we effectively get the joint likelihood of DES and Planck. For a subset of the parameters of interest, we can marginalize over the other parameters by projecting the distribution of the points in the resulting chain.

This importance sampling method is only an approximation in the regime where there are few points. From the two-dimensional likelihood figures in this paper, we can clearly see that fortunately there is clear overlap between the two likelihood contours. This in fact will always be the case for a simulation because we know that there is a perfect model which will fit all the data (i.e. the model chosen as the fiducial model). On the other hand, for real data, there could be some tension on the data and all the weights drift towards zero, so the importance sampling results may yield poor approximations. A further reason why the likelihood is robust is that the Planck chains used were oversampled, as they contain tens of thousands of points so that we do not end up in a situation where few points are left with significant weight.

We compared our results for the Planck-only case with other results in the literature. Our Planck-only chains are somewhat ‘pessimistic’ compared to Perotto et al. (2006). The discrepancies are due to different assumptions on the noise properties and number of channels used. Planck chains derived by Gratton, Lewis & Efstathiou (2008) are similar to our chains, but in fact a bit more ‘pessimistic’ than ours. We also note that one should treat with care comparisons of Fisher results with MCMC results as Fisher results do not take into account a possible non-Gaussianity of the likelihood with respect to the parameters. In summary, we believe that our MCMC results for Planck are robust and consistent, baring
To read the text naturally, here is a transcription:

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Table 3. Table showing derived results neutrino mass $M_\nu$ for two input fiducial values $M_\nu = 0.048$ eV and 0.241 eV.

| $l_{\text{min}}$ | $l_{\text{max}}$ | $\Delta l$ | $M_\nu = 0.048$ eV | $M_\nu = 0.241$ eV |
|------------------|------------------|------------|-------------------|-------------------|
|                  |                  |            | 68 per cent CL    | 95 per cent CL    |
| (1) Planck       | 1                | 100        | $M_\nu < 0.175$   | $M_\nu < 0.386$   |
| (2) Planck&DES   | 1                | 100        | $M_\nu < 0.067$   | $M_\nu < 0.112$   |
| (3) Planck&DES   | 20               | 120        | $M_\nu < 0.063$   | $M_\nu < 0.101$   |
| (4) Planck&DES   | 1                | 100        | $M_\nu < 0.106$   | $M_\nu < 0.216$   |
| (5) Planck&DES   | 1                | 300        | $M_\nu < 0.063$   | $M_\nu < 0.106$   |
| (6) Planck&DES   | 1                | 300        | $M_\nu < 0.052$   | $M_\nu < 0.079$   |
| (7) Planck&DES& VHS | 1            | 100        | $M_\nu < 0.066$   | $M_\nu < 0.110$   |
| (8) Planck&DES& VHS | 1           | 300        | $M_\nu < 0.061$   | $M_\nu < 0.101$   |

Note. The results are given for different combination of mock data sets (DES, VHS, Planck) and different range of spherical harmonics $l_{\text{max}}, l_{\text{min}}$ and smoothing scale $\Delta l$.

5.2 Results for DES and Planck

We first consider a baseline model, so we can see ‘the wood for the trees’, where we assume a linear matter power spectrum (derived from CAMB), a linear biasing parameter $b = 1$ for all 7 photo-z slices, no redshift distortion, and we ignore the mask. In the discussion below, we refer to the 95 per cent CL values. The first entry in Table 3 is for Planck alone, while the second entry is for Planck and DES, both for $l = 1, 2, \ldots, 100$. We see that the addition of DES improves the upper limit to 0.11 eV, more than three times tighter than Planck alone. The corresponding error bar on the high-mass values is 0.13 eV from Planck and DES. The likelihood contours in Figs 4–6 correspond to entry 5 in Table 3, where $l_{\text{max}} = 300$, where $\Delta l = 10$, which roughly represents the DES incomplete sky. The fiducial models are $\Omega_\text{c} = 0.001$ and $\Omega_\text{b} = 0.005$. They show pairs of variables $(\Omega_\text{c}, \sigma_8)$, $(\Omega_\text{b}, h)$ and $(\Omega_\text{c}, \Omega_\text{b})$, and in Fig. 7 the probability for $\Omega_\text{c}$, after marginalizing over all other seven parameters. Numerical results are given in Table 3, as 68 and 95 per cent upper limits. We note the similarity of results of entries 2 and 5 in that table. We also note that in the case of entry 5, the 5σ upper limit is 0.121 eV, compared with the 2σ value of 0.106 eV.

6 EXTENSIONS OF THE ANALYSIS

6.1 Incomplete sky coverage

When the sky coverage is incomplete, the prediction for observed angular power spectrum can be estimated through convolution:

$$\langle C^{\text{obs}}_\ell \rangle = \sum_{\ell'} R_{\ell, \ell'} C_{\ell'},$$

where the ‘mixing matrix’ $R_{\ell, \ell'}$ can be determined from the angular power spectrum of the survey window function. For a survey of 5000 deg$^2$ or so, the mixing matrix smears out harmonics over $\Delta \ell \approx 10$, subject to survey’s geometry (Blake et al. 2007). We illustrate the effect of incomplete sky coverage by averaging the angular power spectra in multipole bands of width $\Delta \ell = 10$:

$$\langle C^{\text{av}}_\ell \rangle = \sum_{\ell'} (2\ell' + 1)C_{\ell'} / \sum_{\ell'} (2\ell' + 1).$$

Entry (4) in Table 3 shows that the upper limit on the neutrino mass is twice as large as for a ‘whole sky DES’ (entry 2 in Table 3). However, if we use harmonics up to $l_{\text{max}} = 300$ (entry 5), then the upper limits are very similar to those in entry (2), where $l_{\text{max}} = 100$.

6.2 DES and VHS photo-z

Entries (7) and (8) in Table 3 illustrate the impact of adding VHS NIR photometry, i.e. having photo-z based on eight filters. It turns out that the results on neutrino mass look very similar to DES alone. This is because the improvement of VHS is at high redshift (Banerji...
6.3 Redshift distortion

These distortions significantly affect the amplitude of the projected power spectrum on large scales $\ell \lesssim 50$, owing to the relative narrowness of each redshift slice. The amplitude of the redshift–space distortions is controlled by a parameter $\beta(z) \approx \Omega_m(z)^{0.6}/b(z)$, where the quantities on the right-hand side of the equation are evaluated at the centre of each redshift slice of our analysis. The effect is to introduce an additional term to the kernel of equation (7) such that it becomes $g_\ell(k) + G_\ell(k)$ where (Fisher et al. 1994; Padmanabhan et al. 2007; Blake et al. 2007)

$$g_\ell(k) = \frac{\beta}{k} \int_0^\infty j_\ell(u) f'(u/k) \, du.$$  

(15)

Fig. 8 shows that the redshift distortion is important for $\ell < 20$. In entry 3 of Table 3, we show the effect of analysing $20 < \ell < 500$. Excluding the low $\ell$, changes only little the results on neutrino mass compared with the case where low-$\ell$ are included (entry 2).

6.4 Non-linear power spectrum

Typically, non-linearity in the power spectrum appears for $k > k_{\text{max}} \approx 0.15 \, h \, \text{Mpc}^{-1}$, at $z = 0$ (e.g. Smith et al. 2003) and higher $k_{\text{max}}$ at higher redshifts. We can estimate the equivalent maximum multipole $\ell_{\text{max}}$ of the angular power spectrum using the scaling relation $k_{\text{max}} \approx \ell_{\text{max}}/r(z)$ (see equation 9). For example, for the shells with mean redshift $z \approx 0.4, 0.8$ and 1.6 and assuming a flat universe with $\Omega_m = 0.25$, this corresponds to $\ell_{\text{max}} \approx 160, 290$ and 510. Roughly speaking, it is safe to assume linear theory up to those $\ell_{\text{max}}$ values.

To check the justification of this simple approximation, we considered a non-linear power spectrum in the presence of massive neutrinos. The total matter density fluctuation can be written as

$$\delta_m = f_{\text{cb}} \delta_{\text{cb}} + f_\nu \delta_\nu,$$

(16)

where $f_{\text{cb}} = 1 - f_\nu$ is the fractional contribution of the cold dark matter (CDM) plus baryon of the present epoch mass density. The resulting non-linear power spectrum can be approximated (Saito,
This approximation is convenient, as the non-linear $P_{NL}^{cb}(k)$ can be taken from fits to $N$-body simulations (Saito et al. 2008 based on Smith et al. 2003; ‘HALOFIT = 1’ in CAMB). Assuming linearity for the power spectra which involve neutrino mass is reasonable, as due to their free-streaming, massive neutrinos remain in the linear regime, rather than joining the non-linear evolution of CDM plus baryons. We also note that the pre-factor $f_\nu$ is small, which justifies further ignoring non-linear neutrino perturbations. For a slightly different approximation, see Hamanishi, Tu & Wong (2006), and further improvements to the non-linear power spectrum were given by Wong (2008) and Lesgourgues et al. (2009).

For comparison, we plot, in Fig. 9, the errors on the $C_\ell$s (e.g. Dodelson 2003; Blake et al. 2007):

$$\sigma(C_\ell) = \sqrt{\frac{2}{f_{sky}}/2l + 1} \left( 1 + \frac{1}{N/\Delta \Omega} \right),$$

which are far larger than the non-linearity effect for $\ell < 100$. As Fig. 10 shows, in this regime the effect of non-linearity is less than 5 per cent.
6.5 Epoch dependent biasing

Another source of uncertainty in constraining neutrino mass from galaxy surveys is galaxy biasing (e.g. Elgarøy & Lahav 2005). The bias systematically increases with redshift for two reasons:

(i) In standard models of the evolution of galaxy clustering, the bias factor of a class of galaxies increases with redshift in opposition to the decreasing linear growth factor, in order to reproduce the observed approximate constancy of the small-scale clustering length (e.g. Magliocchetti et al. 2000; Lahav et al. 2002).

(ii) In a flux limited survey, galaxies in more distant redshift slices are preferentially more luminous (owing to the fixed apparent magnitude threshold) and hence more strongly clustered (Norberg et al. 2002).

Here, we test what happens if the biasing varies with epoch. One simple model is the ‘galaxy evolving model’ (Fry 1996), where the bias evolves as

\[ b(z) = 1 + (b_0 - 1)/D(z). \]  

(19)

where \( b_0 \) is the present galaxy bias for a particular galaxy type and \( D(z) \) is the linear theory growth rate.

The sensitivity to the assumed galaxy biasing scheme is illustrated in Fig. 4 (bottom). The point \( O \) corresponds to \( b = 1.00 \) in the fiducial model for all shells, \( X \) corresponds to \( b = 1.02 \) and \( Y \) corresponds to epoch-dependent \( b(z) \) from equation (19) with \( b_0 = 1.02 \). According to that plot, if \( b \) deviates from unity by more than 2 per cent, then \( \sigma_8 \) changes by 2 per cent and \( \Omega_m \) changes by 7 per cent. Therefore, biasing is the most sensitive quantity in our analysis. In other words, we need to have the bias known to 2 per cent accuracy as a larger bias would introduce a best-fitting value outside the 1σ error bar in Fig. 4.

We see that our results are sensitive to biasing. Fortunately, there are several independent ways of controlling this systematic effect: (i) allowing a bias parameter per redshift slice and marginalizing over it (e.g. Thomas et al. 2009) or modelling the biasing via halo model or semi-analytic simulations and marginalizing over the biasing parameters; (ii) estimating the neutrino mass from galaxy power spectra derived for different galaxy types and checking for consistency; (iii) estimating the bias empirically from weak-lensing map to be produced e.g. from DES itself; (iv) estimating biasing from high-order statistic such as the bispectrum (Ross, Brunner & Myers 2007).

7 CONCLUSIONS

We study the prospects for detecting neutrino masses from the galaxy angular power spectrum in photo-z shells in the DES, combined with CMB fluctuations as will be measured by Planck. Although the core science case for DES is dark energy, we see that DES can provide us with other important extra science, such as neutrino mass. Our main conclusions are:

(i) We forecast for DES and Planck a 2σ error of total neutrino mass \( \Delta M_\nu \approx 0.12 \) eV. If the true neutrino mass is very close to zero, then we can obtain an upper limit of 0.11 eV (95 per cent CL).

(ii) This upper limit from DES + Planck is over three times tighter than using Planck alone, as DES breaks the parameter degeneracies in a CMB-only analysis.

(iii) The results are sensitive to the assumed galaxy biasing, and stand if the galaxy bias is known to be within 2 per cent. This is feasible given other analyses of the galaxy bias such as the three point correlation function.

(iv) The results are robust to uncertainties in non-linear fluctuations and redshift distortion.

(v) The results are similar if we supplement DES bands (grizY) with the VHS NIR band (JHK).

DES can also be used to extract information on neutrino mass via other techniques, e.g. weak gravitational lensing, as considered recently for other imaging surveys (Kitching et al. 2008; Ichiki et al. 2009; Tereno et al. 2009). We note that the level of sensitivity for neutrino mass from DES and Planck is of much relevance for comparison with the direct measurement of the neutrino mass from laboratory experiments, e.g. the Karlsruhe Tritium Neutrino (KATRIN) tritium beta decay experiment. Furthermore, the DES & Planck measurements can be combined with laboratory experiments to derive more accurate neutrino masses (Host et al. 2007).

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