Large-Scale Structure Requirements for the DES

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The following requirements should be applied to the optimally selected subsample containing 40% of all available galaxies (see §I).

1. The bias in the mean photometric redshift, $< |z_{phot} - z_{true}| >$ in a bin of width $\Delta z = 0.1$ centred on any redshift $0.5 < z < 1.5$ should be less than $0.001(1+z)$ (see §II).

2. The root of the covariance between $< |z_{phot} - z_{true}| >$ from any two non-overlapping bins of width $\Delta z = 0.1$ centred on any redshift $0.5 < z < 1.5$ should be less than $0.0005(1+z)$ (see §II).

3. The width of the Gaussian best-fit to the average photo-z error distribution, in a bin of width $\Delta z = 0.1$ centred on any redshift $0.5 < z < 1.5$, will be known to better than 0.003 in sigma (see §II).

4. The fraction of outliers, where $|z_{phot} - z_{true}| > 0.09(1+z)$ (3σ), in any bin of width $\Delta z = 0.1$ centred on any redshift $0.5 < z < 1.5$ should be less than 1.5% (see §II).

5a. Spatially rms correlated errors smaller than 9% (ie 0.09 magnitudes) on scales smaller that 4 degrees for BAO science (see §III C).

5b. Spatially rms correlated errors smaller than 2% on all scales used for other clustering measures, in all bands (see §III D).

6. The star/galaxy separation is to give probabilities that are accurate such that a Monte-Carlo sampling would give the correct star/galaxy ratio to 1% (see §IV).

7a. Stellar contamination of the galaxy sample or the distribution of galaxies misclassified as stars to have a spatial correlation which is smaller than our nominal 9% for BAO science, otherwise misclassification could dominate over calibration errors.

7b. Stellar contamination of the galaxy sample or the distribution of galaxies misclassified as stars to have a spatial correlation which is smaller than our nominal 2% (for all clustering l) rms on scales smaller than 4 degrees.

If requirements 1, 5a or 7a are not met in any given redshift bin we will lose our ability to constrain w from BAO within that bin. If requirement 2 is not met, we will lose our ability to constrain w from BAO over the full redshift range of the survey. If requirements 3, 4, 5b, 6, 7b are not met, clustering at the depth of the survey will be dominated by systematic rather than by sampling variance. This will limit the effective depth of the survey for clustering analysis, and cause problems for analyses that rely on shape information, such as measurements of the neutrino mass. Nevertheless, we believe we will still be able to do BAO science.

I. GALAXY DENSITY IN SUBSAMPLES

It is expected that we will have to subsample the DES galaxies based on galaxy luminosities and colours in order that the subsample used in the analysis passes our requirements. The effect of this subsampling on our ability to constrain dark energy is shown in Figure 1. The DES is oversampled, so we can remove some galaxies without significantly affecting the figure-of-merit (FoM). We set a constraint that we should only reduce the FoM by 1 because of this subsampling, and this corresponds to selecting 40% of all available galaxies in each redshift bin. All of our requirements should therefore be applied to the optimally selected subsample containing 40% of all observed galaxies. The effect of subsampling will depend on redshift because the number density of galaxies changes. For simplicity, we have selected a fixed fraction of galaxies at all redshifts, and set a global constraint on this. It is worth noting that the subsampling has more effect where the number density of galaxies is lowest, at very low and very high redshift.

II. RADIAL/PHOTO-Z CALIBRATION

If photometric redshifts for galaxies are systematically wrong, then the angular BAO scales measured by DES will be assigned to the wrong redshift, and we will infer an incorrect cosmological model. We therefore need to set requirements on

$$f(z_{\rm true}) \equiv < (z_{\rm true} - z_{\rm phot}) > . \quad (1)$$

$f(z_{\rm true})$ is correlated across different redshifts so the redshift interval over which we constrain $f(z_{\rm true})$ is important. Ideally, when we analyse the data with the correct cosmology within any range of redshift, we want the effect of $f(z_{\rm true}) \neq 0$ to shift the the comoving sound horizon scale (r_s) by a small amount. In the following we take bins of width $\Delta z = 0.1$ as our fiducial interval in which to analyse photometric redshifts.

First, we consider estimating the BAO scale r_s from individual redshift bins of width $\Delta z = 0.1$, and require that the systematic error on the recovered value of the sound horizon scale r_s is at most 20% of the random error within this bin. This sets "small scale" constraints on $f(z)$ at all redshifts, shown by the solid line in Fig. 2. A requirement that $|f(z)| < 0.001(1+z)$ would satisfy this criteria, which is requirement (1).

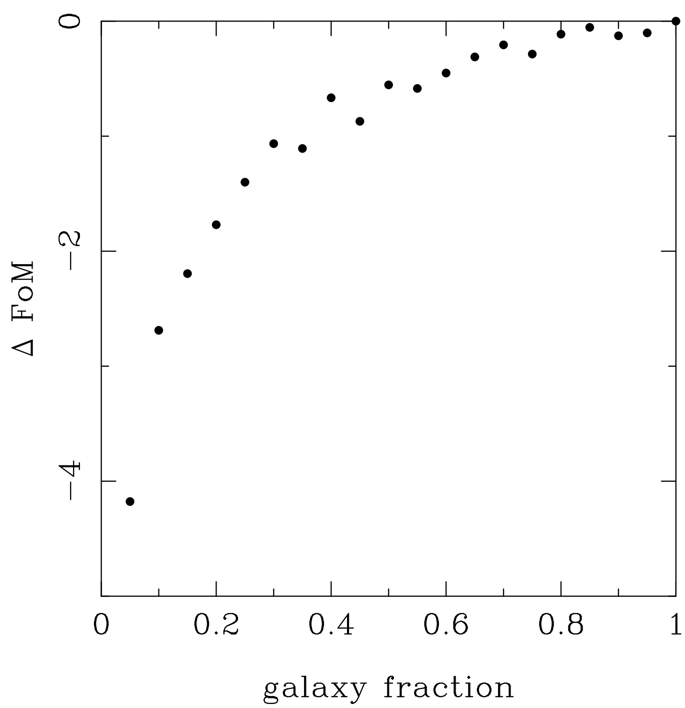

FIG. 1: The decrease in the DETF figure-of-merit if the galaxy density is reduced by a constant factor. Scatter in the data follows from the Monte-Carlo nature of the figure-of-merit calculation.

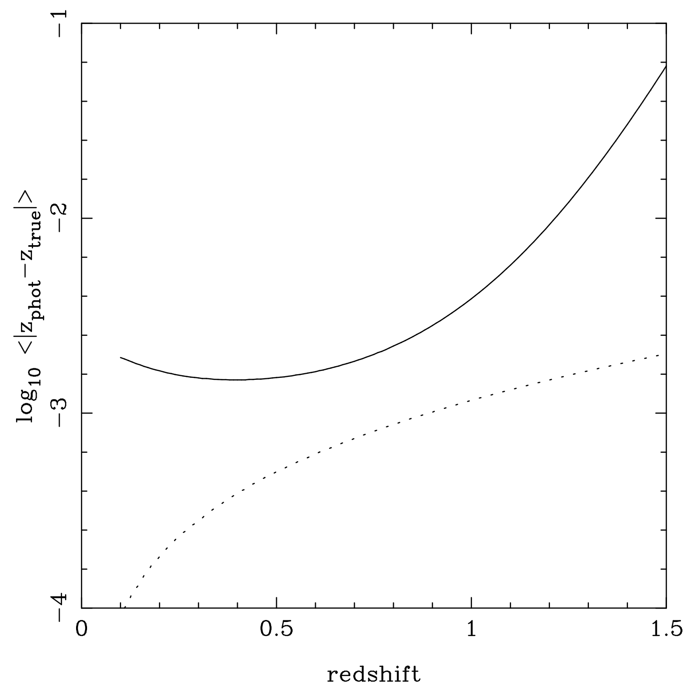

FIG. 2: The photo-z error $<(z_{\rm true} - z_{\rm phot})>$ allowed in bins of width $\Delta z = 0.1$ (solid line), which gives a systematic sound horizon shift corresponding to 20% of the statistical error. If these errors are correlated with a combined systematic error with the same radial distribution as the statistical error, then we set the requirement given by the dotted line. This corresponds to the systematic error on the comoving sound horizon measured from all of the data $0.5 < z < 1.5$ being 20% of the statistical error.

We have to worry that the values of $f(z)$ are correlated between different non-overlapping bins. If we take the conservative approach and assume that $f(z)$ is perfectly correlated across all bins, and has a distribution whose shape matches that of the expected statistical errors, then we need $|f(z)|$ to be less than the values shown by the dotted line in Fig. 2. This leads to the requirement on the covariance between $f(z)$ in different bins, which is requirement (2).

We also consider how well known the photo-z error distributions are. If our estimate of these distributions is wrong, then we effectively convolve the configuration space radial distributions by a new radial function with width given by the unknown part of the distribution. Provided this is a relatively smooth function of redshift, this should not affect the BAO positions, but will reduce the amplitude of the measured power spectrum. Convolution with a Gaussian with $\sigma \simeq 0.003$ would give a 2% reduction in the spherically averaged power. This is requirement (3). Note that such a reduction in power should not affect the BAO positions.

We wish to exclude galaxies with a high probability of catastrophic photometric redshift error. We therefore set a constraint on the number of galaxies that have $|f(z)| > 0.09(1+z)$, which is approximately 3σ for our nominal Gaussian photo-z distribution. Following this fiducial model, we should expect that only 0.3% of galaxies match this criteria. A 1% contamination of missed galaxies with catastrophic redshift errors, would cause a decrease in the power of 2% if they are unclustered. We therefore set a constraint that we should only have an extra 1% of these outlier galaxies, which forms requirement (4). This approach was also used for the star/galaxy separation requirements as discussed below.

III. ANGULAR CALIBRATION

At each angular position θ in the sky were we have a galaxy we can decompose the measured calibrated magnitude m' for that galaxy as:

$$m'(\theta) = m(\theta) + e_r(\theta) + e_s(\theta) \qquad (2)$$

This is the sum of the true magnitude m, plus a random statistical error e_r and a systematic (spatially correlated) error e_s:

$$< e_r(\theta_1) e_r(\theta_2) >= 0 \qquad (3)$$

$$\Delta_m(\theta_{12}) \equiv < e_s(\theta_1) e_s(\theta_2) > \neq 0 \qquad (4)$$

These are the residual errors after correcting the best we can for all known systematics, such as electronic noise, flat-field, dust absorption, air-mass, sky variability....

The random statistical errors have an effect that is reduced as the number of measured galaxies is increased. The systematic errors, however, do not go down with the number of galaxies observed.

A. Random calibration errors

A desirable **requirement** on random magnitude errors is that their effect of $P(k)$ is smaller than errors induced by shot-noise. For one galaxy the shot-noise is $\Delta N/N = 1$, and therefore:

$$\alpha \ \ln 10 \ e_r < 1 \tag{5}$$

where we use $N \sim 10^{\alpha \ m}$ for number counts (typically $\alpha \ln 10 \simeq 1$). If we want to measure $P(k)$ with N_g galaxies we have:

$$< e_r^2 >^{1/2} < \frac{1}{\alpha \ \ln 10 \sqrt{N_g}} \tag{6}$$

were we have assumed that magnitude errors are random and so their variance reduces with $1/N_g$. The above expression depends on the sample we select: depending on galaxy type and luminosity we will have that α and N_g will be different. We will probably want to slice the DES en redshift bins to estimate the power spectrum at different redshift bins and galaxy types. We expect to have $N_g \sim 10^6$ galaxies per sample. The **requirement** for the random error of the $N_g \sim 10^6$ galaxy sample is extremely weak:

$$< e_r^2 >^{1/2} < \frac{0.1\%}{\alpha \ \ln 10}, \tag{7}$$

and consequently we do not include it in our list of requirements.

B. The spectrum of calibration errors

We now consider how fluctuations in the calibration affect the angular power spectrum measured. For a flux limited survey, a systematic magnitude calibration error across the sky $e_s(\theta)$ will result in angular density fluctuations $\delta(\theta)$ given by

$$\delta(\theta) \simeq \alpha \ \ln 10 \ e_s(\theta) \ , \tag{8}$$

where we have assumed the number count relation $N \sim 10^{\alpha \ m}$ (typically $\alpha \ln 10 \simeq 1$). We can decompose the calibration error field in the sky into spherical harmonics. We would like as a requirement that the resulting spectrum of calibration errors C_l^m:

$$C_l^m = 2\pi \int_{-1}^{1} dcos\theta \, \Delta_m(\theta) \, P_l(cos\theta) \tag{9}$$

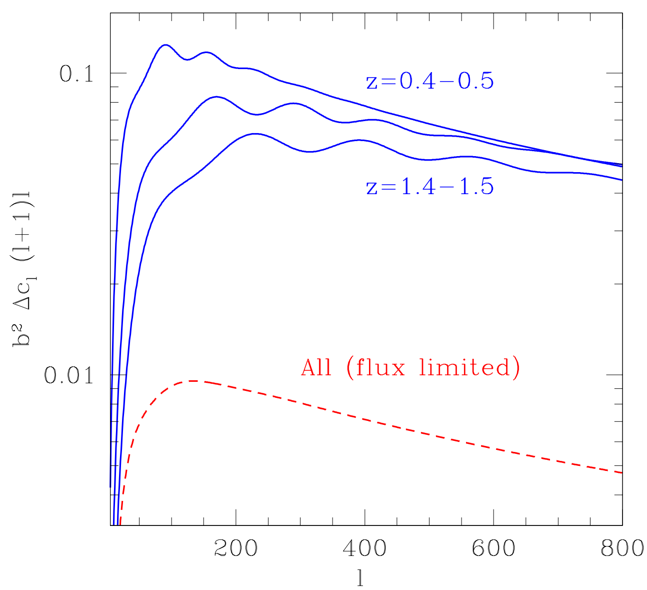

FIG. 3: The expected absolute error (in per cent) in the angular c_l spectrum (scaled by $l(l+1)/2\pi$ to show the contribution of each mode to the total rms variance) for three DES photo-z slices (thick blue continuous lines): $z = 0.4 - 0.5$ (top), $z = 0.9 - 1.0$ (middle), $z = 1.4 - 1.5$ (bottom) and for a flux limited sample (red dashed line) including all galaxies to the depth of DES (mean $z = 0.7$).

to produce errors in the angular power spectrum C_l which are smaller than the sampling variance errors in C_l:

$$C_l^m < \frac{\Delta C_l}{\alpha \ \ln 10} \simeq \frac{C_l}{\alpha \ \ln 10 \sqrt{f_{sky}(l + 1/2)}} \tag{10}$$

We will assume to start with that angular clustering in DES will be sampling variance rather than shot-noise variance dominated. We also assume Gaussian statistics, $f_{sky} \simeq 0.1$ and constant $b = 2$.

In Fig.3 we illustrate the above requirements for different DES photo-z slices with $dz = 0.1$ between $z = 0.45$ and $z = 1.45$ (continuous blue line) and also for a flux limited sample with all galaxies to the DES depth (dashed red line), which is expected to have a mean $z \simeq 0.7$. The relative error is fixed for all samples, as it is given by the number of l-modes and the fraction of sky. Thus, the differences in the figure just reflects the different amplitudes in c_l. Note how the amplitude of the spectrum decreases as we increase the redshift and the BAO features move to smaller angular scales (larger l). The amplitude of the power spectrum is an order of magnitude smaller in the flux limited sample because of the stronger dilution of the projected clustering for a wider slice. Also note how the BAO features disappear for the wide sample.

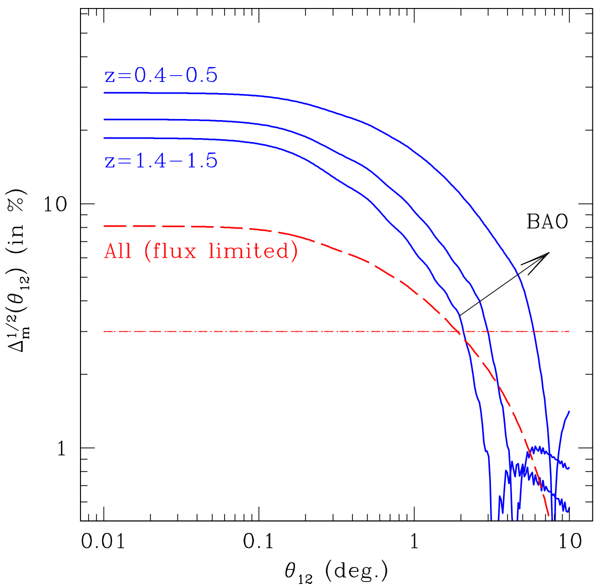

FIG. 4: Required systematic calibration error (rms percentage) in units of $(b/2)/(\alpha \ \ln 10)$ for the same cases show in Fig.3. In these units, at BAO scales (which is a function of z, mark by the arrow) the correlation in calibration error has to be smaller than about 11% for $z \simeq 1.45$ and 9% for $z \simeq 0.45$. For other science it will probably be desirable to target the stronger requirements driven by the flux limited sample, ie $> 2\%$ and $> 10\%$ in correlated errors on scales smaller than 4 and 0.1 degrees respectively, as given by the dashed line.

The corresponding correlation function $\Delta_m(\theta_{12})$:

$$\Delta_m(\theta_{12}) = \sum_l \frac{2l+1}{4\pi} C_l^m \ P_l(cos\theta) \tag{11}$$

for each case is shown in Fig.4. The requirements are stronger for the flux limited sample because the amplitude of the power spectrum is an order of magnitude smaller than in the thin slice case. We show results as percentage errors in the magnitude (in units of $b/2/\alpha/\ln 10$), ie a 10% error corresponds to an error of 0.10 magnitudes.

C. Minimum requirement

For BAO we only need to set up the requirements based on a thin ($dz = 0.1$) DES photo-z slices because the FoM for DE is built on measurements in these photo-z slices. As we will show below, this will in fact help us relaxing a lot the requirements on systematic (correlated) calibration errors with respect to what one needs for the whole (flux limited) sample.

In 3D the BAO scale appears at a physical distance of about 100 Mpc/h. This corresponds to 3.7 degrees for $z = 0.45$ and 0.7 degrees for $z = 1.45$. We do not want any features in the calibration or survey strategy to appear on those scales. Unfortunately the DECam field of view (FoV) is ~ 3 square degrees, which just happens to lie in this window of angular distances (DECam FoV matches the BAO at $z \simeq 1$), so we should be very careful as to how to match and calibrate the different DECam exposures.

The quantitative requirement is shown in Fig.4 were we can see (continuous blue lines) that the error needs to be lowest on the largest angular scales and decreases with the depth of the slice. Fortunately the angular BAO scale (shown by the arrow in the figure) also decreases with depth, which helps getting a weaker requirement. This translates into a correlated magnitude error on BAO angular scale that should be better that 11% for $z = 1.45$ and 9% for $z = 0.45$. At 1.7 degrees, the DECam FoV, the requirement is 10% (this comes form measuring BAO scale at $z \simeq 1$). These requirements degrades as we move to smaller scales, as shown in the Figure. This can be considered as the **Minimum requirement** to accomplish DES science goals on BAO.

Note that here we have assumed that the systematic residual errors are Gaussian. This means that errors are not correlated in harmonic space. This is a natural assumption for errors, but is not the only possibility. In the other extreme, a systematic error could rise as a correlation at a fixed angular scale, which translates into correlated harmonic coefficients. We would like as a requirement that the amplitude of such a systematic error in configuration space should also be smaller than the corresponding sampling variance. Thus, we need the requirements to fulfill both the requirements set by Fig.4 and Fig.3 (eg see §III E below).

D. Desirable requirement

We should also target the constraints from the flux limited sample as we would like the overall angular galaxy correlations in the survey to be sampled variance rather than calibration error dominated. This will allow a good measurement of the shape and amplitude of the angular power spectrum on scales smaller than the BAO scale. This represents a calibration error of about 2% at the largest BAO angular scales (~ 4 degrees) which degrades to about 10% error on scales smaller than 0.1 degrees (ie dashed line in Fig.4) . At DECam FoV scale of $\simeq 1.7$ degrees the calibration error should be better than 5%. These are tighter constraint that the above BAO constraint for the photo-z slices. It can be considered as a **desirable requirement**. For this to become a target requirement it needs to be better justified with particular legacy LSS science cases (neutrino mass, biasing, σ_8, Ω_m, primordial spectrum, galaxy formation, redshift distortions, halo model...).

E. Harmonic space

In harmonic space the requirements for a single mode are shown in Fig.3, where we have plotted the contribution of a single mode to the total variance $< \delta^2 >$, which is $c_l(l+1)l/(2\pi)$. The requirement is about 12% on the BAO scales ($l = 200 - 600$) for $z = 1.4 - 1.5$ and $4 - 5\%$ for the whole survey (flux limited case). But note that these are errors on a single l-mode and the calibration requirement can be more astringent when we combined modes (as in the case for $\Delta_m(\theta_{12})$ in Fig.4).

Note that these errors are in units of $(b/2)/\alpha/\ln 10$, so the requirements will be lower or stronger depending on the value of the bias b and α, which are function of galaxy type, luminosity and redshift. This probably needs a more detailed modeling. The value of $b \simeq 2$ is the average bias that we expect for the main galaxy sample of DES.

IV. STAR/GALAXY SEPARATION

An incorrect star/galaxy separation will change the power spectrum. If stellar contamination, or galaxy misclassification is spatially unclustered, then this only causes a change in the amplitude of the measured power spectrum, and we have to increase the size of the errors to allow for this. Under this assumption, a fractional stellar misclassification of x will cause the measured power to decrease by a factor $(1-x)^2$. To measure the amplitude to 2%, we can therefore allow for a 1% stellar contamination, hence requirement (6) above. If the stellar contamination is clustered, and we cannot model the angular distribution, then this will affect the clustering measurement. We set a constraint on this: requirement (7).