BigBOSS Target Properties and Photometric Selection

Nick Mostek for the BigBOSS Collaboration

July 20, 2009

1 Abstract

BigBOSS is a ground-based Stage-IV dark energy experiment that will measure baryon acoustic oscillations, redshift space distortions, and non-gaussian fluctuations in the large scale structure of the universe. BigBOSS will survey three target samples from $0.2 < z < 3.5$ over 24000 sq. deg. with a multiplexed spectrograph on an existing 4m telescope. The targets are chosen to deliver efficient redshift measurements over this large volume of sky at target densities sufficient to sample the BAO signal with low shot noise. This document details the advantages of the BigBOSS targets, explains the current spectroscopic observing strategy, and explores the photometric selection of BigBOSS targets from current and future photometric surveys. Of the three target samples, the emission line galaxies (ELGs) from $0.7 < z < 2.0$ have the toughest measurement requirements to meet from the ground. The majority of this document will focus mainly on the ability to photometrically select ELGs from existing and planned ground-based resources and measure the [OII] line with BigBOSS spectrographs.

2 BigBOSS Target Properties

The primary goal for the BigBOSS survey is to measure redshifts of galaxies over a large volume of sky to accurately determine the BAO scale and redshift space distortions imprinted in the large scale structure of the universe (Schlegel, 2009). BigBOSS will meet this goal through spectroscopic observations of three different object types over the redshift range $0.2 < z < 3.5$. These objects include luminous red galaxies (LRGs) from $0.2 < z < 1.0$, emission line galaxies (ELGs) from $0.7 < z < 2.0$, and QSOs from $2.0 <$

$z < 3.5$. The combination of these three samples provides the following advantages:

1. **Volume:** The combined sample of objects from $0.2 < z < 3.5$ over 24,000 sq. deg. will measure the BAO scale over an unprecedented volume. Since the accuracy of the distance measurement from the acoustic measurement scales as the volume, BigBOSS will achieve a Figure of Merit (FoM) equivalent to a Stage-IV dark energy experiment (Slozar, 2009) and matching the FoM of the proposed JDEM BAO program.

2. **Systematic Control:** The combined sample of LRGs and ELGs will overlap in the redshift range of $0.7 < z < 1.0$, providing enhanced sampling density during the cosmic time where the acceleration of the cosmic expansion is expected to first begin. Further, LRGs are better suited for measuring BAO since they are more heavily biased to their dark matter halos, whereas the lower biased ELGs are better suited for measuring the early growth of structure and redshift-space distortions. These BigBOSS targets will therefore constrain possible systematic errors through the combined astrophysical sample while capitalizing on the strengths of each sample's properties. The use of multiple mass tracers in a Stage-IV BAO survey is unique to BigBOSS and is unmatched by JDEM. In addition to the inherent cross-checks of different target samples, the design of the BigBOSS spectrographs will eliminate catastrophic redshift contamination by measuring the [OII] emission line doublet as a redshift indicator instead of the single Hα line. The measurement of the [OII] doublet provides critical advantages as it both serves as a unique emission line identifier and can be measured from the ground at wavelengths shortward of 11300Åfor $z \leq 2$.

3. **Enabling Other Science:** In addition to the primary dark energy measurement, the QSO sample of BigBOSS will provide a measurement of early non-gaussianity in the Lyα forest. Since this measurement from $2.0 < z < 3.5$ requires the use of a large primary, high resolution optical spectrograph, and wide field of view, it is best suited for existing ground based telescopes.

The BigBOSS target samples do not require the use of space-based observations for either the pre-selection photometry or the spectroscopic measurement. The LRG and QSO samples build off of existing targeting and measurement techniques in the current BOSS survey while the ELG sample builds off of the successful DEEP2 survey.

2.1 Emission Line Galaxy (ELG) Redshift Coverage

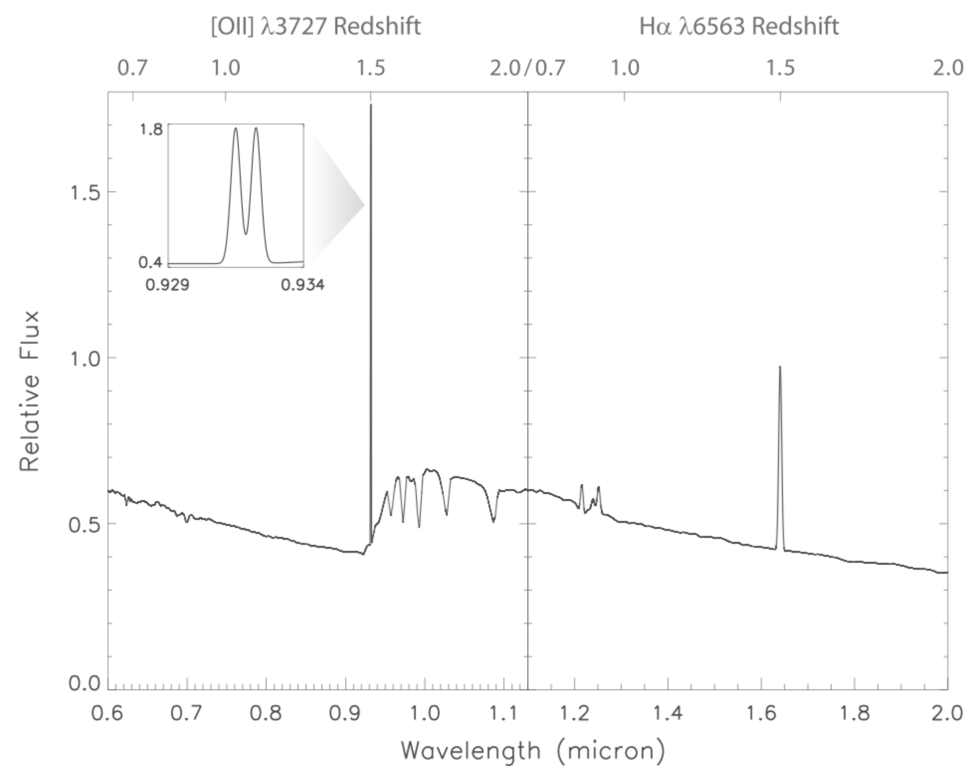

Figure 1: An example z=1.5 emission line galaxy spectrum with the wavelength coverage of BigBOSS (left) and JDEM (right). BigBOSS will measure the [OII]λ3727 doublet and JDEM will measure the Hα λ6563. Both surveys propose to measure galaxies in the redshift range $0.7 < z < 2.0$. The resolution of the spectra in both panels is set to match each experiment (R$\sim$ 5000 for BigBOSS, R$\sim$ 200 for JDEM). The inset figure at left shows the [OII] doublet with 50km/s line velocity. All fluxes are relative to the peak Hα line flux.

The primary sample of BigBOSS will consist of star-forming galaxies from $0.7 < z < 2.0$. These galaxies have strong emission lines coinciding with the hydrogen Balmer series and ionized oxygen which make excellent redshift indicators when the lines are properly identified. In general, a redshift survey targeting these ELGs must choose to target one line or set of lines to optimize the instrument design and survey efficiency. The proposed JDEM BAO program has chosen to survey the Hα λ6563 emission line and the BigBOSS survey has chosen the [OII]λ3727 doublet. Figure 1 shows the wavelength and redshift coverage for these two choices, including effects of resolution for the R$\sim$200 JDEM grism images and the BigBOSS R 5000 spectrographs. To reach z=2.0, the Hα line must be observed at NIR wavelengths while the [OII] doublet can be measured at shorter wavelengths than 11300Å.

2.2 ELG Mass Bias

The effectiveness of ELGs as a tracer of the BAO signal depends on the mass bias relative to their dark matter halos. Using a sample of emission line galaxies from the Subaru XMM-Newton Deep Field, (Sumiyoshi, 2008, hereafter S08) showed that the brightest [OII] ELGs have a linear mass bias that increases with redshift between $z = 1 - 2$. From Fig. 16 of S08 , the ELG bias appears to correspond to a constant clustering amplitude with a z=0 bias of $b(0) \sim 0.8$. Compared to the LRG clustering amplitude of $b(0) = 1.7$ (Padmanabhan, 2006), the ELGs are not as efficient at tracing the BAO signal as LRGs. However, the ELGs are much more numerous from $1 < z < 2$ due to a lower number of galaxy mergers at higher redshifts, therefore making them better BAO targets over this redshift range. In principle, one would sample the ELGs at a high density to recover from their deficient mass bias. In practice, the ELG sample is constrained by the total number of instrumentable spectrograph fibers. The 5000 fiber BigBOSS instrument has a source density of $dn/(dz\ deg^2)$=2000, corresponding to a constant comoving number density of $3.4 \times 10^{-4}(h/Mpc)^3$.

2.3 The [OII] luminosity function

To estimate the [OII] line flux and derive a MDLF for BigBOSS, we looked at two recent surveys of the [OII] line fluxes with large datasets and high completeness on the bright end ($L_{[OII]} > 42$) of the luminosity function. The first source used flux calibrated [OII] line emission measurements from $\sim 14,000$ DEEP2 galaxies out to redshift z 1.5 (Zhu et al., 2008). They find the [OII] luminosity function fit follows a power law,

$$\Phi(\log L)d(\log L) = 10^{(\alpha+1)(\log L - 42.5)+\beta} d(\log L), \quad (1)$$

where L is $L_{[OII]}$ in erg s^{-1}, and α and β are dimensionless parameters that equal ∼-3.0 and ∼3.6, respectively, over our redshift range of interest. For $z > 1.5$, the line fluxes have been projected using the same α and β values derived from the highest DEEP2 redshifts, which should conservatively estimate an evolving [OII] luminosity function. To achieve a projected sky density of $dn/(dz\ deg^2)$=2000 in a ΛCDM universe, BigBOSS requires a galaxy space density of $10^{-3.76}$ dex^{-1} Mpc^{-3} at z=2 and therefore must measure a minimum single-line [OII] luminosity of $\sim 10^{42.6}$ ergs s^{-1}.

The second source of data comes from the zCOSMOS fit galaxy template catalog and calibrated [OII] line emission from VVDS spectra (Ilbert et al., 2008). The zCOSMOS catalog contains $> 500,000$ galaxies with $i < 26$ over a 1.3 deg^2 field of view and photometric redshifts with $\Delta z < 0.01$. Ilbert et al. applied [OII] line emission to the best-fit galaxy template spectral energy distributions (SEDs) using a M(UV)-[OII] calibration (Kennicutt, 1998) empirically derived from VVDS measurements.

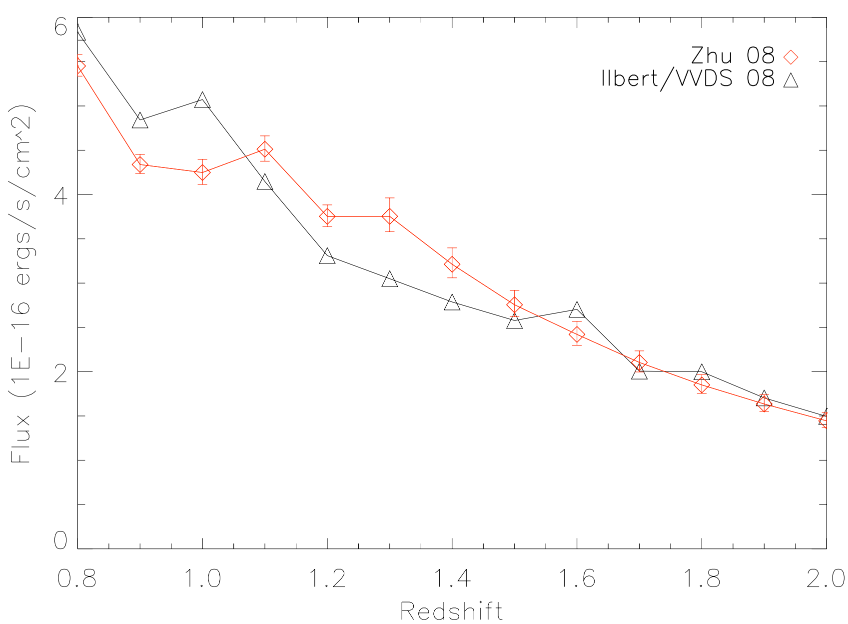

Figure 2: Comparison of the MDLF required to achieve the BigBOSS goal source density (Zhu et al, 2008, Ilbert et al, 2008). The plotted line fluxes are for the unresolved [OII] doublet line flux.

Figure 2 shows a comparison of the MLDF derived from the Zhu luminosity function and the Ilbert catalog with M(UV)-[OII] line flux calibration. Both data sources seem to be in good agreement over the redshift range $1 < z < 2$, keeping in mind that the [OII] line fluxes beyond $z > 1.5$ have been extrapolated from the available low redshift data. At $z = 2$, BigBOSS will be required to measure a MDLF$\sim 1 \times 10^{-16}$ ergs s^{-1} cm^2 for an unresolved [OII] emission line, or 5×10^{-17} cgs for the resolved doublet. However, it is often the case that such luminosity functions can vary from different data sources by more than a factor of 2 since the data over this redshift range is limited in both depth and area. Therefore, a conservative MDLF estimate for the split [OII] doublet is 5×10^{-17} cgs from $1.1 < z < 1.5$ and 2.5×10^{-17} cgs from $1.5 < z < 2.0$

3 Observing Strategy

The observing strategy for BigBOSS is driven by two key factors: sky coverage and sampling density per exposure. To survey 24,000 square degrees in 10 years, BigBOSS must survey 2,400 deg^2/year. Assuming 180 nights a year with 50% useable nights and an average of 8 hours of observation a night, the survey will need to cover a minimum of 2.4 deg^2/hour. For a 2.5 deg diameter focal plane (4.9 deg^2), this leaves 1.5 hours of exposure time per field pointing, including any overhead required for repositioning fibers. For BOSS, manual fiber positioning was a 20 minute penalty for each new field. BigBOSS will reduce this overhead to less than two minutes using electronic fiber positioning, comparable to the read out time of the 10 spectrographs

To achieve the target sampling density of $dn/(dz\ deg^2)$=2000 for both ELGs and LRGs, BigBOSS must observe 2950 galaxies/deg^2 (2600 ELGs, 350 LRGs). BigBOSS must also include 80 QSO objects/deg^2 and designate roughly 40 spectra/deg^2 to sky observations and standard stars. Further, we assume an average photometric targeting efficiency of 80%, requiring that BigBOSS must measure a total of $\sim$ 3840 spectra/deg^2 to meet the target density requirements.

The BigBOSS spectrograph has 5000 instrumented fibers over 4.9 deg^2, giving 1020 available fibers/deg^2 for spectroscopic measurement. To meet the target density and sky coverage requirements, the BigBOSS survey must have an <u>average</u> exposure time per target of 23.9 minutes. BigBOSS will achieve this average exposure time with the following breakdown of target exposure times:

Table 1: The exposure time allocation for each BigBOSS target sample.

	ELG ($z < 1.5$)	ELG ($z > 1.5$)	LRG	QSO	Sky + Cal
no./deg^2	1730	870	350	80	40
exp. time (min)	15	30	30	90	90

- QSO, sky, and calibration observations will last for the entire 1.5 hour duration of the field pointing, contributing 4% (3.5 minutes) to the average fiber exposure time per field pointing.
- ELGs below $z < 1.5$ will meet the MDLF in 15 minute exposures and repositioned 6 times during the field pointing, contributing 57% (8.6 minutes) to the average fiber exposure time per field pointing.
- ELGs at $z > 1.5$ and LRG targets will have 30 minute exposures and reposition 3 times during the field pointing, contributing 40% (11.8 minutes) to the average fiber exposure time per field pointing.

Table 1 summarizes the required final target sample and exposure time allocation. Assuming a conservative 65% detection rate of galaxy redshifts (including losses due to marginal seeing conditions as measured by SDSS), the final BigBOSS spectroscopic sample will consist of approximately 50 million galaxy redshifts and 1 million QSO Lyα forest spectra.

This observing strategy represents a conservative approach. The strategy has not yet been optimized, but it meets the target science goals for BigBOSS. Many factors still under consideration may contribute to reducing the estimated number of nights required for the BigBOSS survey. For example: Kitt Peak weather statistics averaged over several decades show that the site delivers 65% useable dark nights (rather than the 50% assumed above); initial technical studies suggest that the field size and unobscured telescope aperture may be increased beyond the baseline design assumed here; dynamic allocation of fibers coupled with rapid redshift measurement algorithms can improve on-the-fly targeting efficiency. Optimization trade studies are underway to mazimize the science impact while minimizing the total required resources for BigBOSS.

3.1 Spectrograph Sensitivity

The notional BigBOSS design draws heavily on the spectrograph design of the SDSS-III / BOSS spectrographs (Smee et. al., 2006). To first order, one can scale the flux sensitivities in SDSS-III with aperture area, fiber size, and resolution to the design of BigBOSS. Figure 3 shows the extracted line flux sensitivity for a S/N=8 in a standard BigBOSS 30 minute exposure given the current spectrograph design. The plotted wavelengths correspond to the spectrograph arms that will obtain Lyα absorbed QSOs and LRGs to $z < 0.5$. Note that the sensitivity is degraded shortward of 4000Å due to falling efficiencies in the detector and gratings, absorption in the fibers, and atmospheric effects.

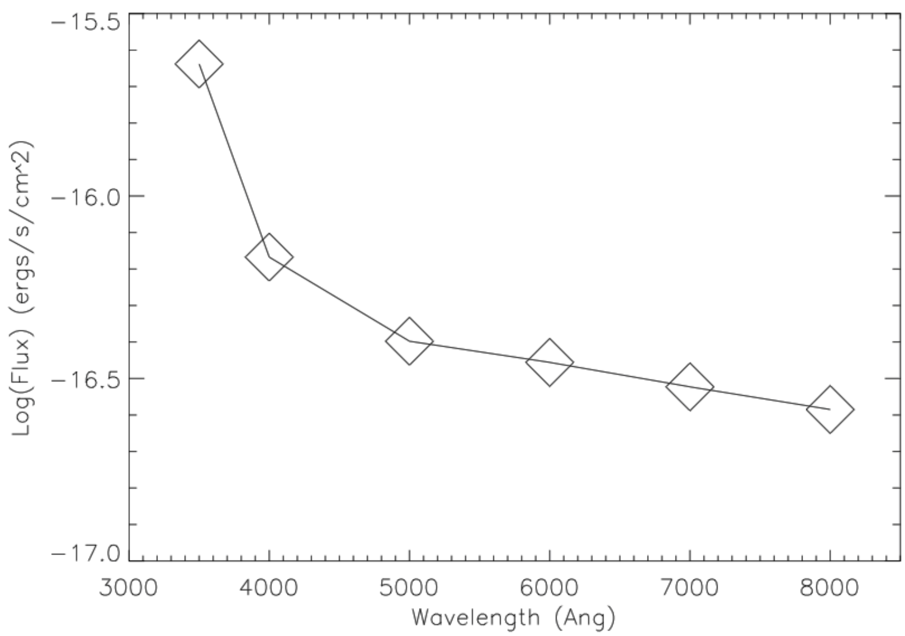

Figure 3: The line flux sensitivity for extracted spectral lines in the BigBOSS Blue and Visible spectrograph arms.

Observations at longer wavelengths than 8000Å will encounter bright sky lines that will degrade the S/N for specific wavelengths. The sky lines will have the largest impact on the detection, extraction, and redshift measurement of the [OII] emission line doublet from $1 < z < 2$. BigBOSS will mitigate this impact by designing a spectrograph with high resolution (R$\sim$5000) and throughput, characterized monochromatic spots, and minimal scattered light. Figure 4 shows the optimal extraction of the single [OII]λ3726 emission line over the redshift range covered by the Red spectrograph arm. There will be small redshift ranges ($\delta z < 0.001$) where the single-line MDLF cannot be achieved due to background sky noise contributed from bright OH sky lines. The split [OII] doublet allows us to identify and measure the additional doublet line [OII]λ3729, recovering 95% of the redshifts affected by sky lines.

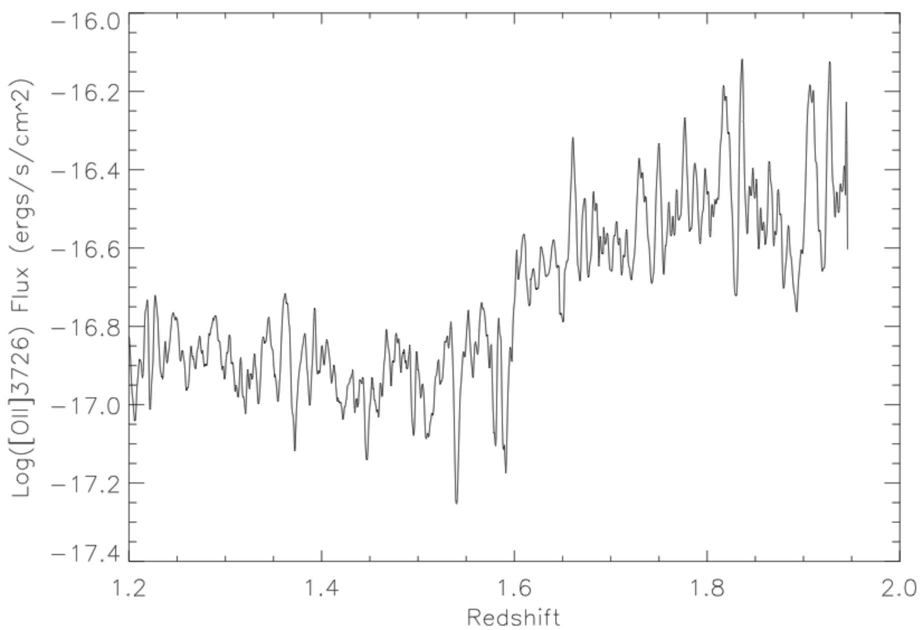

Figure 4: The optimal extracted line flux sensitivity for S/N=8 [OII]λ3726 at 50km/s line width in the BigBOSS Red spectrograph arm (8000-11000Å). The sensitivity has been smoothed by 10Åto show the larger variations due to night sky lines. The systematic decrease in sensitivity at z=1.6 corresponds to a higher noise background from the NIR detectors. Note that BigBOSS will operate with a sensitivity limit of log(flux)=-16.6, while the expected JDEM S/N=8 line sensitivity will be log(flux)=-15.3.

4 Photometric Target Selection

4.1 LRG Target Selection

The photometric selection of LRGs in the redshift range $0.2 < z < 0.7$ for the BOSS survey uses SDSS *gri* photometry (Padmanabhan, 2005a). The selection colors are based on measuring the 4000Åbreak as it is redshifted through the *gri* bands. The BigBOSS LRG target selection will extend this color selection to the z band where the break is redshifted out to z=1. The photometry measured by Pan-STARRS-1 (Northern Hemisphere) and LSST (Southern Hemisphere) will have sufficient depth and sky coverage in the *griz* bands to serve as the LRG target selection catalog for BigBOSS.

4.2 QSO Target Selection

Like the LRG target selection, the QSO target selection for BigBOSS will build off of the current target selection in BOSS where SDSS colors are used to identify QSOs between $2.0 < z < 3.5$. The selection has been shown to be 40% efficient but is limited by the u band depth and lack of variability data. The BigBOSS QSO selection will be $> 90\%$ complete and $> 85\%$ efficient using variability data from the next generation of synoptic surveys (Vanden Berk et al, 2004).

4.3 ELG Target Selection

In order to perform an efficient large-area survey with a minimal number of instrumented spectroscopic fibers, the BigBOSS spectrograph will need to effectively select ELG targets from available photometric data. The SEDs for late-type galaxies with strong star-formation histories have stars that are both young and evolved, leading to a composite galaxy spectrum that is relatively flat in the optical spectrum. Further, the large redshift range of $0.7 < z < 2$ and a wide variety of possible dust extinction values can lead to degeneracies in the SEDs and insufficient separation between passive and active star forming galaxies in color-color space. However, SEDs of late-type galaxies can be identified with a signature Hydrogen Balmer absorption due to the composite spectra of young B, A, and F stars in the galaxy SED (Adelberger, 2004). This absorption occurs at a rest-frame wavelength of ~ 3700Å and can be separated from older late-type galaxies that have CaII H&K breaks near 4000Å. The color discrimination from the Balmer absorption is accessed through *gri* colors to redshift $z = 1$ and can be extended to $z < 1.5$ with the addition of z-band measurements. These optical color measurements will be achieved with the upcoming Pan-STARRS survey over 30k sq. degrees.

For $z > 1.5$, a selection could continue to be based on the Balmer break as it is redshifted into NIR bands. However, for the purposes of requiring data that will most likely be available during the next decade, we restrict the photometric targeting sample to optical *ugriz* bands which should be the measured at the BigBOSS required depths and sky coverage. BigBOSS will select ELGs beyond $z > 1.5$ based on the Lyα absorption feature of these high-redshift galaxies using *ugr* colors. It should be possible to extend photometry in u-band with a wide array of existing telescopes and CCD technology. Color selection based on the Lyman-break can extend out to $z < 3$, but we will restrict our color space to $z < 2$, trading exposure time on faint objects for a larger survey area.

Using the best-fit galaxy SED templates, [OII] line fluxes, and photo-zs of the Ilbert zCOSMOS catalog, we have generated synthetic magnitudes using the *LePhare* photo-z software (Ilbert, 2008, priv. com.) and a set of *ugriz* filter bands. Figure 5 shows the *ugr* color space for all zCOSMOS galaxies with $r < 24$. In this case, the synthetic magnitudes are assigned a flat 0.02 magnitude error to demonstrate the ideal color selection box for bright [OII] emitters.

Strong [OII] line emitters can also be selected using the Lyman-break feature and optical *ugr*-band measurements. Figure 6 shows the *ugr* color plane with gray contours corresponding to all galaxies with $r < 24.0$ and red cross data points corresponding to galaxies with split $\log(F_{[OII]}) > -16.6$ between $1.5 \leq z \leq 2.0$. The limiting magnitude of $r < 24$ is fainter than the *grz* selection to achieve the goal projected sky source density out to $z = 2$. The MDLF has also been reduced by a factor of 2 following the discussion of Section 2.3.

4.4 Selection Efficiencies

For both color selections, the selection efficiency of ELG targets within a $\delta z \sim 0.5$ window will depend on the photometric error delivered by large area surveys at our magnitude limits. At present, we consider the sources in Table 2 for photometry in the Northern Hemisphere: the Palomar Transient Factory (PTF), PanSTARRS (PS), and an example u-band survey that could be carried out on CFHT. The photometric signal to noise ratio for various telescope parameters is modeled with

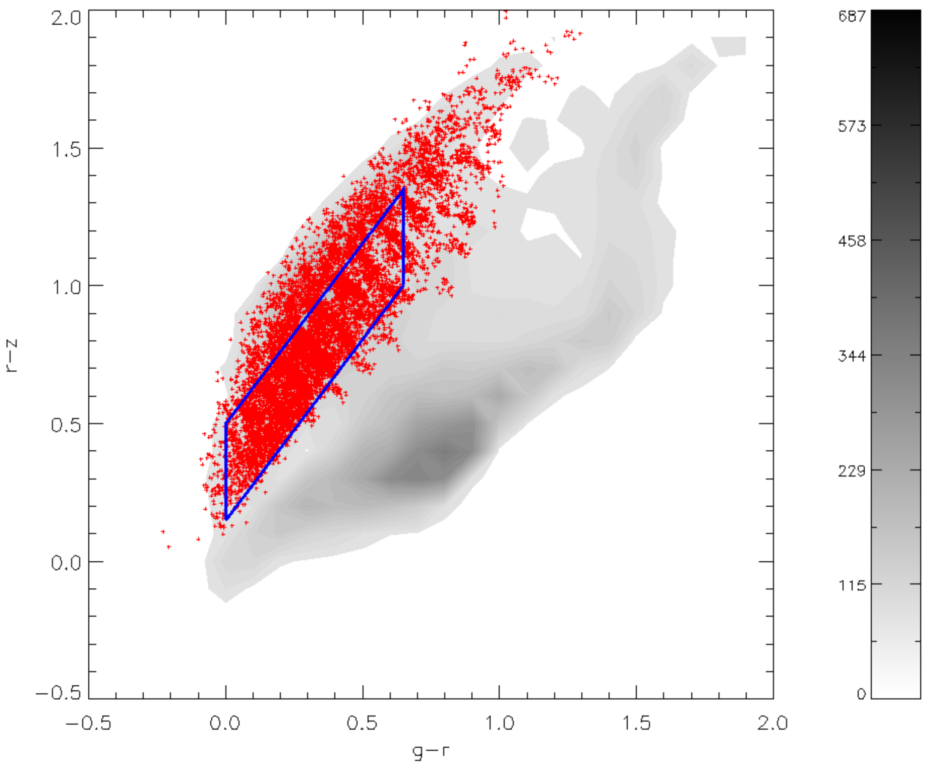

Figure 5: Colors of the zCOSMOS fit galaxy template SEDs in the grz color plane. The gray contours correspond to all galaxies with $r < 23.5$ and the red crosses correspond to the BigBOSS galaxy targets from $1.1 \leq z \leq 1.5$ and split line flux $F_{[OII]} > 5 \times 10^{-17}$ cgs. The blue box shows an example color selection criterion that could be used for these objects.

$$S/N = 10^{(-0.4m+0.2\mu+0.2m_1)} \times \left(\frac{t}{\pi\omega^2}\right)^{1/2} \tag{2}$$

where m is the source magnitude, μ is the sky brightness in magnitudes per square arcsecond, m_1 is the band magnitude that produces $1e^-$/sec on the detector, t is the total exposure time, and ω is the FWHM of the source in arcseconds. We also add in a 0.015 mag error floor to account for systematic calibration errors entering into the photometry. Figure 7 shows the calculated magnitude errors for each of the surveys considered in this document.

Table 2: The bandpass sensitivity and sky brightness for possible photometric selection sources in the Northern Hemisphere.

Survey	band	m_1	μ (mag/arcsec^2)	t (s)	ω (arcsec)
CFHT	u*	25.77	21.3	400	1.2
PTF	g	24.02	22.11	10800	1.8
PTF	r	25.27	21.06	10800	1.8
PS	i	25.00	20.15	1200	1.0
PS	z	24.63	19.26	1200	1.0

$$S/N = 1.00017 \times 10^{-2.0(2m-\mu-m_1)} \times \left(\frac{t}{\pi\omega^2}\right)^{1/2} \qquad (3)$$

where m is the source magnitude, μ is the sky brightness in magnitudes per square arcsecond, m_1 is the telescope-dependent sensitivity that produces $1e^-$/sec, t is the total exposure time, and ω is the FWHM of the source in arcseconds. The $griz$ bands each have independent values of m_1 and μ shown in Table **??**. Figure **??** shows the magnitude error for each of the filters at the PS1 final 3 year exposure time. For these estimates, I have chosen ω=1" since BigBOSS will be interested in extended objects at high redshift.

Using the photometric error functions shown in Figure 7 for the $ugriz$ filter bands, we generate normally distributed errors for the zCOSMOS synthetic magnitudes and reproduce the color selection shown in Figure **??**. The grz color plane for the synthetic magnitudes and errors (Figure 8) clearly shows the distribution of strong [OII] galaxies have spread out in color space, particularly where z and u bands have the highest error. Expanding the color selection box in an attempt to recover [OII] quickly degrades the selection efficiency as interlopers from outside the desired redshift windows enter the sample.

Figure 9 shows the color selected redshift distributions for both of these color cuts. The ugr and grz color selections are $> 85\%$ efficient at selecting objects with bright [OII] emission above the BigBOSS MDLF. These cuts also deliver the desired BAO target number density of 2000 $dn/(dzdeg^2)$ where the redshift distribution is essentially flat. Interestingly, the ugr color selection alone provides a well sculpted redshift distribution over the entire $0.7 < z < 2$ range as lower redshift interlopers are scattered into the selection box. However, we must note that this specific selection efficiency for [OII] emission beyond $z > 1.5$ is not yet confirmed with direct measurements should be further tested. We are in the process of collecting available *ugr* data to test and optimize this color selection.

5 References

Adelberger, K. L., et al., 2004, ApJ, 607,226.
Ilbert, O., et al., 2008, [arxiv:0809.2101v1].
Kennicutt, R.C. 1998, ARA&A, 36, 189
Padmanabhan, N., et al., 2005a, MNRAS, 359, 237
Padmanabhan, N., 2006, [arxiv:0605302v2]
Schlegel, D. J., et al., 2009, [0904.0468v3]
Slozar, A., 2009, PASAG submitted document
Smee, Barkhouser, & Glazebrook, 2006, SPIE 6269
Sumiyoshi, M., et al., 2009, [arxiv:0902.2064]
Vanden Berk, D. E., et al, 2004, ApJ, 601, 692
Zhu, G., et al., 2008, [arxiv:0811.3035].

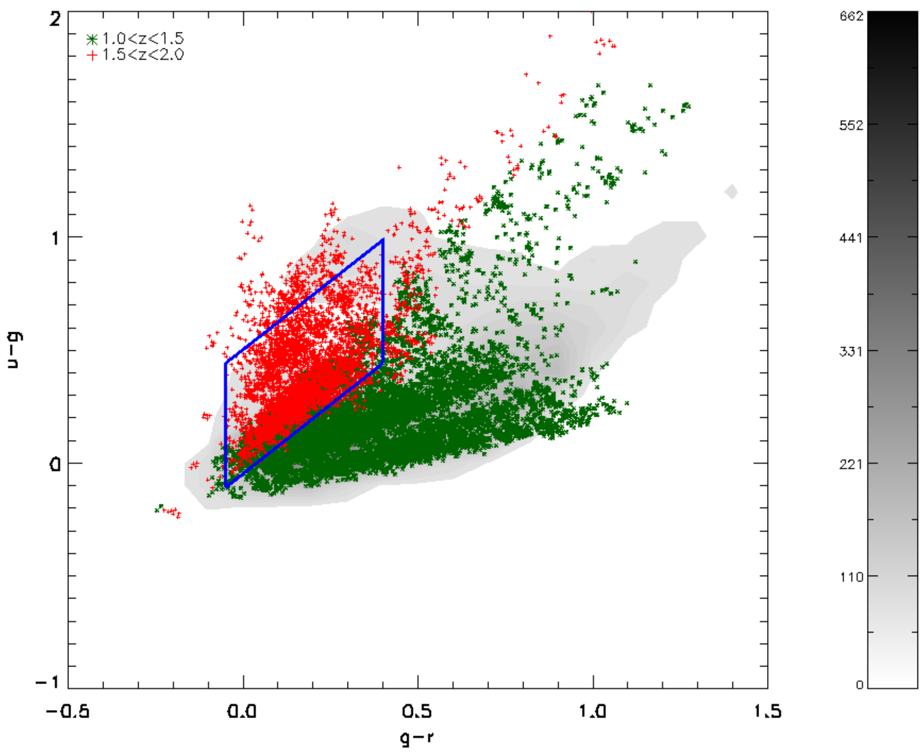

Figure 6: Colors of the zCOSMOS fit galaxy template SEDs in the ugr color plane. The gray contours correspond to all galaxies with $r < 24.0$, the red crosses correspond to the BigBOSS galaxy targets from $1.5 \leq z \leq 2.0$ and split line flux $F_{[OII]} > 2.5 \times 10^{-17}$ cgs, and the green stars have the same flux cut for $1.0 \leq z \leq 1.5$. The blue box shows an example color selection criterion that could be used for these objects.

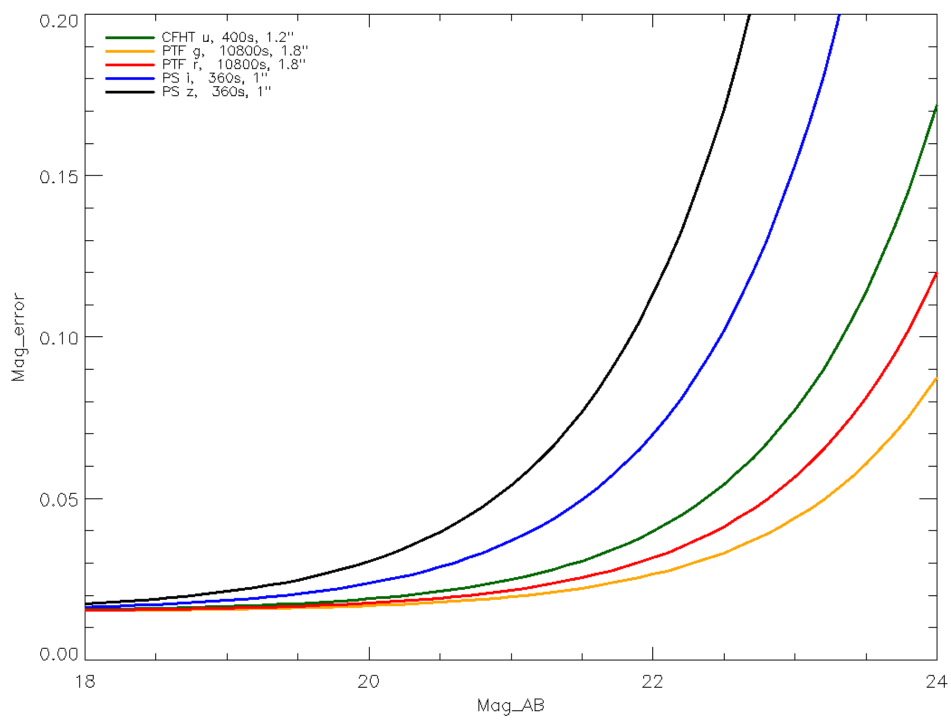

Figure 7: Assumed magnitude errors for the Palomar Transient Factory, PanSTARRS, and an example CFHT u-band survey. All magnitude errors have an assumed error floor value of 0.015 mag.

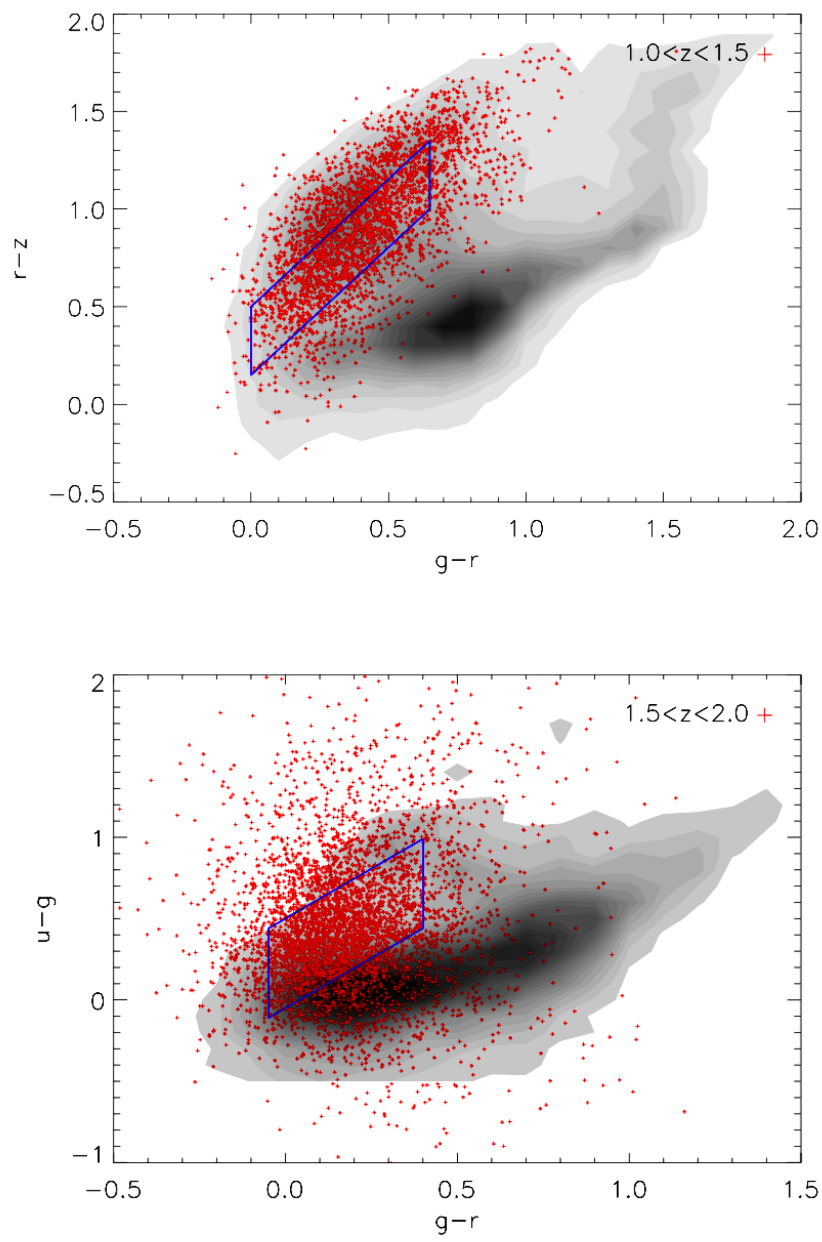

Figure 8: The grz and ugr color space for synthetic magnitudes and associated photometric errors from PTF, PanSTARRS, and CFHT surveys. The selection boxes are reproduced from ideal cuts made in Figure 5 and Figure 6.

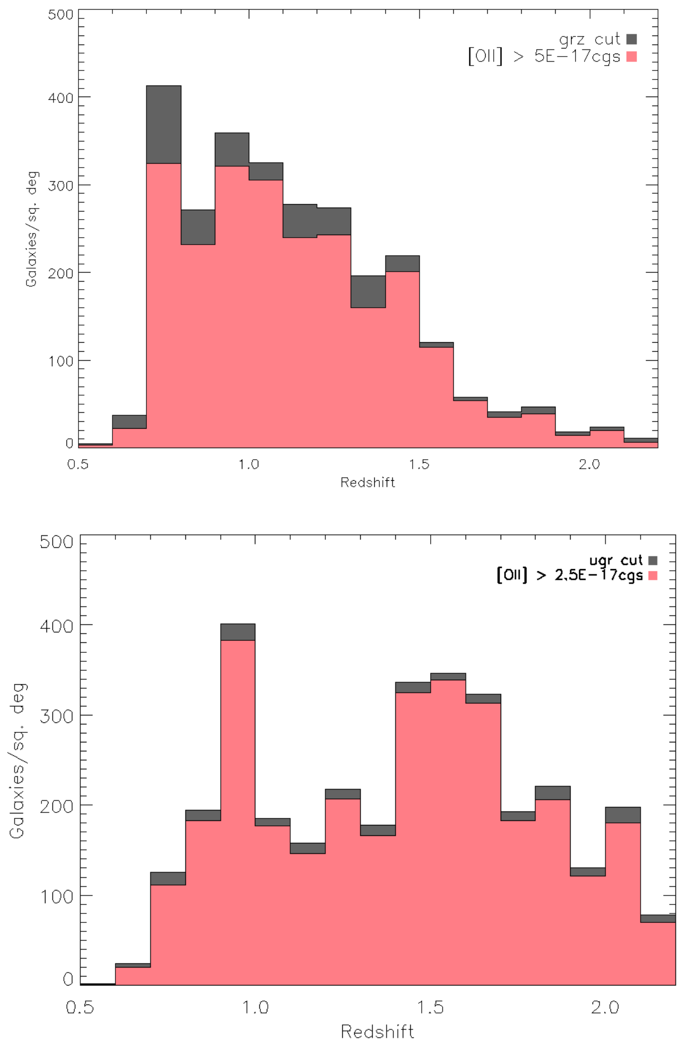

Figure 9: Histograms of the grz and ugr color selected galaxies (gray) and the zCOSMOS galaxies with $\log(F_{[OII]}) > -16.3$ (pink). The color cuts are $> 85\%$ efficient at selecting bright [OII] emitters and also deliver the target number density of 2000 $dn/(dz\ deg^2)$. Overlapping selections between $1 < z < 1.5$ will provide additional selection cross-checks.