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Authors
Myers, AD
Palanque-Delabrouille, N
Prakash, A
et al.

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THE SDSS-IV EXTENDED BARYON OSCILLATION SPECTROSCOPIC SURVEY: QUASAR TARGET SELECTION

Adam D. Myers\textsuperscript{1,2}, Nathalie Palanque-Delabrouille\textsuperscript{3}, Abhishek Prakash\textsuperscript{4}, Isabelle Paris\textsuperscript{5}, Christophe Yéche\textsuperscript{3}, Kyle S. Dawson\textsuperscript{6}, Jo Bovy\textsuperscript{7}, Dustin Lang\textsuperscript{8,9}, David J. Schlegel\textsuperscript{10,11}, Jeffrey A. Newman\textsuperscript{11,16}, Jean-Paul Kneib\textsuperscript{12,13}, Pierre Laurent\textsuperscript{14}, Will J. Percival\textsuperscript{14,15}, Ashley J. Ross\textsuperscript{14,15}, Hee-Jong Seo\textsuperscript{15}, Jeremy L. Tinker\textsuperscript{9}, Ian D. McGreer\textsuperscript{10,22}, Eric Armengaud\textsuperscript{16}, Joel Brownstein\textsuperscript{17}, Ethesne Burtin\textsuperscript{18}, Johan Comparat\textsuperscript{19}, Masha Kaviraj\textsuperscript{20,21,22}, Shrinivas R. Kulkarni\textsuperscript{23}, Russ Laher\textsuperscript{24}, David Levitan\textsuperscript{25}, Cameron K. McBride\textsuperscript{26}, Ian D. McGreer\textsuperscript{12,22,27}, Peter Nugent\textsuperscript{10,28}, Eran Ofek\textsuperscript{29}, Graziano Rossa\textsuperscript{30}, John Ruan\textsuperscript{31}, Donald P. Schneider\textsuperscript{32,33}, Branimir Sesar\textsuperscript{34}, Alina Streblyanska\textsuperscript{35,36}, Jason Surace\textsuperscript{24}

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ABSTRACT

As part of the Sloan Digital Sky Survey IV the extended Baryon Oscillation Spectroscopic Survey (eBOSS) will improve measurements of the cosmological distance scale by applying the Baryon Acoustic Oscillation (BAO) method to quasar samples. eBOSS will adopt two approaches to target quasars over 7500 deg\textsuperscript{2}. First, a “CORE” quasar sample will combine optical selection in ugriz using a likelihood-based routine called XDQSOz with a mid-IR-optical color-cut. eBOSS CORE selection (to $g < 22$ or $r < 22$) should return $~70$ deg\textsuperscript{-2} quasars at redshifts $0.9 < z < 2.2$ and $~7$ deg\textsuperscript{-2} $z > 2.1$ quasars. Second, a selection based on variability in multi-epoch imaging from the Palomar Transient Factory should recover an additional $~3-4$ deg\textsuperscript{-2} $z > 2.1$ quasars to $g < 22.5$. A linear model of how imaging systematics affect target density recovers the angular distribution of eBOSS CORE quasars over 96.7\% (76.7\%) of the SDSS North (South) Galactic Cap area. The eBOSS CORE quasar sample should thus be sufficiently dense and homogeneous over 0.9 < $z < 2.2$ to yield the first few-percent-level BAO constraint near $\bar{z} \sim 1.5$. eBOSS quasars at $z > 2.1$ will be used to improve BAO measurements in the Lyman-$\alpha$ Forest. Beyond its key cosmological goals, eBOSS should be the next-generation quasar survey, comprising > 500,000 new quasars and > 500,000 uniformly selected spectroscopically confirmed 0.9 < $z < 2.2$ quasars. At the conclusion of eBOSS, the SDSS will have provided unique spectra of over 500,000 quasars.

Subject headings: catalogs — cosmology: observations — galaxies: distances and redshifts — galaxies: photometry — methods: data analysis — quasars: general
1. INTRODUCTION

Over 50 years have elapsed since the discoveries that quasars are bright, blue, extragalactic sources in optical imaging (Schmidt 1963) and that the vast majority of unresolved, extragalactic objects that are bluer than the stellar main sequence are quasars (Sandage 1965). Since this time, many imaging surveys used a UV-excess (UVX) criterion, as manifested in simple optical color cuts, to provide a mechanism for targeting quasars (e.g. Sandage & Lytten 1969; Braccesi et al. 1970; Formigoni et al. 1980; Green et al. 1986; Boyle et al. 1990). The UVX approach, which mainly targets quasars at redshifts around 0.5 < z < 2.5, precipitated increasingly extensive spectroscopically confirmed quasar samples as the capabilities of imaging surveys improved, such as the Large Bright Quasar Survey (Hewett et al. 1995), the 2dF QSO Redshift Survey (Croton et al. 2003), and the 2df-SDSS LRG and QSO Survey (Croton et al. 2009).

Modifications of the UVX approach to target all of color space beyond the stellar locus, rather than just the blue side (e.g. Warren et al. 1987; Kennefick et al. 1995; Newberg & Yanny 1997), extended the selection of large numbers of quasars to z > 2.5. The Sloan Digital Sky Survey (SDSS; York et al. 2000) applied this methodology to imaging taken using a new ugriz filter system (Fukugita et al. 1996). SDSS eventually spectroscopically confirmed an unprecedentedly large sample of over one-hundred-thousand quasars (Richards et al. 2002; Schneider et al. 2010) as part of the SDSS-I and II surveys.

In addition to optical color space, SDSS-I and II selected about 10% of their quasar sample via radio matches to the FIRST survey (Becker et al. 1995; Helfand et al. 2015), or X-ray matches to the ROSAT All Sky Survey (Voges et al. 1999). The proliferation of such large, multi-wavelength surveys, as well as multi-epoch surveys, has made quasar classification approaches that do not rely on optical colors (but still may use optical imaging to constrain morphology or brightness) increasingly attractive. Such approaches include: the use of the radio (e.g. White et al. 2000; McGregor et al. 2009), near-infrared (e.g. Banerji et al. 2012), or both (e.g. Gilfanov et al. 2012); the lack of an observed proper motion (e.g. Krong & Cimino 1981), the use of the mid-infrared (e.g. Lacy et al. 2004; Stern et al. 2005; Richards et al. 2009b; Stern et al. 2012), X-rays (e.g. Trinchas et al. 2012), or both (e.g. Lacy et al. 2007; Hickox et al. 2007; 2009); the use of slitless spectroscopy (e.g. Osmer 1982; Schmidt et al. 1986) and the use of variability (e.g. Usher 1978; Rengstorf et al. 2004a; Schmidt et al. 2010; Butler & Bloom 2011; MacLeod et al. 2011; Palanque-Delabrouille et al. 2011).

Even after the first iterations of the SDSS, the selection of quasars at z ≥ 2.5 remained relatively incomplete. This problem arose partially because SDSS-I and II targeted quasars a magnitude or more brighter than the limits of SDSS imaging, thus sampling only the high luminosity regime at these redshifts, and partially because the stellar and quasar loci intersect in ugriz color space around the “quasar redshift desert” near z ∼ 2.7 (Fan 1999). In order to target quasars at z > 2.1 for cosmological studies of the Lyman-a Forest, the SDSS-III (Eisenstein et al. 2011) Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013) attempted to circumvent these problems of quasar selection near z ∼ 3 by applying sophisticated, multi-wavelength, multi-epoch star-quasar separation techniques to the full depth of SDSS imaging. BOSS spectroscopically identified ∼ 170,000 new quasars of redshift 2.1 ≤ z < 3.5 to a depth of g < 22 (I. Párás et al. 2016, in preparation; henceforth DR12Q), a sample about ten times larger than for the same redshift range in SDSS-I and II. BOSS may only be ∼ 60% complete (e.g. Ross et al. 2013), raising the possibility that there are additional g < 22 quasars to be discovered in this redshift regime.

In combination, SDSS-I/II/III targeted quasars at 2.1 ≤ z ≤ 4 to a magnitude limit of g < 22 or r < 21.85 (Ross et al. 2012) and quasars at all redshifts to i < 19.17 (Richards et al. 2002). There remains an obvious, highly populated discovery space using SDSS imaging data—namely, z < 2.1 quasars fainter than i = 19.1. In addition, since the advent of BOSS, new and extensive multi-wavelength and multi-epoch imaging has become available, allowing z > 2.1 quasars to be targeted that may have been missed by BOSS. In particular, mid-IR colors provide a powerful mechanism for separating quasars and stars and Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) data therefore provide additional information for targeting quasars that otherwise resemble stars in optical color space (e.g. Stern et al. 2012; Asset et al. 2013; Yan et al. 2013).

The remaining potential of SDSS and other imaging for targeting new quasars has obvious synergy with the now mature field of using Baryon Acoustic Oscillation features (BAOs) to measure the expansion of the Universe (Eisenstein et al. 1998; Seo & Eisenstein 2003; Linden 2009). No strong BAO constraint currently exists in the redshift range 1 ≤ z ≤ 2, and BAO measurements at yet higher redshift remain a particularly potent constraint on the evolution of the angular diameter distance, D_A(z) and of the Hubble Parameter H(z) (Aubourg et al. 2014). These factors led to the conception of a new survey—the extended Baryon Oscillation Spectroscopic Survey (eBOSS; Dawson et al. 2015) as part of SDSS-IV.

It has been difficult to detect BAO features using quasars as direct tracers due to their low space density. eBOSS will circumvent this issue by surveying quasars over a huge volume, corresponding to 7,500 deg^2 of sky. The quasar component of eBOSS will attempt to statistically target and measure redshifts for ∼ 500,000 quasars at 0.9 < z < 2.2 (including spectroscopically confirmed quasars from SDSS-I/II, which will not need to be re-targeted). We will refer to this homogeneous tracer sample as the eBOSS CORE quasar target selection. BOSS targeted quasars at z > 2.2 with the main goal of using them as indirect tracers to study cosmology in the
Lyman-α Forest. In contrast, eBOSS will open up the $i > 19.1, z < 2.2$ parameter space to directly use quasars themselves as cosmological tracers.

In addition, analyses of the Lyman-α Forest with BOSS have provided substantial new insights into cosmological constraints (e.g. Song et al. 2011, 2013). Studies (e.g. Nottet et al. 2012, Busca et al. 2013, Kirkby et al. 2013, Pahlevan-Debrajou et al. 2013, Font-Ribera et al. 2014, Delubac et al. 2015), eBOSS will therefore also (heterogeneously) observe over $60,000$ new $z > 2.1$ quasars and will reobserve low signal-to-noise ratio $z > 2.1$ quasars from BOSS. The main goals of this targeting campaign are to produce measurements of the BAO scale (in both $d_A(z)$ and $H(z)$) in the Lyα Forest that approach $\sim 1.5\%$ at $z \sim 2.5$ and that probe an entirely new redshift regime via quasar clustering at $z \sim 1.5$ with $\sim 2\%$ precision (see §2). In total, at the conclusion of eBOSS, the SDSS surveys will have spectroscopically confirmed more than 800,000 quasars. The scope of the science that can be conducted with a large sample of quasars across a range of redshifts has been shown to be vast. Beyond Lyman-α Forest science, BOSS also facilitated additional, diverse quasar science, from measurements of quasar clustering and the quasar luminosity function to studies of Broad Absorption Line quasars. (e.g. Filiz Ak et al. 2012, 2013, White et al. 2012, Alexander et al. 2013, Finley et al. 2013, McGreer et al. 2013, Ross et al. 2013, Vikas et al. 2013, Greene et al. 2014, Effekharzadeh et al. 2015). eBOSS will seek to augment many of these measurements. In addition to higher-redshift studies, SDSS-IV/eBOSS will produce a $z < 2.2$ sample of quasars about six times larger than the final SDSS-II quasar catalog (Schneider et al. 2010) and will further benefit from upgrades conducted for SDSS-III (such as larger wavelength coverage for spectra; see Simcoe et al. 2013) for extensive details of upgrades). Many high-impact projects that used the original SDSS-1/II quasar samples can therefore potentially be revisited using much larger samples with eBOSS, such as composite quasar spectra, rare types of quasars, and precision studies of the quasar luminosity function (e.g. Vanden Berk et al. 2001, Inada et al. 2003, McLaren & Dunlop 2004, Hennawi et al. 2006, Richards et al. 2006, York et al. 2006, Netzer & Trakhtenbrot 2007, Kaspi et al. 2007, Shen et al. 2008, Boroson & Lauer 2009).

In this paper, we describe quasar target selection for the SDSS-IV/eBOSS survey. Further technical details about eBOSS can be found in our companion papers which include an overview of eBOSS (Dawson et al. 2015) and discussions of targeting for Luminous Red Galaxies (Prakash et al. 2015a), see also Prakash et al. 2015b), and Emission Line Galaxies (Comparat et al. 2015a). eBOSS will run concurrently with two surveys: the SPeroscopic IDentification of ERosita Sources survey (SPIDERS) and the Time Domain Spectroscopic Survey (TDSS) (Morganson et al. 2015). These associated surveys are further outlined in our companion overview paper (Dawson et al. 2015).

In §2 we discuss how forecasts for BAO constraints at different redshifts drive targeting goals for eBOSS quasars. The parent imaging used for eBOSS quasar target selection is outlined in §3. Those interested in the main quasar targeting details for eBOSS (targeting algorithms, the meaning of targeting bits, the criteria for re-targeting of previously known quasars) should read §4 of this paper. In §5, we use the results from an extensive pilot survey (SEQUELS; The Sloan Extended QUasar, ELG and LRG Survey, undertaken as part of SDSS-III) to detail our expected efficiency and distribution of quasars for eBOSS. An important criterion for any large-scale structure survey is sufficient homogeneity to facilitate modeling of the distribution of the tracer population—the “mask” of the survey. In §6 we use the full eBOSS target sample to characterize the homogeneity of eBOSS quasar selection. In §7, we provide our overall conclusions regarding eBOSS quasar targeting, and provide a bulleted summary of the final eBOSS CORE quasar selection algorithm.

Unless we state otherwise, all magnitudes and fluxes in this paper are corrected for Galactic extinction using the dust maps of Schlegel et al. (1998). Specifically, we use the correction based upon the recalibration of the SDSS reddening coefficients measured by Schlafly & Finkbeiner (2011). For WISE we adopt the reddening coefficients from Fitzpatrick (1999). The SDSS photometry has been demonstrated to have colors that are within 3% (Schlafly & Finkbeiner 2011) of being on the AB system (Oke & Gunn 1983). WISE is calibrated to be on the Vega system. We use a cosmology of $(\Omega_m, \Omega_{\Lambda})$, $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1} = (0.315, 0.685, 0.67)$ consistent with recent results from Planck (Planck Collaboration et al. 2014).

2. COSMOCOLOGICAL GOALS OF eBOSS AND IMPLICATIONS FOR QUASAR TARGET SELECTION

2.1. CORE and Lyman-α quasars

The goal of the eBOSS quasar survey is to study the scale of the BAO in two distinct redshift regimes—$z \sim 1.5$ using the clustering of quasars, and $z \sim 2.5$ using high redshift quasars as backlights to illuminate the Lyman-α Forest. Broadly, this approach requires a sample of statistically selected quasars in the redshift range $0.9 < z < 2.2$—which we will refer to as “CORE quasars”—and quasars selected at $z > 2.1$—which we will refer to as “Lyman-α quasars”.

A major difference between the two samples is the homogeneity of the target selection technique. The selection of CORE quasars must be statistically uniform. Lyman-α quasars, however, can be selected heterogeneously, as a clustering measurement using the Lyman-α Forest does not require the background quasars to have a uniform (or even a reproducible) selection. In fact, the full redshift range of the CORE sample will extend well beyond $0.9 < z < 2.2$, and many CORE quasars can thus be utilized as Lyman-α quasars. The terminology “CORE quasars” therefore refers to how the quasars were targeted whereas the terminology “Lyman-α quasars” refers to the redshift of the quasar.

2.2. Target Requirements for CORE and Lyman-α quasars

Full details of the techniques used to forecast requirements for eBOSS quasars are provided in our companion overview paper (Dawson et al. 2015). Those forecasts imply the following broad requirements for quasar target selection, driven by instrument capabilities and a 2%
measurement of the BAO distance scale (G. Zhao et al. 2016, in preparation). For the CORE quasars:

1. Survey area > 7500 deg$^2$

2. Total number of 0.9 < z < 2.2 quasars > 435,000 (this corresponds to 58 deg$^{-2}$ over exactly 7500 deg$^2$)

3. A total density of assigned fibers of < 90 deg$^{-2}$ (effectively a target density of ≤ 115 deg$^{-2}$ for reasons noted at the end of this section)

4. Redshift precision < 300 km s$^{-1}$ RMS for z < 1.5 and (300 + 400(z − 1.5)) km s$^{-1}$ for z > 1.5

5. Catastrophic redshift errors (exceeding 3000 km s$^{-1}$) < 1%, where the redshifts are not known to be in error

6. Maximum absolute variation in target density as a function of imager sensitivity, stellar density, and Galactic extinction of < 15% within the survey footprint

7. Maximum fluctuations in target density due to imaging zero-point errors of < 15% in each individual band used for targeting

Once these CORE requirements are met, remaining fibers not allocated to other eBOSS target classes are assigned to the Lyman-α target class. These Lyman-α quasars have the following additional constraints and requirements:

1. BOSS quasars within the eBOSS area with SNR pixel$^{-1}$ = 4 or 0.75 < SNR pixel$^{-1}$ < 3 must be reobserved

2. Flux calibration at least as accurate as BOSS

3. Recalibration of the BOSS high-z quasar sample using a spectroscopic pipeline that is consistent with that of eBOSS

A subtlety arises for item (3) of the CORE requirements: targets with existing good spectroscopy from earlier iterations of the SDSS are not assigned fibers as part of eBOSS (see [4.10.10]). On average, this saves 25 fibers deg$^{-2}$. Typically, therefore, this paper will quote a total target density of 115 deg$^{-2}$ but this corresponds to a density of assigned fibers of only 90 deg$^{-2}$ for CORE quasars.

2 see the eBOSS overview paper (Dawson et al. 2015) for a discussion of this requirement and Hewett & Wild (2010) for details of the precision of SDSS quasar redshifts.

3 SNR is defined as the mean S/N per Lyman-α Forest pixel measured over the rest-frame wavelength range of 1040 Å < λ < 1200 Å. A “pixel” here refers to a single bin of wavelength in a BOSS spectrum. The logic behind retargeting SNR pixel$^{-1}$ = 0 spectra is that they are almost certainly bad, whereas 0 ≤ SNR pixel$^{-1}$ < 0.75 spectra are “good” but are of irrecoverably low S/N (see [4.2.22])

3.1. Updated calibrations of SDSS imaging

All eBOSS quasar targets are ultimately tied to the SDSS-I/II/III images collected in the ugriz system (Fukugita et al. 1996) using the wide-field imager (Gunn et al. 1998) on the SDSS telescope (Gunn et al. 2006). SDSS-I/II mostly derived imaging over the ~ 8400 deg$^2$ “Legacy” area, ~ 90% of which was in the North Galactic Cap (NGC). This imaging was released as part of SDSS Data Release 7 (DR7; Abazajian et al. 2009). The legacy imaging area of the SDSS was expanded by ~ 2500 deg$^2$ in the South Galactic Cap (SGC) as part of DR8 (Ai-hara et al. 2011). The SDSS-III/eBOSS survey used DR8 imaging for target selection over ~ 7600 deg$^2$ in the NGC and ~ 3200 deg$^2$ in the SGC (Dawson et al. 2013). Quasar targets are selected for eBOSS over the same areas as BOSS, and ultimately eBOSS will observe quasars over a subset of at least 7500 deg$^2$ of this area.

Although adopting the same area as BOSS, eBOSS target selection takes advantage of updated calibrations of the SDSS imaging. Schlafly et al. (2012) have applied the “uber-calibration” technique of Padmanabhan et al. (2008) to Pan-STARRS imaging (Kaiser et al. 2010), achieving an improved global calibration compared to SDSS DR8. Targeting for eBOSS is conducted using SDSS imaging that is calibrated to the Schlafly et al. (2012) Pan-STARRS solution, as fully detailed in D. Finkbeiner et al. (2016, in preparation). We will refer to this set of observations as the “updated” imaging.

The specific version of the updated SDSS imaging used in eBOSS target selection is as stored in the calib_obj or “data sweep” files (Blanton et al. 2005). These data correspond to the native files used in the SDSS-III data model and the updated Pan-STARRS-calibrated data sweeps will be made available in a future SDSS Data Release. The magnitudes derived from these data sweeps are AB magnitudes not, e.g., with “Luptitudes” (Lupton et al. 1999). Note that the XQSOZ targeting technique (Bovy et al. 2012) adopted by eBOSS is designed to handle noisy data, so can rigorously incorporate small (and even negative) fluxes when classifying quasars.

3.2. WISE

The Wide-Field Infrared Survey Explorer (WISE: Wright et al. 2010) surveyed the full sky in four mid-infrared bands centered on 3.4 μm, 4.6 μm, 12 μm, and 22 μm, known as W1, W2, W3 and W4. For eBOSS we use only the W1 and W2 bands, which are substantially deeper than W3 and W4. Over the course of its primary mission and “NEOWISE post-cryo” continuation, WISE completed two full scans of the sky in W1 and W2. Over 99% of the sky has 23 or more exposures in W1 and W2; the median coverage is 33 exposures. We investigate whether the non-uniform spatial distribution of WISE exposure depth presents a problem for modeling CORE quasar clustering in [4].

We use the “unWISE” coadded photometry from Lang (2014) applied to SDSS imaging sources (as detailed in Lang et al. 2014). This approach produces forced photometry of custom coadds of the WISE imaging at the
Figure 1. Flowchart depicting eBOSS quasar target selection. Red boxes represent sources of input information such as imaging (see §3) or catalogs of known objects. Black boxes depict cuts that are made to the input sources as part of the target selection algorithm (see §4). Blue boxes depict output target selection bits (see §4.4). The Boolean terms in purple describe how the four bits produced by matching to previous spectra are combined to set the DO\_NOT\_OBSERVE bit (see §4.4.10). The dashed blue arrow indicates that QSO\_REOBS targets are always reobserved, regardless of the value of DO\_NOT\_OBSERVE. The sample of known objects undergoes the CORE flag and magnitude cuts rather than the PTF magnitude cuts. Consequently, PTF selection could re-target previously known objects with bad IMAGE\_STATUS and/or with 22 < g < 22.5.
positions of all SDSS primary sources. Using forced photometry rather than catalog-matching avoids issues such as blended sources and non-detections. Since the WISE scale is 2.75\(^\circ\) pixel\(^{-1}\) (roughly seven times as large as SDSS), and since many of our targets have WISE fluxes below the “official” WISE catalog detection limits, using forced photometry is of significant benefit.

3.3. PTF

The Palomar Transient Factory (PTF) is a wide-field photometric survey aimed at a systematic exploration of the optical transient sky via repeated imaging over 20,000 deg\(^2\) in the Northern Hemisphere (Rau et al. 2009, Law et al. 2009). The PTF image processing is presented in Laher et al. (2014), while the photometric calibration, system and filters are discussed in Ofek et al. (2012). In February 2013, the next phase of the program, iPTF (intermediate PTF), began. Both surveys use the CFHT12K mosaic camera, mounted on the 1.2m Samuel Oschin Telescope at Palomar Observatory. The camera has an 8.1 deg\(^2\) field of view and 11\(^\prime\) sampling. Because one detector (CCD03) is non-functional, the usable field of view is reduced to 7.26 deg\(^2\). Observations are mostly performed in the Mould-R broad-band filter, with some in the SDSS g-filter. Under median seeing conditions, the images are obtained with 2.0\(^\prime\) FHWM, and reach 5\(\sigma\) limiting AB magnitudes of \(m_R \simeq 20.6\) and \(m_g \simeq 21.3\) in 60-second exposures. The cadence varies between fields, and can produce one measurement every five nights in regions of the sky dedicated to supernova searches. Four years of PTF survey operations have yielded a coverage of \(\sim 90\%\) of the eBOSS footprint.

Two automated data processing pipelines are used in parallel in the search for transients; a near-real-time image subtraction pipeline at Lawrence Berkeley National Laboratory (LBNL), and a database populated on timescales of a few days at the Infrared Processing and Analysis Center (IPAC). The eBOSS analysis uses the individual calibrated frames available from IPAC (Laher et al. 2014).

We have developed a customized pipeline based on the SWarp (Bertin et al. 2002) and SCAMP (Bertin 2006) public packages to build coadded PTF images on a timescale adapted to quasar targeting—i.e., typically 1 to 4 epochs per year depending on the cadence and total exposure time within each field. Using the same algorithms, a full stack is also constructed by coadding all available images. This full stack is complete at 3\(\sigma\) to \(g \sim 22.0\), and has over 50\% completeness to quasars at \(g \sim 22.5\). The full stack is used to extract a catalog of PTF sources from each of the coadded PTF images. The light-curves (flux as a function of time) for all of these PTF sources are measured.

4. QUASAR TARGET CLASSES

As only a limited number of fibers are available in the eBOSS experiment, each target class is assigned a different target density to optimize scientific return. eBOSS will attempt to make the first 2\% measurement of the BAO scale at a redshift near \(z \sim 1.5\), and the uniqueness of this measurement led to statistically selected 0.9 < \(z < 2.2\) quasars being prioritized at a density of 90 deg\(^{-2}\) fibers. As noted in (2.2) because objects targeted by past SDSS projects do not need to be reobserved, this fiber allocation effectively corresponds to a density of 115 deg\(^{-2}\) targets. eBOSS will also attempt to augment BAO measurements of clustering in the Lyman-\(\alpha\) Forest, improving BAO constraints from near 2\% to closer to 1.5\%. This program is assigned the remaining available eBOSS fibers once other target classes have been accounted for, typically resulting in \(\sim 20\) deg\(^{-2}\) targets. The combined cosmological constraints that can be achieved by this overall program design are detailed in G. Zhao et al. (2016, in preparation).

As further discussed in (2.2) there are therefore two distinct target classes in eBOSS: CORE quasars and Lyman-\(\alpha\) quasars. The CORE quasars are targeted in a statistically reproducible fashion, with the intention of using them to measure clustering over redshifts of 0.9 < \(z < 2.2\). The Lyman-\(\alpha\) quasars are targeted to lie at \(z > 2.1\) to augment the BAO signal detected by BAO. These two categories of quasars are not mutually exclusive, in that the CORE quasars are not constrained to lie at \(z < 2.1\) and so the CORE selection algorithm can also identify Lyman-\(\alpha\) quasars. In the rest of this section, we discuss each of the eBOSS target classes in detail. The full targeting algorithm is also depicted by a flow-chart in Fig. 4.1.

4.1. Broad overview of the CORE quasar sample

The eBOSS CORE sample is designed to provide a statistically selected sample of 115 deg\(^{-2}\) targets that, after eBOSS spectroscopy of the 90 deg\(^{-2}\) targets that do not have existing good SDSS spectra, comprises >58 deg\(^{-2}\) total quasars with accurate redshifts in the range 0.9 < \(z < 2.2\) (see (2.2)). This >58 deg\(^{-2}\) quasars will consist of both new quasars from eBOSS spectroscopy and previously known quasars from the sample of 25 deg\(^{-2}\) targets that have existing SDSS spectroscopy. To achieve this goal eBOSS uses two complementary methods: an optical selection using the XDQSOz method of Bovy et al. (2012), and a mid-IR-optical color cut using WISE imaging. The specifics of these two methods are detailed in the next few sections.

The starting sample for CORE targeting is all point sources in SDSS imaging that are PRIMARY, have (de-extincted) PSF magnitudes of \(g < 22\) OR \(r < 22\) and a FIBER2MAG\(^6\) of \(i > 17\), and that have good IMAGE_STATUS\(^7\). These basic initial cuts are discussed further in (4.3).

Point sources in the SDSS are denoted by the flag objc_type == 6, corresponding to a magnitude cut based on star-like or galaxy-like profile fits of psmag – modelMag \leq 0.145 (Stoughton et al. 2002). A concern might be that a selection to \(r \sim 22\) might suffer incompleteness to quasars at \(r \gtrsim 21\) where star-galaxy separation in SDSS imaging was initially argued to break down due to errors on profile fits (e.g. Stoughton et al.).

\(^5\) See http://irsa.ipac.caltech.edu/Missions/ptf.html for the public PTF data

\(^6\) FIBER2MAG corresponds to the flux through a fiber with a 2\(\prime\) diameter, appropriate to BOSS. Surveys with the SDSS spectrographs instead used FIBERMAG, appropriate to a 3\(\prime\) fiber diameter.

\(^7\) in fact, all target classes detailed in this paper undergo these cuts with the exception of the variability-selected sample discussed in (4.2).
In general, though, at the limit of the SDSS imaging, the trend is to classify faint, ambiguous sources as point-like. The expectation is then that a selection approaching $r \sim 22$ will become increasingly contaminated by galaxies that are classified as unresolved, rather than miss quasars that are classified as resolved (see also the discussion in §4.5.1 of Richards et al. 2009a). Further, requiring \texttt{objc\_type} = 6 and applying $XDQSO\_z$ reduces galaxy contamination to $\lesssim 10\%$ even at $i \sim 22$ (see Figure 11 of Bovy et al. 2012), so we expect our selection to remain robust even to $r \sim 22$ (which, on average, corresponds to $i \sim 21.85$ for $0.9 < z < 2.2$ quasars).

From the initial sample of magnitude-limited PRIMARY point sources, objects are targeted if they have an $XDQSO\_z$ probability of being a quasar at $z > 0.9$ of more than $20\%$, i.e., $PQSO(z > 0.9) > 0.2$. It is important to note the subtle distinction between the specific goal of the CORE sample and the sample it produces. The goal of the CORE is to uniformly target $> 58\, \text{deg}^{-2}$ quasars in the redshift range $0.9 < z < 2.2$ but no attempt is made to restrict the upper redshift range of the CORE quasar sample. The CORE is left free to recover quasars at $z > 2.2$ because, although such quasars are outside the preferred CORE redshift range, they remain useful as tracers of the Lyman-α Forest. To this moderate-probability $XDQSO\_z$ sample, a WISE-optical color cut is applied to further reduce the target density by filtering out obvious stars based on optical-mid-IR colors. Finally, objects are not targeted if they have existing good spectroscopy from earlier iterations of the SDSS unless a visual inspection as part of $BOSS$ produced an ambiguous classification. The resulting set of objects comprises the $eBOSS$ CORE quasar sample.

### 4.1.1. $XDQSO\_z$

$XDQSO$ (Bovy et al. 2011b) is a method of classifying quasars in flux-space using extreme deconvolution ($XD$, Bovy et al. 2011a) to estimate the density distribution of quasars as compared to non-quasars. Effectively, $XDQSO$ takes any test point in flux-space, together with its flux errors, and convolves that error envelope with deconvolved distributions of the quasar and of the non-quasar loci. By weighting this convolution with a prior for the properties of quasars as compared to non-quasars, the test point is assigned a probability of being a quasar. $XDQSO$ inherits many desiderata from $XD$, including the rigorous incorporation of (and extrapolation from) errors on fluxes, and the ability to distinguish the effect on quasar probabilities of data that are completely missing from data that are merely of low significance. This feature is a boon for quasar classification near the limits of imaging data where flux errors are large. For $eBOSS$ targeting, we adopt the $XDQSO\_z$ method (Bovy et al. 2012) which extends the $XDQSO$ schema to provide probabilistic classifications for quasars in any specified range of redshift.

In pursuit of the eBOSS CORE goal of $> 58\, \text{deg}^{-2}$ $0.9 < z < 2.2$ quasars, a test spectroscopic survey in the W3 field of the CFHT Legacy Survey was conducted. This CFHTLS-W3 test survey was deemed necessary as there is no iteration of the SDSS-I/II/III specifically targeted quasars to as faint as $r \sim 22$ over the redshift range $0.9 < z < 2.2$. Although the CFHTLS-W3 test survey informed the initial quasar target selection for $eBOSS$, and so will be used to describe the broad ideas behind that target selection, it only contained $\sim 1,600$ quasars and was easily supplanted by the SEQUELS survey described in §5, which comprised $\sim 21,700$ quasars. Readers interested in an up-to-date description and depiction of the properties of $eBOSS$ quasars as compared to $SDSS$/I/II/III, should therefore consult [3] and, in particular, Fig. 17 and Fig. 18.

The CFHTLS-W3 test survey is detailed in the appendix of Alam et al. (2015). Broadly, an optical selection was applied to SDSS-DR8 imaging, restricting to PRIMARY point sources in the (PSF, unextincted) magnitude range $17 < r < 22$. From this initial sample, objects were targeted for follow-up spectroscopy if they had an $XDQSO\_z$ probability of greater than $0.2$ of being a quasar at any redshift (i.e., $PQSO(z > 0.0) > 0.2$).

As the CFHT W3 test survey targeted objects regardless of their redshift probability density (all objects with $PQSO(z > 0.0) > 0.2$) the results of the survey could be optimized to better recover quasars in the eBOSS CORE redshift range of $0.9 < z < 2.2$. One initial outcome of the CFHT W3 test survey, then, was that objects with $PQSO(z > 0.0) > 0.2$ but $PQSO(z > 0.9) < 0.2$ were rarely quasars in the eBOSS redshift range of interest, as demonstrated in Table 1. Further, restricting the redshift range of $eBOSS$ quasar targets to $z > 0.9$ is desirable to mitigate losses of, e.g., $eBOSS$ Luminous Red Galaxies targeted at $z < 0.9$ (c.f. Prakash et al. 2015b) due to fiber collisions between neighboring targets. Therefore, it was decided to focus only on targets with $PQSO(z > 0.9) > 0.2$ for $eBOSS$ targeting; we will subsequently restrict our discussion to such targets.

Fig. 2 shows the typical positions of $XDQSO\_z$ PQSO ($z > 0.9$) $> 0.2$ quasars in SDSS colors. To demonstrate the position of $XDQSO\_z$-selected quasars in optical color space, we use the large spectroscopically confirmed quasar sample from the DR10 quasar catalog of Pâris et al. (2014). In general, $XDQSO\_z$ selects similar regions of color space to $SDSS$ targets from earlier surveys (e.g., Richards et al. 2001), with the majority of
the quasar-star separation occurring in the ugr filters.

Whether an eBOSS PQSO \((z > 0.9)\) selection alone is sufficient to meet the eBOSS targeting goal of \(58 \, \text{deg}^{-2}\) quasars is investigated in Fig. 3 where the sky density of XDSOz-selected targets as a function of probability threshold is compared to that of confirmed quasars in the requisite CORE redshift range \((0.9 < z < 2.2)\); see (2.2). Fig. 3 displays three curves that correspond to source densities in the CFHTLS-W3 test program, which can be used to estimate the “true” densities of quasars and targets expected in eBOSS. The lowest (magenta) curve represents all sources in SDSS imaging in the CFHTLS-W3 field that meet the basic CORE cuts (i.e., PRIMARY point sources within the CORE magnitude limits); as a fraction of the total density of \(\sim 3330 \, \text{deg}^{-2}\) such sources. The central (red) curve represents all quasars that were spectroscopically confirmed as part of the CFHTLS-W3 program as a fraction of the total density of \(\sim 135 \, \text{deg}^{-2}\) such sources. The upper (blue) curve represents all quasars in the specific CORE redshift range of \(0.9 < z < 2.2\) that were spectroscopically confirmed as part of the CFHTLS-W3 program as a fraction of the total density of \(\sim 85 \, \text{deg}^{-2}\) such sources. As the CFHTLS-W3 program was limited to PQSO \((z > 0.0)\) \(> 0.2\), the test sample is partially incomplete to quasars that have PQSO \((z > 0.9)\) \(< 0.2\); such quasars only appear in the CFHTLS-W3 test data due to targeting approaches that did not use XDSOz-selection. Fig. 3 therefore provides best estimates only for PQSO \((z > 0.9)\) \(< 0.2\).

Fig. 3 can be used to estimate the total density of quasars and targets that might be expected in eBOSS for different PQSO \((z > 0.9)\) constraints. For example, to estimate the sky density of all quasars at PQSO \((z > 0.9)\) \(> 0.6\), one would find the corresponding Fraction of Total \((\sim 0.57)\) and multiply by the total for all quasars \((134.3 \, \text{deg}^{-2})\) to obtain \(\sim 77 \, \text{deg}^{-2}\). The vertical lines in Fig. 3 depict the necessary constraints to achieve the requisite eBOSS CORE density of \(58 \, \text{deg}^{-2}\) \(0.9 < z < 2.2\) and the requisite eBOSS target density of \(115 \, \text{deg}^{-2}\) \(< z < 2.2\).

The resulting N(z) distributions are broadly similar, but the PQSO \((z > 0.9)\) \(> 0.2\) selection has a tail to \(z < 0.9\) and contains a smaller fraction of quasars in the CORE target range of \(0.9 < z < 2.2\). This drop is more than offset by the PQSO \((z > 0.9)\) \(> 0.2\) selection containing more total quasars (c.f., Figs. 4). The peak near \(z \sim 1.3\) is likely an artifact of the small sample size in the CFHTLS-W3 test program (c.f., Fig. 17). Fig. 4 demonstrates that the majority of quasars selected at PQSO \((z > 0.9)\) \(> 0.2\) remain useful for eBOSS by being in the CORE redshift range of \(0.9 < z < 2.2\). In fact, there is an additional advantage to relaxing the XDSOz probability; doing so tends to introduce new quasars at \(z > 2.1\) while retaining the quasars in the CORE redshift range of \(0.9 < z < 2.2\).
4.1.2. Mid-IR-optical color cuts

Starlight tends to greatly diminish at wavelengths redwards of 1–2 µm, making galaxies, and in particular stars, dim in the mid-IR, whereas Active Galactic Nuclei (AGN) have considerable IR emission. Photometric selection techniques based on WISE data can therefore be used to target active galaxies, and such techniques uncover both unobscured and obscured quasars over a range of luminosities (e.g. Stern et al. 2012; Assef et al. 2013; Yan et al. 2013).

Significantly more than half of the objects targeted using mid-IR selection are low-luminosity unobscured AGN at $z < 1$ or obscured quasars (e.g., Lacy et al. 2013; Hainline et al. 2014). This makes a pure WISE selection approach imperfect for eBOSS targeting, as objects without an optical spectrum and/or AGN at $z < 0.9$ will not typically have utility for the eBOSS CORE goal of targeting $> 58$ deg$^{-2}$ 0.9 < $z$ < 2.2 quasars. WISE remains ideal, however, for removing contaminating stars from eBOSS quasar selection. Fig. 5 demonstrates the utility of a WISE-optical color cut in selecting against stars. This color cut is based on stacking optical and WISE fluxes to attain as great a depth as possible. A stack is created from SDSS PSF fluxes according to

$$m_{\text{opt}} - m_{\text{WISE}} \geq (g - i) + 3, \quad (3)$$

where $m_{\text{opt}}$ and $m_{\text{WISE}}$ are as defined in Eqn. 1 and Eqn. 2 after converting the stacked fluxes to magnitudes.

An inclusive star-galaxy separation of objc$_{\text{type}} = 6$ OR $m_{\text{opt}} - m_{\text{model}} < 0.1$, where $m_{\text{model}}$ is the equivalent of Eqn. 1 but for SDSS model magnitudes, was adopted. This is inclusive in the sense that objc$_{\text{type}} = 6$ corresponds to a star-galaxy separation of psfMag - modelMag $\leq 0.145$ (as also discussed further in § 4 but based on SDSS fluxes in all bands, not just the bands stacked in $m_{\text{opt}}$. In addition, magnitude limits of 17 < $m_{\text{opt}}$ < 22 were enforced. Finally, an optical color cut of $g - i < 1.5$ was applied in an attempt to excise the highest redshift quasars (this cut is not obvious in Fig. 5 as other programs in the CFHTLS-W3 test program repopulated this parameter space). The squares with error bars in Fig. 5 depict the typical range of colors of spectroscopically confirmed quasars in different redshift bins. The separation of these points from the green line suggests that WISE is robust for quasar selection across the CORE redshift range of 0.9 < $z$ < 2.2.

Fig. 6 demonstrates whether a WISE-optical cut of the scatter at the faint end of eBOSS, demonstrating the power of the WISE data in filtering stars that other methods target due to these stars’ resemblance to quasars in optical colors.

As part of the the CFHTLS-W3 test survey introduced in (1.1) WISE was photometered at the positions of SDSS PRIMARY sources (see § 3.2) in the CFHT Legacy survey W3 field. A WISE-SDSS selected sample was created by applying the cut depicted in Fig. 5 to these W3-test-field sources;

Optical Stack $= f_{\text{opt}} = (f_{g} + 0.8f_{r} + 0.6f_{i})/2.4$, (1)

and from fluxes in the bluest (and also deepest) WISE bands according to

$$\text{WISE Stack} = f_{\text{WISE}} = (f_{W1} + 0.5f_{W2})/1.5. \quad (2)$$

where the weights are chosen to roughly yield the highest combined S/N for a typical $z < 2$ quasar. The sample depicted by black points in Fig. 5 represents objects with any eBOSS quasar targeting bit set (see § 4.4). This sample has been limited to $r > 21$ and $g < 22$ to illustrate this cut was also eventually used for eBOSS CORE quasar target selection.
As for Fig. 4 but for the adopted WISE-optical cut.

The x-axis depicts the number of sources for a cut of $x > 4.0$ where $x$ is defined by $(m_{\text{opt}} - m_{\text{WISE}}) = (g - i) + x$ and $m_{\text{opt}}$ and $m_{\text{WISE}}$ are the magnitudes from the optical and WISE stacks. The grey (Poisson) error contours have been omitted from the blue curve for visual clarity, but are comparable to the errors on the red curve. All samples depicted have been limited to SDSS PRIMARY point sources with $i > 17$ and de-extincted PSF magnitudes of $g < 22$ OR $r < 22$ (the initial cuts for the eBOSS CORE). As the CFHTLS-W3 program was limited to $(m_{\text{opt}} - m_{\text{WISE}}) > (g - i) + 3$ the test sample is partially incomplete to quasars for $x > 3$. This figure can be used to estimate target densities in a similar manner to Fig. 3.

$m_{\text{opt}} - m_{\text{WISE}} \geq (g - i) + x$ is sufficient, in isolation, to meet the eBOSS targeting goal of 58 deg$^{-2}$ $0.9 < z < 2.2$ quasars, (modulo our additional restrictive cuts to the W3-test-field targets, such as $g - i < 1.5$).

Fig. 6 is an exact analog of Fig. 3 and a detailed description of how these figures can be interpreted is provided in [4.1.2] and [4.1.3]. Fig. 6 implies that a cut of about $m_{\text{opt}} - m_{\text{WISE}} \geq (g - i) + 4.25$ is necessary to meet the requisite eBOSS target density of 115 deg$^{-2}$ and that, therefore, only 34.1 deg$^{-2}$ CORE quasars could be obtained with a WISE-optical selection alone. As discussed further in [4.1.3] by combining XDQSOz selection with WISE eBOSS could use the “Adopted cut...” plotted in Fig. 6. This relaxed cut does achieve eBOSS targeting goals.

Fig. 7 demonstrates that relaxing cuts on $x$ in the function $m_{\text{opt}} - m_{\text{WISE}} \geq (g - i) + x$ does not strongly affect the redshift distribution of targeted quasars. This figure shows that 65–70% of quasars selected by this WISE-SDSS cut are in the CORE redshift range regardless of the value of $x$. Overall, there is less variation in the eBOSS CORE $0.9 < z < 2.2$ redshift distribution with $x$ as compared to the variation in Fig. 4 because the WISE-optical cut has less power to discriminate redshift as compared to ugriz over most of the CORE range (c.f. Fig. 5). Instead of augmenting the CORE quasar range, relaxing $x$ tends to expand the fraction of quasars at about $z > 2$. This outcome is desirable, given that $z > 2.1$ quasars can be used as part of the eBOSS Lyman-$\alpha$ sample (see [4.1.2]).

By redshifts of $z \sim 6$, about half of quasars aren’t detected in the WISE W1 and W2 bands ([Blain et al. 2013]). In addition, a 10σ detection in WISE W2 is equivalent to $i \sim 19.8$ ([Stern et al. 2012]), which may not detect all quasars to the effective eBOSS limits of $r \sim 22$. Thus it is worth investigating whether the WISE data pho-

1\begin{align*}
\text{PQSO}(z > 0.9) &> 0.2 \\
\text{m}_{\text{opt}} - m_{\text{WISE}} &\geq (g - i) + 3 \quad (4)
\end{align*}

The “Adopted cut...” lines in Fig. 3 and Fig. 4 demonstrate that in combination these constraints easily achieve the eBOSS CORE goal of 58 deg$^{-2}$ $0.9 < z < 2.2$ quasars. It turns out that the combined XDQSOz- and WISE-optical constraints that correspond to these adopted cuts require close to the maximum eBOSS quasar target density of 115 deg$^{-2}$ (see [4.2.2]) and achieve an overall density of $\sim 70$ deg$^{-2}$ $0.9 < z < 2.2$ quasars. The expected eBOSS CORE quasar density arising from these constraints is explored in more detail in [5.1].

4.2. Broad overview of the Lyman-$\alpha$ quasar sample
The goal of eBOSS Lyman-α quasar targeting is to compile as large a sample of new $z > 2.1$ quasars as possible using the remaining available fibers that were not allocated to other eBOSS targets. The eBOSS Lyman-α sample is not required to be homogeneously selected; it is therefore targeted using several different selection algorithms and sources of imaging—even imaging that only partially covers the eBOSS footprint.

The majority of new eBOSS Lyman-α quasars are targeted using two techniques. First, the CORE sample described in §4.1 is a source of new Lyman-α quasars, since its selection contains no requirement to intentionally remove $z > 2.1$ quasars. Second, a variability selection is used to target additional Lyman-α quasars. The CORE and the variability-selected samples each select $\sim 5$ deg$^{-2}$ new Lyman-α quasars, with only $\sim 1.5$ deg$^{-2}$ in common (see also Table 4 in §5.2). The variability-selected targets undergo a different set of initial flag and flux cuts as compared to other target classes (see §4.2.1).

eBOSS uses two additional techniques to target more Lyman-α quasars and to acquire more signal in the Lyman-α Forest. First, all previously unidentified sources within 1′′ of a radio detection in the FIRST survey (Becker et al. 1995; Helfand et al. 2015) are targeted. Finally, quasars that had low signal-to-noise ratio spectra in BOSS are re-targeted. The target categories specific to Lyman-α selection are detailed below, and are summarized in §4.4.

**4.2.1. Variability selection**

Time-domain photometric measurements can exploit quasars’ intrinsic variability in order to distinguish them from stars of similar colors (e.g., van den Bergh et al. 1973; Hawkins 1983; Cimatti et al. 1993; Rengstorf et al. 2004a,b; Claeskens et al. 2006; Sesar et al. 2007; Kozłowski et al. 2010; MacLeod et al. 2010; Schmidt et al. 2010; Palanque-Delabrouille et al. 2011, 2013a, 2015). The time-variability of astronomical sources can be described using the “structure function,” a measure of the amplitude of the observed variability as a function of the time delay between two observations (e.g., Cristiani et al. 1996; Giveon et al. 1999; Vanden Berk et al. 2004).

**Figure 8.** The fraction of $0.9 < z < 2.2$ (DR10) BOSS quasars that are missed as a function of WISE signal-to-noise ratio in the W1 band (blue solid line) and in the stack of $(f_{W1} + 0.5f_{W2})/1.5$ that is actually used in eBOSS CORE quasar selection (black dashed line). The red (dot-dashed) line displays the fraction of such quasars missed by the overall eBOSS CORE quasar target selection.

**Figure 9.** Structure function parameters for 6-epoch R-band light curves from PTF. Quasars (red) and stars (black), whether variable or non-variable, populate distinct regions of the $\gamma - A$ plane. Stars are a subsample of 1500 random point-like objects delimiting Equatorial Coordinates by $52^\circ < \delta_{\text{J2000}} < 54^\circ$ and $211^\circ < \alpha_{\text{J2000}} < 216^\circ$. Quasars are the previously identified quasars (mostly from BOSS) in the same field. Rengstorf et al. (2006). This function can be modeled as a power law parameterized in terms of $A$, the mean amplitude of the variation on a one-year timescale (in the observer’s reference frame), and $\gamma$, the logarithmic slope of the variation amplitude with respect to time (Schmidt et al. 2010). With $\Delta m_{ij}$ defined as the difference between the magnitudes of the source at time $t_i$ and $t_j$, and assuming an underlying Gaussian distribution of $\Delta m$ values, the model predicts an evolution of the variance $\sigma^2(\Delta m)$ with time according to

$$\sigma^2(\Delta m) = [A(\Delta t_{ij})^\gamma]^2 + (\sigma_i^2 + \sigma_j^2),$$

where $\sigma_i$ and $\sigma_j$ are the imaging errors at time $t_i$ and $t_j$. Quasars should lie at high $A$ and $\gamma$, non-variable stars near $A = \gamma = 0$ and variable stars should have $\gamma$ near 0 even if $A$ is large. In addition, variable sources (whether stars or quasars) are expected to deviate greatly from a model with constant flux. This deviation is quantified by computing the $\chi^2$ of the fit of the light curve compared to a constant-flux model.

Using customized PTF R-band stacks (see section §3.2), light curves are built for all of the PTF sources. The PTF sources are matched to SDSS imaging catalogs, and the selection is restricted to SDSS PRIMARY point sources. With the PTF light curves in hand, all additional cuts are then applied using SDSS imaging information. SDSS cuts of $g < 22.5$ and $r > 19$ are then applied. When SDSS r-band data are available, the R-band PTF light curve, adjusted to SDSS $r$, is extended to include the SDSS fluxes. These PTF+SDSS light-curves typically contain 3 to 4 PTF “coadded epochs,” where each PTF “coadded epoch” is obtained by coadding the exposures within a given PTF observational season. The number of exposures in each season varies from $\sim 10$ to a few dozen for typical fields.

Because the density of PTF images varies across the sky, so does the efficiency of the variability-based selection. To account for this, the thresholds of the variability cuts are adapted as a function of position in order to reach an average target density of $\sim 20$ deg$^2$ across the eBOSS footprint. Constraints of $5.0 < \chi^2 < 200.0$ for combined PTF+SDSS measurements are typ-
have SNR pixel measured reliably, such as light curves with fewer than 3 PTF epochs.

To maximize the efficiency of quasar selection, the variability selection is complemented by loose color cuts designed to reject stars. Cuts of \( c_3 < 1.4 - 0.55 \times c_1 \) and \( c_3 < 0.3 - 0.1 \times c_1 \) are imposed, where

\[
\begin{align*}
c_1 &= 0.95(u-g) + 0.31(g-r) + 0.11(r-i) \\
c_3 &= -0.39(u-g) + 0.79(g-r) + 0.47(r-i)
\end{align*}
\]  

as defined in Fan (1999). In these equations, \( ugr \) are PSF magnitudes measured in the SDSS imaging. This color cut is illustrated in Fig. 10 where the regions above the red and green lines are rejected.

Finally, a region in color-space mostly populated by bright variable stars, that passes both the color and the variability cuts, is removed. These stars are apparent in the top panel of Fig. 11—but are clearly absent in the lower panel, which depicts known quasars. These contaminating variable stars are removed by rejecting sources that lie in the color box \( 0.85 < c_1 < 1.35 \) and \( c_3 > -0.2 \) if they are brighter than \( r = 20.5 \). This cut is not applied to fainter sources.

### 4.2.2. Reobservation of BOSS quasars

The mean density of Lyman-\( \alpha \) quasars in BOSS (once Broad Absorption Line quasars are removed) is \( \sim 15 \text{deg}^{-2} \). Roughly 60% of these quasars have a signal-to-noise ratio (SNR) \( < 3 \), thus reducing their utility for tracing large-scale structure. Here, SNR is defined as the mean S/N per Lyman-\( \alpha \) Forest pixel measured over the rest-frame wavelength range of 1040 \( \AA \) < \( \lambda \) < 1200 \( \AA \). With the exception of BOSS spectra that have SNR pixel\(^{-1} = 0 \) (signifying an observational error) quasars with \( 0 \leq \text{SNR pixel}^{-1} < 0.75 \) do not contribute as much to the Forest signal as placing a fiber on a new quasar target, so such quasars are not worth reobserving. Within eBOSS, BOSS quasars are therefore targeted if they lie in the eBOSS footprint and have \( 0.75 \leq \text{SNR pixel}^{-1} < 3 \) OR SNR pixel\(^{-1} = 0 \). The density of these targets varies over the eBOSS footprint from \( \sim 6 \text{deg}^{-2} \) to \( \sim 10 \text{deg}^{-2} \), depending upon the underlying density of BOSS Lyman-\( \alpha \) quasars.

### 4.2.3. Radio selection

eBOSS also targets all SDSS point sources that are within 1" of a radio detection in the 13 June 05 version\(^{11} \) of the FIRST point source catalog (Becker et al. 1995; Helfand et al. 2015). The density of such sources (that are not already included in another target class) is low (< 1 deg\(^{-2} \)), and these additional targets are expected to identify some previously unknown high redshift quasars.

### 4.3. Additional Cuts

SDSS imaging includes a great deal of meta-data\(^{12} \) and, notably, contains flags (in the form of bitmasks)
Figure 12. Sky density of quasars and targets *removed* by a specific SDSS flag cut. Flag numbers 0–31 correspond to the 32 bits in the SDSS *objcflags* bitmask and flag numbers 32–63 are the 32 bits in the SDSS *objcflags2* bitmask. The final three bits in *objcflags2* do not correspond to an imaging flag. The red (empty) histogram is the density of targets discarded from the CFHTLS-W3 test data and the blue (filled) histogram is the density of genuine $z > 0.9$ quasars discarded by the same flag cut. In the upper panel we display the ratio of the two histograms, which is the fraction of targets discarded that would be useful quasars for eBOSS.

that can be used to characterize photometric quality. Initially, eBOSS adopts a set of obvious and necessary cuts on SDSS imaging parameters. The target selection is restricted to PRIMARY sources in the SDSS to avoid duplicate sources. Targets are cut on (deextincted) PSFMAG to the near the limits of SDSS imaging, in part driven by the necessary exposure times to obtain spectra of reasonable signal-to-noise ratio. These limits are $g < 22$ OR $r < 22$ for CORE quasars and $g < 22.5$ for the Lyman-$\alpha$ quasar sample—which can be more speculative and inhomogeneous in its selection. A bright limit of FIBER2MAG $i > 17$ is adopted for all eBOSS targets to prevent light leaking between adjacent fibers (see Dawson et al. 2015). Quasars selected by variability and intended purely for Lyman-$\alpha$ studies have a more restrictive bright-end cut of $r > 19$, as there are few high-redshift quasars brighter than $r = 19$. Finally, the restriction that quasar targets must be unresolved in imaging ($objc_type=6$) is imposed. This is necessary as at fainter magnitudes, extended sources begin to dominate SDSS imaging, and at $r > 21.2$ there are three times as many *objc_type=3* (extended) sources as *objc_type=6* (point-like) sources. Targeting extended sources would greatly increase the eBOSS fiber budget, while recovering few $z > 0.9$ quasars.

Our CFHTLS-W3 test program (outlined in §4.1.1) had relaxed limits on star-galaxy separation and magnitude, meaning that it is possible to show that our basic flag cuts for eBOSS quasar targeting represent sensible choices. Adopting the selection outlined in §4.1.3, a cut on *objc_type=6* discards only 4.6% of quasars but requires $3.5\times$ fewer fibers. Enforcing faint limits of $g < 22$ OR $r < 22$ discards 5.8% of quasars but requires $11.5\times$ fewer fibers.

Typically, previous SDSS quasar targeting algorithms (Richards et al. 2002; Ross et al. 2012) have employed additional constraints on image quality to reduce spurious targets. Given that the CFHTLS-W3 test program did not adopt strict flag cuts, it could be used to assess which flag cuts might be worthwhile for eBOSS targeting (see Fig. 12). A range of individual SDSS flag cuts are plotted in Fig. 12 which demonstrates that there are essentially no SDSS flags that discard targets without also discarding useful $z > 0.9$ quasars. The one exception is the DEBLENDED AS MOVING flag (number 32), which does not obviously discard quasars, but which only saves 0.3 deg$^{-2}$ targets. In addition to the results in Fig. 12 we also tested numerous standard combinations of flags used by other SDSS quasar targeting algorithms, such as the INTERP PROBLEMS and DEBLENDED PROBLEMS combinations outlined in the appendices of Bovy et al. (2011b) and Ross et al. (2012). In no case did we find a flag combination that removed significant numbers of targets without also discarding useful quasars. We do not study why the SDSS image quality flags have limited utility for eBOSS targeting—speculatively the flags may become less meaningful near the faint limits of SDSS imaging and/or our incorporation of WISE data may ameliorate SDSS artifacts. In any case, based on this analysis and the fact that the basic eBOSS selection already achieves the requisite target density, we make no additional SDSS flag cuts.

It is likely that certain regions of the SDSS imaging will have to be masked further for quasar clustering analyses, due to, e.g., areas around bright stars (both in WISE and SDSS imaging), bad imaging fields (e.g. see Ross et al. 2011 and 2012). For instance, due to how the SDSS geometry was initially defined for “uber-calibration,” small overlap regions ($\sim 1$ deg$^2$) in SDSS run 752 are misaligned between SDSS and our WISE photometering. Such regions do not have a major impact on target homogeneity, however, and may differ for different eBOSS target classes, so such geographic areas will be masked post-facto depending on a specific science purpose. One set of regions that was masked a priori for BOSS quasar targeting corresponded to bad u-columns (e.g. see Fig. 1 of White et al. 2012). Specifically testing target density in areas with bad SDSS u-columns did not suggest they have greatly different eBOSS CORE target densities ($\sim 116$–$118$ deg$^{-2}$ versus the average of $\sim 115$ deg$^{-2}$ for the typical survey area), so bad u-columns are not specifically masked a priori for eBOSS targeting.

In general, the only large geographic areas that should certainly not be photometric in SDSS imaging are regions with catastrophic values of IMAGE_STATUS. For eBOSS CORE quasar targeting, we avoid all areas with IMAGE_STATUS set to any of BAD_ROTATOR, BAD_ASTRON, BAD_FOCUS, SHUTTERS, FF_PETALS, DEAD_CCD or NOISY_CCD in any filter. Quasars targeted on the basis of their variability in PTF for Lyman-$\alpha$ studies do not undergo cuts on IMAGE_STATUS as there is no requirement for Lyman-$\alpha$ quasars to be selected homogeneously. The full set of flag cuts eventually adopted is outlined succinctly in Fig. 1.
Table 2

| eBOSS quasar targeting bits and their numerical equivalents |
|-------------------------------------------------------------|
| Bit Name | Bit Name |
| 0 | DO.NOT.OBSERVE |
| 10 | QSO_EBOSS_CORE |
| 11 | QSO_PTF |
| 12 | QSO_REOBS |
| 13 | QSO_EBOSS_KDE |
| 14 | QSO_EBOSS_FIRST |

The tests summarized in §4.3 provide sufficient information to justify the choices made to target quasars in eBOSS. This section provides an outline of how the eBOSS targeting bits directly correspond to the specified choices. A visual representation of the overall targeting algorithm is also provided in Fig. [1]. Unless otherwise specified, each target class is derived from the imaging outlined in [3] and undergoes the basic flag cuts outlined in [4.3] (PRIMARY, objc_type=6, magnitude cuts, and good IMAGE_STATUS). The numerical value of each of the eBOSS quasar targeting bits is listed in Table 2. The density and success rate of each class of target is described further in §4.3.

4.4.1. QSO_EBOSS_CORE

Quasars that comprise the main eBOSS CORE sample are assigned the QSO_EBOSS_CORE bit. The main goal of the CORE sample is to obtain > 58 deg$^{-2}$ 0.9 < z < 2.2 quasars (assuming an exactly 7500 deg$^2$ footprint for eBOSS). We make no attempt to limit the upper end of the CORE redshift range, meaning that the CORE also selects z > 2.1 quasars that have utility for Lyman-α Forest studies. Quasars in the CORE are selected by XDQSOz and WISE as described in [4.1.3].

4.4.2. QSO_PTF

Quasars intended for Lyman-α Forest studies typically do not have to be selected in a uniform manner. This freedom allows variability selection to be applied to inhomogeneous imaging in order to target additional z > 2.1 quasars for eBOSS. The QSO_PTF bit indicates such quasars, which have been selected using multi-epoch imaging from the Palomar Transient Factory. PTF targets undergo slightly different initial cuts to other quasar target classes; they are limited in magnitude to r > 19 and g < 22.5 and they are observed in areas with bad IMAGE_STATUS. These choices are justified in [4.3] PTF quasars are selected as described in [4.2.1].

4.4.3. QSO_REOBS

Quasars previously confirmed in BOSS that are of reduced (but not prohibitively low) signal-to-noise ratio have decreased utility for Lyman-α Forest studies. In addition, high probability BOSS quasar targets that have zero spectral signal-to-noise ratio in BOSS are likely to have been spectroscopic glitches. The QSO_REOBS bit signifies quasars that were measured to have 0.75 ≤ SNR pixel$^{-1}$ < 3 or SNR pixel$^{-1}$ = 0 in BOSS. Quasars are selected for reobservation as described in [4.2.2].

4.4.4. QSO_EBOSS_KDE

The QSO_EBOSS_KDE bit has been discontinued for eBOSS but formed part of the targeting for SEQUELS (see §5.1). Targets that had the QSO_EBOSS_KDE bit set in SEQUELS were drawn from the Kernel Density Estimation catalog of Richards et al. (2009a) and had uvwts==1 set within that catalog. As the QSO_EBOSS_KDE bit is discontinued, the origin of this target class is not described further in this paper.

4.4.5. QSO_EBOSS_FIRST

Powerful radio-selected quasars can be detected by FIRST at z > 2.1 and can therefore have utility for Lyman-α Forest studies. The QSO_EBOSS_FIRST bit indicates quasars that are targeted because they have a match in the FIRST radio catalog, as described in [4.2.3].

4.4.6. QSO_BAD_BOSs

Some likely quasars with spectroscopy obtained as part of BOSS have uncertain classifications or redshifts upon visual inspection. Such objects are designated as QSO? or QSO_27 in DR12Q (c.f. Parris et al. 2014). The QSO_BAD_BOSs bit signifies such objects, to ensure that ambiguous BOSS quasars are always reobserved, regardless of which other targeting bits are set. Prior to 4 November, 2014 (effectively prior to the eboss6 tiling; see Dawson et al. 2015) a close-to-final but preliminary version of DR12Q was used to define this sample, but as of eboss6 the final sample of DR12Q was used to define the QSO_BAD_BOSs bit. This change effectively means that a small number of quasars with ambiguous BOSS spectra may not have been reobserved prior to eboss6.

4.4.7. QSO_BOSS_TARGET

In an attempt to reduce the overall target density, eBOSS quasar targeting does not retarget any objects with good spectra from BOSS unless otherwise specified. The QSO_BOSS_TARGET bit is set to indicate such objects. We define an object as having good BOSS spectroscopy if it appears in the file of all spectra that have been observed by BOSS, and if it does not have either LITTLE_COVERAGE or UNPLUGGED set in the ZWARNING bitmask (see Table 3 of Bolton et al. 2012).

4.4.8. QSO_SDSS_TARGET

eBOSS quasar targeting will not retarget objects with good pre-BOSS spectra from the SDSS (i.e., spectra from prior to DR8). The QSO_SDSS_TARGET bit is set to indicate such objects. A “good” spectrum is defined using LITTLE_COVERAGE and UNPLUGGED as for the QSO_BOSS_TARGET bit. SDSS spectral information is obtained from the final DR8 spectroscopy file.

4.4.9. QSO_KNOWN

eBOSS quasar targeting will not reobserve objects with previous good spectra (defined by the QSO_BOSS_TARGET and QSO_SDSS_TARGET bits). The purpose of the QSO_KNOWN bit is to track which previously

15 Specifically the combination of v5.7.0 and v5.7.1 of the BOSS SpAll file (http://data.sdss3.org/datamodel/files/BOSS_SPECTRA/BOSS_SPECTRA/BOSS_SPECTRA.html) circa May 30, 2013.
16 Specifically the (line-by-line) parallel spectroscopy and imaging catalogs at http://data.sdss3.org/sas/dr8/sdss/spectro/redux/photoObjPlate-dr8.fits and http://data.sdss3.org/sas/dr8/sdss/spectro/redux/specObj-dr8.fits
In Boolean notation, is a quasar). Targets are not observed if any of 
set, and redshift should already exist (if the object
an additional spectrum because a good classification and redshift overlaps that of earlier iterations of the SEQUEST and BOSS targeting process, which is outlined in 4.4. To determine whether the targeting approaches detailed so far in this paper truly met quasar targeting always uses the updated imaging allowed eBOSS to target a larger number of Lyman-α quasars using the QSO_PTF method, and may ultimately result in a larger total area for eBOSS.

5. RESULTS FROM A LARGE PILOT SURVEY

The approaches discussed so far for eBOSS quasar targeting were mostly based upon an ~ 11 deg
test survey, that was conducted in the CFHT Legacy Survey W3 field (e.g., see [4.1.1] and [4.1.2]). This test field alone was sufficient to define a mature eBOSS quasar targeting test. Figure 13. The targeting completeness of CORE quasars as a function of position across the first 66 plates of SEQUELS. Blue corresponds to a completeness of greater than 90%, red of only greater than 10%. Gray lines depict sectors of SEQUELS that have yet to be observed. The structure of the overlapping plates in defining complete areas is apparent, and the quasar density is a function of that completeness. Overall, the depicted SEQUELS plates with completenesses above zero comprise 299.3 deg
targeting completeness) of only 236.3 deg.

Note. — (1) The r limit for which the efficiencies are derived; (2) The fraction of all quasar targets with a highly confident classification and redshift; (3) The fraction of all quasar targets for which the SEQUEST spectroscopic pipeline redshift is accurate; (4–5) As for columns (2–3) but for targets classified as quasars on visual inspection; (6–7) As for columns (2–3) but for quasar targets classified as 0.9 < z < 2.2 (i.e., “CORE”) quasars on visual inspection.

4.4.11. DR9_CALIB_TARGET: Which version of the SDSS imaging was used?

eBOSS quasar targeting always uses the updated imaging described in §4.3. In [5] we describe a preliminary survey called SEQUELS that bridged the SDSS-III and SDSS-IV surveys. SEQUELS targeted quasars selected in both the DR9 imaging used for BOSS and the updated imaging used in eBOSS. The DR9_CALIB_TARGET bit signifies quasars that were selected for SEQUELS using the DR9 imaging calibrations.

5. RESULTS FROM A LARGE PILOT SURVEY

The approaches discussed so far for eBOSS quasar targeting were mostly based upon an ~ 11 deg test survey, that was conducted in the CFHT Legacy Survey W3 field (e.g., see [4.1.1] and [4.1.2]). This test field alone was sufficient to define a mature eBOSS quasar targeting process, which is outlined in [4.4]. To determine whether the targeting approaches detailed so far in this paper truly met eBOSS goals, and to provide a sample for initial scientific analyses, a larger pilot survey was conceived as part of the Sloan Extended Quasar, ELG and LRG Survey (SEQUELS), in the context of whether they meet the goals outlined in §2.2.

5.1. Details of the SEQUELS survey

SEQUELS comprises two chunks of BOSS
covering ~ 810 deg
total area. SEQUELS approximates the

\[
\text{BOSS, QSO, SDSS} \quad \text{NOT} \quad \text{BOSS} \quad \text{BAD} > 0.1 \quad \text{BOSS} \quad \text{KNOWN} \quad \text{REOBS} \quad \text{CALIB} \quad \text{BAD} \quad \text{BOSS} \quad \text{TARGET} \quad \text{TARGET} > 0.3 \quad > 0.5 \quad > 0.7 \quad \text{CALIB} \quad \text{NOT} \quad \text{BAD} \quad \text{TARGET} \quad \text{SDSS} \quad \text{SDSS} \quad \text{BAD} \quad \text{KNOWN} \quad \text{BOSS} \quad \text{REOBS} \quad \text{SDSS} \quad \text{BOSS} \quad \text{BAD} \quad \text{KNOWN} \quad \frac{1}{8} \times \frac{1}{8} \text{targeting completeness across the first 66 plates of SEQUELS. Blue corresponds to a completeness of greater than 90%, red of only greater than 10%. Gray lines depict sectors of SEQUELS that have yet to be observed. The structure of the overlapping plates in defining complete areas is apparent, and the quasar density is a function of that completeness. Overall, the depicted SEQUELS plates with completenesses above zero comprise 299.3 deg\(^2\) of area, but an effective area (area \times \text{targeting completeness}) of only 236.3 deg\(^2\).

known objects have a reliable, visually inspected (or otherwise highly confident) redshift and classification from prior spectroscopy. Objects classified as having excellent prior spectroscopy are those that are of SDSS provenance and match the sample used to define known objects in BOSS (see Ross et al. [2012], or those that match the final BOSS quasar catalog [DR12Q; c.f. Pâris et al. [2014]]. The QSO\_KNOWN bit is intended to represent that subset of objects deliberately not observed that have a reliable spectrum—because objects without such a reliable spectrum are almost certainly not quasars. The main utility of this bit is to populate catalogs for scientific analyses with reliable previous redshifts and classifications. The version of the DR12Q catalog used to set QSO\_KNOWN changed at the time of the eboss6 tiling in the same manner as described for the QSO\_BAD\_BOSS bit.

4.4.10. DO NOT OBSERVE: Which previously known quasars are targeted?

The parameter space for eBOSS quasar targeting overlaps that of earlier iterations of the SDSS. The bits QSO\_BAD\_BOSS, QSO\_BOSS\_TARGET, QSO\_SDSS\_TARGET, and QSO\_KNOWN work together to determine a sample of objects for which eBOSS does not need to obtain an additional spectrum because a good classification and redshift should already exist (if the object is a quasar). Targets are not observed if any of QSO\_BOSS\_TARGET, QSO\_SDSS\_TARGET or QSO\_KNOWN are set unless QSO\_BAD\_BOSS is set. In addition, QSO\_REOBS always forces a reobservation of an earlier BOSS quasar. In Boolean notation, DO NOT OBSERVE is then set according to quasar target bits if:

\[
\text{(QSO\_KNOWN || QSO\_BOSS\_TARGET || QSO\_SDSS\_TARGET) } && \lnot \text{(QSO\_BAD\_BOSS || QSO\_REOBS)}.
\]

The reduction in target density from implementing this schema is significant. Broadly, the total density of

| r | f\(_{\text{cont}}\) | f\(_{\text{x}}\) | f\(_{\text{qcont}}\) | f\(_{\text{qos}}\) | f\(_{\text{reccont}}\) | f\(_{\text{corea}}\) |
|---|---|---|---|---|---|---|
| 21.0 | 0.981 | 0.960 | 0.996 | 0.970 | 0.997 | 0.973 |
| 21.1 | 0.980 | 0.960 | 0.995 | 0.970 | 0.996 | 0.973 |
| 21.2 | 0.978 | 0.958 | 0.994 | 0.970 | 0.996 | 0.972 |
| 21.3 | 0.977 | 0.958 | 0.993 | 0.970 | 0.995 | 0.972 |
| 21.4 | 0.977 | 0.957 | 0.993 | 0.970 | 0.995 | 0.972 |
| 21.5 | 0.975 | 0.956 | 0.992 | 0.969 | 0.995 | 0.972 |
| 21.6 | 0.971 | 0.953 | 0.991 | 0.968 | 0.993 | 0.971 |
| 21.7 | 0.968 | 0.950 | 0.989 | 0.967 | 0.992 | 0.970 |
| 21.8 | 0.964 | 0.947 | 0.987 | 0.966 | 0.990 | 0.970 |
| 21.9 | 0.960 | 0.944 | 0.986 | 0.966 | 0.989 | 0.969 |
| 22.0 | 0.957 | 0.941 | 0.984 | 0.965 | 0.987 | 0.968 |

Table 3

Redshift and classification efficiency from SEQUELS for CORE quasars upon visual inspection

Note. — (1) The r limit for which the efficiencies are derived; (2) The fraction of all quasar targets with a highly confident classification and redshift; (3) The fraction of all quasar targets for which the SDSS spectroscopic pipeline redshift is accurate; (4–5) As for columns (2–3) but for targets classified as quasars on visual inspection; (6–7) As for columns (2–3) but for quasar targets classified as 0.9 < z < 2.2 (i.e., “CORE”) quasars on visual inspection.
Figure 14. Two representative spectra of $g \sim 20$ quasars from SDSS plate 7284 (part of SEQUELS). Plate 7284 had a total exposure time of 75 minutes. The spectra have not been smoothed or otherwise enhanced. The dotted lines and associated labels mark the positions of some typical quasar emission lines with rest-frame wavelengths taken from Van-den Berk et al. (2001). Emission lines that are close to the edges of the covered wavelength range are not marked. Other labels are the object name, redshift, and (observed, not de-extincted) $g$-band target magnitude. The blue solid line depicts the flux density ($f_{\lambda}$), the green depicts the $1\sigma$ error on $f_{\lambda}$, and the red depicts the best-fit template output by the SDSS pipeline.

Figure 15. As for Fig. 14 but for $g \sim 21$ quasars.

Figure 16. As for Fig. 14 but for $g \sim 22$ quasars.

1. The bright-end cut enforced on all target classes in SEQUELS was $i > 17$ on FIBER2MAG rather than on FIBER2MAG. This choice makes a tiny difference to the selected targets, of order 0.2%.

2. IMAGE_STATUS flags were not applied in SEQUELS. More than 97% of the SEQUELS area has good IMAGE_STATUS according to our definition from §4.3. The remaining $\sim 3\%$ of area, however, would not have been observed in eBOSS proper.

3. The QSO_EBOSS_KDE target class (see §4.4) was observed in SEQUELS but discontinued for eBOSS.

4. CORE quasar targets in eBOSS are all selected from the updated imaging described in §3.1. In SEQUELS the superset arising from both the updated and DR9 imaging was targeted, because the updated imaging calibrations were considered to be preliminary. As we shall outline in this section, the updated imaging is sufficient to meet eBOSS goals, so targeting using DR9 imaging was discontinued after SEQUELS. In this section of the paper, we only discuss the results arising from the use of the updated imaging.

5. For SEQUELS the QSO_PTF target density was set at $\sim 35\,\text{deg}^{-2}$, which is higher than the typical eBOSS density of this target class of $\sim 20\,\text{deg}^{-2}$.

Spectroscopic observations for SEQUELS were conducted in the same fashion as general BOSS plates (see Dawson et al. 2013) with average exposure times of 75 minutes. The SEQUELS observations contained in DR12 consist of 66 plates over an effective area of $236.3\,\text{deg}^2$. The coverage is depicted in Fig. 13. The targeting completeness, defined as the fraction of all targets that have received a fiber in each overlapping sector of the survey, is plotted. Sectors are derived using the MANGLE software package (e.g. Swanson et al. 2008).

Every object targeted as a quasar or identified as a likely quasar by the automated pipeline (Bolton et al. 2012) was visually inspected following the procedures presented in Paris et al. (2014). The final classifications are described in DR12Q. A summary of the results is reported in Table 3. Fig. 14–16 display typical SEQUELS spectra as a function of $g$-band magnitude. It is apparent that even the faintest quasars observed in SEQUELS (Fig. 16) can be identified and assigned a redshift on visual inspection, even with no smoothing or other enhancements to the spectrum. A caveat is that SEQUELS was conducted during particularly good observing conditions, and there is therefore no guarantee that the quality of SEQUELS spectra will be representative of the full eBOSS survey.
eBOSS quasars

Table 4

Density of SEQUELS quasar targets that are confidently a quasar upon visual inspection

| Comp. > 0.9 | Total Area | Eff. Area | 0.9 < z < 2.2 from CORE | ALL z from CORE | New z > 2.1 from CORE |
|-------------|------------|-----------|------------------------|----------------|----------------------|
| (1)         | (2)        | (3)       | (4)                    | (5)            | (6)                  |
| 0.00        | 298.5      | 237.1     | 57.9                   | 13.1           | 71.1                 |
| 0.05        | 189.9      | 183.5     | 58.3                   | 13.4           | 71.6                 |
| 0.85        | 187.6      | 181.6     | 58.3                   | 13.3           | 71.6                 |
| 0.90        | 174.5      | 170.0     | 58.4                   | 13.4           | 71.8                 |
| 0.95        | 125.9      | 124.7     | 59.2                   | 12.8           | 72.0                 |

Note. — (1) Targeting completeness (fraction of CORE targets which received a fiber) limit of the sectors used for a given row of the table (see also Fig. 13). eBOSS should be > 95% complete; (2) Total SEQUELS area above this completeness (deg²); (3) The effective area (area in deg² weighted by per-sector completeness); (4) Completeness-weighted total density of new (i.e. previously unconfirmed) 0.9 < z < 2.2 quasars (deg⁻²) targeted by the CORE (i.e. having the QSO-Core, QSO, QSO.CORE bit set). We define a quasar as an object classified QSO or QSO.CORE as in Table 2 of Paris et al. (2014); (5) The total density of previously confirmed 0.9 < z < 2.2 quasars from earlier SDSS surveys (deg⁻²) targeted by the CORE; (6) Total density (completeness-weighted) of 0.9 < z < 2.2 quasars that would comprise the CORE clustering sample (deg⁻²). We only include objects classified as a quasar—a further 1.5-2 deg⁻² of CORE targets are galaxies (or unidentified objects) at 0.9 < z < 2.2; (7-9) As for columns (4-6) but for all quasars selected by the CORE (not just those that are at 0.9 < z < 2.2 on visual inspection); (10) New quasars selected by the CORE as for columns (4) and (7) but specifically at z > 2.1 (the Lyman-α quasar redshift range); (11) New quasars (heterogeneously) selected by only PTF (i.e., having the QSO.PTF bit set), this column is not completeness-weighted; (12) Total density of new z > 2.1 quasars that would compose the eBOSS sample of Lyman-α quasars.

5.2. Projected eBOSS Targeting efficiency

Perhaps the most critical aspect of eBOSS quasar targeting is that a sufficiently high density of quasars is obtained to make meaningful and/or improved measurements of the BAO distance scale. Contingent on the effective area of SEQUELS (as depicted in Fig. 13) we can estimate the quasar density expected for eBOSS. Making this estimate is relatively straightforward—it is obtained by dividing the total number of spectroscopically confirmed quasars in SEQUELS by the completeness-weighted area of the survey as a function of targeting approach and of redshift. For this purpose, “completeness” means targeting completeness to the statistically selected quasar sample, which is defined, here, to be the fraction of CORE quasar targets that received a fiber for spectroscopic observation. Targeting incompleteness occurs in SEQUELS for two main reasons: First, due to collisions, a fiber cannot always be placed on neighboring targets, causing general incompleteness on a plate; and, second, certain plates in SEQUELS are yet to be observed, causing significant incompleteness in areas where yet-to-be-observed plates overlap completed plates. Table 4 presents estimates of the eBOSS quasar density. In addition to weighting the CORE quasar counts by completeness on a sector-by-sector basis, Table 4 details results as a function of completeness. Ultimately, eBOSS is expected to be have a targeting completeness of 0.95 (due to collisions, fibers will only be placed on 95% of quasar targets), so it is worth noting that the statistics in Table 4 are somewhat dependent on completeness.

The results in Table 4 have been produced in a manner that should reflect the eventual targeting schema for eBOSS. One subtlety is that most, but not all, BOSS observations had been completed in the depicted area in Fig. 13 by the time of SEQUELS observations. To better mimic eBOSS, estimates in Table 4 are produced by substituting non-SÉQUELS (BOSS) identifications from DR12Q over SEQUELS targets, where they exist, and such objects are treated as previously observed, known quasars—i.e., when such objects have a good spectrum from DR12Q, they are treated as if they had a known redshift from BOSS and as if the DO NOT OBSERVE bit had been set (see 4.14.10). At the outset of SEQUELS, 8921 potential SEQUELS targets had the DO NOT OBSERVE bit set due to a prior good spectrum in SDSS-1, II or III. Based on our substitution process, only an additional 267 (~3%) quasars would have had the DO NOT OBSERVE bit set due to yet-to-be-completed BOSS observations, and only 92 (~1%) of these additional quasars would have been in the redshift range 0.9 < z < 2.2.

It is critical for users of eBOSS data to be able to accurately track previously known quasars from earlier versions of the SDSS. Table 4 implies that of order ~ 13 deg⁻² 0.9 < z < 2.2 quasars will be included in eBOSS as a prior confirmation. This number of ~ 13 deg⁻² previously identified CORE quasars is as might be expected. The SDSS-1/II quasar catalog of Schneider et al. (2010) contains ~ 75,000 0.9 < z < 2.2 quasars spread over 9400 deg² (~ 8 deg⁻²). The BOSS quasar catalog of DR12Q contains ~ 65,000 0.9 < z < 2.2 quasars spread over 10,700 deg² (~ 6 deg⁻²). These catalogs also contain ~ 1 deg⁻² mutual 0.9 < z < 2.2 quasars. Depending on SEQUELS sector, the number of known quasars in the CORE redshift range can vary widely from as few as 5 deg⁻² to as many as 25 deg⁻² due to the complex set of ancillary programs that were conducted as part of BOSS (see, e.g., Dawson et al. 2013).

The main purpose of this section is to investigate whether the eBOSS target selection as applied to SEQUELS meets the requirements discussed in [22] which...
amount to a success rate of $> 58\,\text{deg}^{-2}$ $0.9 < z < 2.2$ quasars over 7500 deg$^2$. Whether the area requirements of 0.2 will be met are discussed in Dawson et al. (2015). The results from the SEQUELS area suggest that eBOSS will meet its quasar targeting requirements in terms of number densities. For a targeting completeness reflective of eBOSS ($\sim 95\%$), a completeness-weighted density of 72.0 deg$^{-2}$ $0.9 < z < 2.2$ quasars were identified in SEQUELS. This suggests that the eBOSS CORE quasar selection will identify (0.95 $\times$ 72.0 =) 68.4 deg$^{-2}$ $0.9 < z < 2.2$ quasars.

The SDSS imaging in the SEQUELS area may be of above-average quality, which could inflate these expectations (see §5.2). There are also reasons to believe, however, that the eBOSS quasar density may be higher than SEQUELS expectations. For instance, SEQUELS data were reduced using the SDSS-III spectroscopic pipeline, which, with augmentations, might improve on the $\sim 1\%$ loss due to unidentifiable quasars listed in Table 3. Also, there are 1.5–2 deg$^{-2}$ additional objects in the CORE redshift range in SEQUELS that are not included in Table 4 because they are classified as “unknown” or as galaxies upon visual inspection. In theory these objects can also be used for eBOSS clustering analyses (although such objects have a median redshift of $\sim 1.1$).

Fibers not allocated to other eBOSS target classes are assigned to finding new Lyman-α quasars ($z > 2.1$). In Table 4 we show that SEQUELS contains (7.0 $\times$ 0.95) $\sim 6.7\,\text{deg}^{-2}$ new Lyman-α quasars acquired by the CORE selection and (4.1 $\times$ 0.95) $\sim 3.9\,\text{deg}^{-2}$ new Lyman-α quasars acquired by other selections (mainly objects with the QSO_PTF bit set). These results are likely robust for CORE targets (given the caveats discussed in the previous paragraph). Lyman-α quasar target density may fluctuate across the survey with the availability of PTF imaging (see §4.2.1), so SEQUELS is a reasonable but imperfect estimate of the success rate for new

Figure 17. The redshift distribution of quasars from SEQUELS. Red lines represent all quasars identified in SEQUELS, blue lines represent quasars targeted just by the CORE algorithm, and solid lines represent all quasars that would have been assigned a fiber by the SEQUELS targeting algorithm (i.e., including known SDSS or BOSS quasars that do not need to be reobserved as they have the DO_NOT_OBSERVE bit set). Dashed (dotted) lines represent quasars that were (were not) previously spectroscopically confirmed in the SDSS or BOSS. The solid lines, which are the sum of the dotted and dashed lines, are quantified in columns 3 and 6 of Table 5 and have been completeness-corrected as described in that table.

Figure 18. The (i-band) absolute-magnitude-redshift plane for quasars targeted in SEQUELS. The blue crosses depict new quasars that would be observed as part of SDSS-IV/eBOSS. The other points represent quasars that would be targeted by eBOSS but that would not receive a fiber due to being previously observed in SDSS-I/II (orange) SDSS-III (red) or in both (brown; mostly ancillary targets or QSO_KNOWN_SUPPZ targets; see Dawson et al. 2013). The lines track quasars representative of the extremes of SDSS target selection between $i = 18$ (purple) and $i = 22$ (green). The grey box illustrates the power of eBOSS for detecting new quasars in the CORE redshift range. All magnitudes are based on PSF fluxes, and have been de-extincted. Absolute magnitudes have been K-corrected to $z = 2$ using Table 4 of Richards et al. 2006 and assume $H_0 = 70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$.

QSO_PTF Lyman-α quasars in eBOSS. In particular, the target density of QSO_PTF sources was 35 deg$^{-2}$ in SEQUELS but is expected to be close to 20 deg$^{-2}$ across the entire eBOSS footprint (see §5.1). The expected density of new $z > 2.1$ quasars from the eBOSS QSO_PTF program is therefore quoted as 3–4 deg$^{-2}$ in the abstract of this paper. There are also reasons to believe, however that results from SEQUELS may underestimate the success of eBOSS. Most notably, our companion surveys such as TDSS (Morganson et al. 2015) will target some Lyman-α quasars in addition to those targeted by the QSO_EBOSS_CORE and QSO_PTF approaches (see, e.g., J. Ruan et al. 2016, in preparation).

5.3. Overall characteristics of eBOSS quasars

Beyond the cosmological goals of eBOSS, the quasar sample produced by SDSS-IV should be unparalleled, exceeding the depth and numbers of any previous quasar sample. As there is likely to be significant interest in the nature of eBOSS for quasar science, quasars observed as part of SEQUELS are broadly characterized in this section. Because SEQUELS observations were conducted in tandem with BOSS, some quasars that would not normally receive a fiber in eBOSS because of existing BOSS spectroscopy did receive a SEQUELS fiber. Throughout this section, we treat such objects as if they had the DO_NOT_OBSERVE bit set by correctly incorporating (non-SEQUELS) redshifts and classifications from the DR12 quasar catalog (I. Pâris et al. 2016, in preparation), as also described in the discussion of Table 3 in §5.2.

The redshift distribution of quasars in SEQUELS is plotted in Fig. 17 and is similar to the expectation from Fig. 4. The measurements of the SEQUELS $N(z)$ are listed in Table 5. When combined with the expected
Table 5

| z     | CORELS quasars | All quasars |
|-------|----------------|-------------|
|       | Nraw | N  | dN  | Nraw | N  | dN  |
| 0.05  | 3    | 3.8 | 0.001 | 4    | 4.8 | 0.001 |
| 0.15  | 6.3  | 0.002 | 14   | 14.3 | 0.004 |
| 0.25  | 28.1 | 0.016 | 62   | 65.1 | 0.019 |
| 0.35  | 70.8 | 0.025 | 189  | 198.8 | 0.059 |
| 0.45  | 310.0 | 0.108 | 361  | 404.0 | 0.120 |
| 0.55  | 445.2 | 0.155 | 575  | 639.2 | 0.190 |
| 0.65  | 632.4 | 0.221 | 751  | 834.4 | 0.249 |
| 0.75  | 817.2 | 0.285 | 922  | 1007.2 | 0.300 |
| 0.85  | 1118.7 | 0.390 | 1215 | 1350.7 | 0.402 |
| 0.95  | 1386.6 | 0.484 | 1303 | 1528.6 | 0.455 |

Note. — (1) Redshift; (2) Number of SEQUELS quasars selected by the CORE targeting algorithm; (3) As for column (2) but completeness-corrected; (4) As for column (3) but normalized; (5-7) As for columns (2-4) but for SEQUELS quasars selected by any targeting algorithm. Completeness corrections are conducted by multiplying the counts of all newly identified CORE quasars by 298.5/237.1 (see the first row of Table 3). Counts of all other quasars in SEQUELS are not completeness-corrected as they are dominated by quasars that were previously confirmed in the SDSS or BOSS—such quasars are effectively assigned a fiber 100% of the time. A quasar is defined using QSO or QSO_27 as in Table 4.

Fig. 19. Histograms of the surface density of CORE quasar targets predicted by the regression models described in §6.1 (the "PSD"). The blue histogram represents the NGC, with some blue lines depicting the window within which angular fluctuations in quasar target density meet the ≤15% requirement of 2.2. The green histogram and dotted green lines depict the same quantities for the SGC. The histograms demonstrate that ~97% (~77%) of the NGC (SGC) footprint meets the homogeneity requirements of eBOSS (see 2.2). The PSD and the fractional deviation from the mean PSD in each pixel are depicted as a sky map in Fig. 20.

6. Tests of the homogeneity of the CORE quasar sample

In order to perform clustering measurements to characterize the BAO scale, it is necessary to mimic the angular distribution imposed by the target selection. This survey "mask" is often expressed as a random catalog, or control sample, that mimics the characteristics of the targeted population but in the absence of any clustering. At its simplest, this process involves uniformly distributing random points over the footprint of the target imaging. This simple approach, however, is rarely adequate because survey systematics such as seeing, sky brightness, Galactic extinction etc. alter the target density in a complex manner. A related issue is that zero-point calibrations in SDSS imaging can vary across the survey, also producing non-cosmological variations in target density.

6.1. Target density fluctuations due to systematics

Previous studies of large-scale galaxy clustering over the SDSS footprint (e.g., Ross et al. 2011) have demon-
stratified that systematics that produce target density variations at a level of ~15% or less can be controlled for by weighting the random catalog by a model of the effect of that systematic. Beyond the 15% level, systematics become more difficult to “weight” for, perhaps because some major systematics are covariant. When the effect of systematics exceeds the 15% level, that area of the survey may have to be excised from clustering analyses.

As part of eBOSS target selection, a set of regression tests have been devised to study how possible systematics in SDSS and WISE imaging may affect target density—and whether such effects are below the ~15% level that could be modeled with a suitable weighting scheme. The slate of systematics, which represents a reasonable (but not necessarily exhaustive) list of quantities that could bias eBOSS target density, is further detailed in a companion paper (Prakash et al. 2015b). Relevant to the WISE imaging: the systematics include the median numbers of exposures per pixel, the fraction of exposures contaminated by the Moon, and the total flux per pixel, all in the W1 band (W1median, moon, lev, Wmedian). Relevant to the SDSS imaging; the systematics include the FWHM and background sky-level in SDSS z-band, which are used to track the quality of the seeing and the sky brightness. Additional systematics include Galactic latitude (to map the density of possible contaminating stars) and Galactic dust (extinction in the r-band is used to represent this systematic).

The adopted regression technique is also detailed in Prakash et al. (2015b). Briefly, the potential eBOSS imaging footprint is deconstructed into equal-area pixels of 0.36 deg². The eBOSS CORE quasar target density and the mean value of each systematic is determined for each of these pixels. The observed surface density (SDobs) of eBOSS CORE quasar targets in each pixel can be expressed as a linear model of systematics

$$SD_{\text{obs}} = S_0 + \sum_{i=1}^{7} S_i x_i + \epsilon,$$  \hspace{1cm} (8)

where $S_0$ is the mean target density across the pixels, $S_i$ is the weight accorded to fluctuations in target density $(x_i)$ due to systematic $i$, and $\epsilon$ is the combined effect of noise and variance, which is approximated as a Gaussian. Multi-linear regression is used to determine $S_0$ and $S_i$ by minimizing the value of reduced $\chi^2$ across the pixels. This regression is conducted separately in each Galactic hemisphere, such that different coefficients are derived for the NGC and SGC regions of the SDSS imaging.

Once the coefficients of the linear regression model for systematics have been established, a statistic designated the Predicted Surface Density or “PSD” is computed. The PSD is obtained by using $S_0$ and $S_i$ to calculate what the eBOSS CORE quasar density should be in a given pixel if the linear regression model is an adequate description

$$\text{PSD} = S_0 + \sum_{i=1}^{7} S_i x_i.$$  \hspace{1cm} (9)

Fig. 19 presents a histogram of the CORE quasar PSD as predicted from the derived linear regression model coefficients across all of the systematics. A total of 96.7% of the SDSS imaging footprint in the NGC fluctuates in CORE quasar PSD at less than 15%. The corresponding fraction is 76.7% in the SGC footprint.

Fig. 20 illustrates these deviations on the sky using a map of the PSD statistic, which serves to illustrate the most problematic areas of the SDSS footprint for eBOSS. The right-hand panel of Fig. 20 approximates the “mask” that will be necessary to ameliorate the effects of systematics on clustering measurements that use eBOSS CORE quasars. The effective area or random catalog in each region of the eBOSS footprint can be re-weighted by the values displayed in the right-hand panel of Fig. 20, although regions that deviate by more than 15% from expectation may need to be excised from the survey in only the area that could be useful for targeting, due to scheduling constraints, is considered (see Dawson et al. 2015)}
Figure 21. Systematics distributions and linear regression surface density models for eBOSS CORE quasar targets. Each row of panels corresponds to one of the systematics outlined in §6.1 (“Latitude” refers to Galactic latitude). The left-hand (right-hand) column of panels displays results for these systematics for the NGC (SGC). The green histograms depict the distribution of pixels as a function of the mean value of each systematic in each pixel. The number of pixels is quantified on the right-hand axis of each plot. The red data points and blue lines depict, instead, measures of the Residual SD (Eqn. 10), which is quantified on the left-hand axis of each plot. The points are the measured values of the Residual SD averaged over 4000 sky pixels in the NGC or 2000 pixels in the SGC. The error bars depict the standard error on the mean across the pixels. The lines show the best-fit regression models. A linear regression model appears to be an adequate description of how each displayed systematic affects eBOSS CORE quasar target density.
order to reach the target density variation requirement of \([4.2] \). The central panel of Fig. 20 is a particularly clear illustration of why the PSD is recessed separately in the NGC and SGC regions—the NGC appears to be more robust to systematics than the SGC.

To determine whether a linear regression adequately models the effect of systematics on the target density of eBOSS CORE quasars, the statistics designated the Reduced_PSD, and the Residual_PSD in \cite{Prakash2015} can be calculated. The Reduced_PSD is derived from the PSD by omitting the \(j\)'th systematic term when calculating the PSD—in order to represent the deviation from the PSD caused by each systematic. The difference between the PSD and the observed sky density of targets, called the Residual Surface Density, or “Residual SD,” is then calculated. If a linear model is an appropriate representation of the regression of a given systematic, then the Residual_PSD should be well-represented by a model with a slope of \(S_j\). Formally:

\[
\text{Reduced}_P SD_j = \text{PSD} - S_j \times x_j \\
\text{Residual}_P SD_j = \text{SD}_{\text{obs}} - \text{Reduced}_P SD_j. \tag{10}
\]

Fig. 21 shows how the CORE quasar Residual SD varies as a function of each of the individual systematics, together with the underlying distributions of those systematics. In general, a linear regression seems to be adequate for modeling variations in CORE quasar target density. Fig. 21 suggests that sky brightness, and, in particular, Galactic extinction, are the main culprits in causing variations in eBOSS CORE quasar target density. The SGC has a 68% range of \(r\)-band extinction of 0.075 to 0.19 with a median of 0.12, whereas the NGC has a 68% range of \(r\)-band extinction of 0.032 to 0.10, with a median of only 0.057. The corresponding numbers for \(z\)-band sky flux are 4.1 to 6.8 with a median of 5.1 in the SGC and 3.3 to 4.6 with a median of 3.8 in the NGC. The higher median and wider range of values of these systematics in the SGC are likely responsible for both the suppressed density of SGC targets and the larger RMS in predicted surface density that can be seen in Fig. 20. These systematics will act to reduce the effective depth of an exposure and hence to increase the error on the fluxes of a test object being assigned a quasar probability by the XDQS02 method. In effect, as the flux errors for a test object increase, the formal probability that the object is a quasar is reduced, and fewer objects are then assigned PQSO (\(z > 0.9\)) > 0.2 by XDQS02.

Table 6

Results of how zero-point fluctuations affect target density

| \(N^{-1}(\Delta N/\Delta m)\) | zero-point error fluctuation |
|-------------------------------|-----------------------------|
| \(u\) | 0.544 | 13 \times 10^{-4} | 2.8% |
| \(g\) | 0.856 | 9 \times 10^{-4} | 3.1% |
| \(r\) | 0.514 | 7 \times 10^{-4} | 1.4% |
| \(i\) | 0.475 | 7 \times 10^{-4} | 1.3% |
| \(z\) | 0.061 | 8 \times 10^{-3} | 0.2% |
| \(W\) | 0.223 | 20 \times 10^{-3} | 1.8% |

Note. — (1) Fractional deviation in target density that results from a \(\pm 0.01\) mag scatter in each band; (2) Zero-point RMS error in each band in magnitudes. Values for the SDSS are taken from D. Finkbeiner et al. (2016, in preparation); Values for the WISE stack are estimated from Jarrett et al. (2011). (3) 95% \((\pm 2\sigma)\) values in target density fluctuation corresponding to \(100\% \times 4 \times [N^{-1}(\Delta N/\Delta m)]\)

6.2. Target density fluctuations due to zero-point variations

A further requirement of eBOSS is that fluctuations in target density due to shifting zero-point calibrations across the SDSS imaging footprint are well-controlled. Similar to \([6.1]\) such fluctuations need to be kept below the 15% level (see also \([6.2]\)). To study how changes in zero-point affect the density of eBOSS CORE quasar targets, each of the bands used in the eBOSS CORE quasar selection is offset by \(\pm 0.01\) mags (i.e. scaled by 1% in flux) and the resulting fractional changes in target density are determined after re-running the target selection pipeline. Each SDSS band is tested individually. As the WISE bands are only incorporated into eBOSS CORE quasar target selection in a stack (see Eqn. 2), both \(W1\) and \(W2\) are simultaneously shifted by \(\pm 0.01\) mags and the result is reported as a single band (henceforth denoted \(W\)).

The resulting fractional fluctuations in target density from these offsets \((N^{-1}(\Delta N/\Delta m))\) can then be multiplied by the zero-point RMS error expected for the imaging calibrations used by eBOSS (see \([3]\)) to determine the expected RMS variation in number density due to zero-point calibrations shifting across the eBOSS footprint. We adopt the zero-point errors in \([u, g, r, i, z]\) of \([13, 9, 7, 7, 8]\) mmag RMS from D. Finkbeiner et al. (2016, in preparation) and conservatively estimate a zero-point error of 20 mmag RMS for the \(W\) stack (see Jarrett et al. 2011). Assuming that the zero-point errors can be modeled using a Gaussian distribution, 95% of CORE quasar targets in eBOSS will be within \(\pm 2\sigma\) of the expected RMS variation. In other words, 95% fractional variance in target density can be interpreted as meaning that 95% of the area of the sky is expected to be described by fluctuations of \(\pm 2\sigma\). Thus, the overall 95% fractional vari-

\[20\] This 15% limit is on the two-tailed distribution (i.e. between the peaks due to a positive and a negative fluctuation in zero-point)
ance in target density due to zero-point errors can be expressed (as a percentage) as $100\% \times 4 \times \text{[zero-point error]} \times [\text{N}^{-1}(\Delta N/\Delta m)]$. Table 6 displays the results of this analysis, which indicate that $g$-band is the least robust to zero-point variations when selecting eBOSS CORE quasars. Even $g$-band, however, causes a $(2\sigma)$ variation of only 3%, far less than the 15% limit outlined in §2.2. eBOSS CORE quasar target selection is thus completely robust to zero-point errors.

7. CONCLUSIONS AND SUMMARY

The fourth iteration of the Sloan Digital Sky Survey will include the extended Baryon Oscillation Spectroscopic Survey, a project with the overarching goal of using galaxies and quasars to measure the BAO scale across a range of redshifts. This paper details the construction of a sample of quasars that can provide the first 2% constraints on the BAO scale at redshifts $0.9 < z < 2.2$ through clustering measurements, referred to as the eBOSS “CORE” sample. The final eBOSS CORE algorithm, which is designed to be a homogeneous and reproducible selection, is:

1. Take all targets in the D. Finkbeiner et al. (2016, in preparation) recalibrations of SDSS imaging, which are stored in the calib.obj or “Data Sweep” format [Blanton et al. 2005].

2. Select PRIMARY point sources (objc.type==6) that have (de-extincted) PSF magnitudes of $g < 22$ or $r < 22$, a FIBER2MAG of $i > 17$, and good IMAGE.STATUS.

3. Apply the XDQSOz method of [Bovy et al. 2012] to these sources and restrict to objects with PQSO($z > 0.9$) $> 0.2$.

4. Force-photometer WISE imaging at the positions of the resulting sources using the Lang (2014) approach, or, equivalently, match to the force-photometered catalog of Lang et al. (2014).

5. Create band-weighted stacks from the fluxes of these sources using photometry from the SDSS $f_{\text{opt}} = (f_g + 0.8f_r + 0.6f_i)/2.4$ and from WISE $f_{\text{WISE}} = (f_{\text{w1}} + 0.5f_{\text{w2}})/1.5$.

6. Convert these flux stacks to magnitudes and restrict to sources with $m_{\text{opt}} - m_{\text{WISE}} \geq (g - i) + 3$

The resulting set of sources comprise the eBOSS CORE quasar sample. Not all such sources, however, are targets for spectroscopy in eBOSS. The eBOSS survey does not place a fiber on any target that has an existing good spectrum from earlier iterations of the SDSS (see §4.4.10).

This paper also describes a $z > 2.1$ quasar sample that can be used to refine the BAO scale measured from clustering in the Lyman-α Forest, referred to as the eBOSS “Lyman-α” sample. The various techniques used to target Lyman-α quasars for eBOSS are not designed to be homogeneous and reproducible, so are only discussed in full in the body of this paper (see, e.g., Fig. [1]).

The CORE and Lyman-α quasar targeting algorithms have been used to select targets for a spectroscopic survey over a large area in the SDSS NGC region, in order to test whether these algorithms meet the requirements for eBOSS. This $\sim 810\deg^2$ survey is known as the Sloan Extended Qusar, ELG and LRG Survey (SEQUELS). Observations over the first $\sim 300\deg^2$ of SEQUELS have been completed and visual inspections of all SEQUELS targets are used to project outcomes for eBOSS (see, e.g., Table [1]).

The algorithms developed in this paper meet all of the requirements of eBOSS quasar targeting that can be projected from SEQUELS. In particular, the requisite number densities for eBOSS are $> 58\deg^{-2}$ uniformly selected quasars in the redshift range $0.9 < z < 2.2$, leaving as many fibers as possible to target new Lyman-α quasars. Results from SEQUELS suggest that eBOSS will recover $\sim 70\deg^{-2}$ $0.9 < z < 2.2$ quasars using the CORE selection technique and $\sim 10\deg^{-2}$ new $z > 2.1$ quasars from various Lyman-α selection techniques. In addition, the adopted SDSS and WISE imaging is sufficiently homogeneous for quasar targeting that the statistics projected from SEQUELS are expected to remain valid over close to 90% of the eBOSS footprint. The few eBOSS quasar sample requirements or assumptions that are not discussed in this paper are verified elsewhere. These include a survey area of at least $7500\deg^2$ and precise and accurate redshifts for quasars (see [Dawson et al. 2015]).

Ultimately, eBOSS will uniformly target in excess of 500,000 quasars in the redshift range $0.9 < z < 2.2$, exceeding previous such clustering samples by a factor of more than ten. Samples of new spectroscopically confirmed quasars across all redshifts in eBOSS will exceed 500,000 quasars, which will be at least three times larger than all previous samples across the eBOSS footprint in combination. At the conclusion of eBOSS, in excess of 800,000 confirmed quasars should have spectra from some iteration of the SDSS. In essence, eBOSS will be the next-generation quasar survey, and, in the wake of 20 years of observations from SDSS-I, II, III and IV, eBOSS will usher in the era of million-fold spectroscopic quasar samples.

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Lang, D., Hogg, D. W., & Schlegel, D. J. 2014, ArXiv e-prints, arXiv:1410.7397
Law, N. M., Kulkarni, S. R., Dekany, R. G., et al. 2009, PASP, 121, 1395
Linder, E. V. 2003, Phys. Rev. D, 68, 083504
Lupton, R. H., Gunn, J. E., & Szalay, A. S. 1999, AJ, 118, 1406
MacLeod, C. L., Ivezić, Ž., Kochanek, C. S., et al. 2010, ApJ, 721, 1014
MacLeod, C. L., Brooks, K., Ivezić, Ž., et al. 2011, ApJ, 728, 26
McGreer, I. D., Helfand, D. J., & White, R. L. 2009, AJ, 138, 1925
McGreer, I. D., Jiang, L., Fan, X., et al. 2013, ApJ, 768, 105
McLure, R. J., & Dunlop, J. S. 2004, MNRAS, 352, 1390
Morgan, E., Green, P. J., Anderson, S. F., et al. 2015, ApJ, 806, 244
Netzer, H., & Trakhtenbrot, B. 2007, ApJ, 654, 754
Newberg, H. J., & Yanny, B. 1997, ApJS, 113, 89
Noterdaeme, P., Petitjean, P., Carithers, W. C., et al. 2012, A&A, 547, L1
Oke, E. O., Laher, R., Law, N., et al. 2012, PASP, 124, 62
Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713
Osmer, P. S. 1982, ApJ, 253, 28
Palanque-Delabrouille, N., Yeche, C., Myers, A. D., et al. 2011, A&A, 530, A122
Palanque-Delabrouille, N., Magneville, C., Yeche, C., et al. 2013a, A&A, 551, A29
Palanque-Delabrouille, N., Yeche, C., Barde, A., et al. 2013b, A&A, 559, A85
Palanque-Delabrouille, N., Magneville, C., Yeche, C., et al. 2015, ArXiv e-prints, arXiv:1509.05607
Páris, I., Petitjean, P., Aubourg, É., et al. 2014, A&A, 563, A54
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, A16
Prakash, A., Licquia, T. C., Newman, J. A., & Rao, S. M. 2015a, ApJ, 803, 105
Prakash, A., Licquia, T. C., Newman, J. A., et al. 2015b, ArXiv e-prints, arXiv:1508.04478
Rau, A., Kulkarni, S. R., Law, N. M., et al. 2009, PASP, 121, 1334
Rengstorf, A. W., Brunner, R. J., & Wilhite, B. C. 2006, AJ, 131, 1923
Rengstorf, A. W., Mufson, S. L., Abad, C., et al. 2004a, ApJ, 606, 741
Rengstorf, A. W., Mufson, S. L., Andrews, P., et al. 2004b, ApJ, 617, 184
Richards, G. T., Fan, X., Schneider, D. P., et al. 2001, AJ, 121, 2308
Richards, G. T., Fan, X., Newberg, H. J., et al. 2002, AJ, 123, 2945
Richards, G. T., Strauss, M. A., Fan, X., et al. 2006, AJ, 131, 2766
Richards, G. T., Myers, A. D., Gray, A. G., et al. 2009a, ApJS, 180, 67
Richards, G. T., Deo, R. P., Lacy, M., et al. 2009b, AJ, 137, 3884
Ross, A. J., Ho, S., Cuesta, A. J., et al. 2011, MNRAS, 417, 1350
Ross, N. P., Myers, A. D., Sheldon, E. S., et al. 2012, ApJS, 199, 3
Ross, N. P., McGreer, I. D., White, M., et al. 2013, ApJ, 773, 14
Sandage, A. 1965, ApJ, 141, 1560
Sandage, A., & Luyten, W. J. 1969, ApJ, 155, 913
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Schlafly, E. F., Finkbeiner, D. P., Jurić, M., et al. 2012, ApJ, 756, 158
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schmidt, K. B., Marshall, P. J., Rix, H.-W., et al. 2010, ApJ, 714, 1194
Schmidt, M. 1963, Nature, 197, 1040
Schmidt, M., Schneider, D. P., & Gunn, J. E. 1986, ApJ, 306, 411
Schneider, D. P., Richards, G. T., Hall, P. B., et al. 2010, AJ, 139, 360
Scroton, R., Johnston, D., Dekel, D., et al. 2002, ApJ, 579, 48
Seo, H.-J., & Eisenstein, D. J. 2003, ApJ, 598, 720
Sesar, B., Ivezić, Ž., Lupton, R. H., et al. 2007, AJ, 134, 2236
Shen, Y., Greene, J. E., Strauss, M. A., Richards, G. T., & Schneider, D. P. 2008, ApJ, 680, 169
Slosar, A., Font-Ribera, A., Pieri, M. M., et al. 2011, JCAP, 9, 1
Slosar, A., Irsic, V., Kirkby, D., et al. 2013, JCAP, 4, 26
Smeel, S. A., Gunn, J. E., Uomoto, A., et al. 2013, AJ, 146, 32
Stern, D., Eisenhardt, P., Góriján, V., et al. 2005, ApJ, 631, 163
Stern, D., Assef, R. J., Benford, D. J., et al. 2012, ApJ, 753, 30
Stoughton, C., Lupton, R. H., Bernardi, M., et al. 2002, AJ, 123, 188
Swanson, M. E. C., Teegmark, M., Hamilton, A. J. S., & Hill, J. C. 2008, MNRAS, 387, 1391
Trichas, M., Green, P. J., Silverman, J. D., et al. 2012, ApJS, 200, 17
Usher, P. D. 1978, ApJ, 222, 40
van den Bergh, S., Herbst, E., & Pritchet, C. 1973, AJ, 78, 375
Vanden Berk, D. E., Richards, G. T., Bauer, A., et al. 2001, AJ, 122, 549
Vanden Berk, D. E., Wilhite, B. C., Kron, R. G., et al. 2004, ApJ, 601, 692
Vikas, S., Wood-Vasey, W. M., Lundgren, B., et al. 2013, ApJ, 768, 38
Voges, W., Aschenbach, B., Boller, T., et al. 1999, A&A, 349, 389
Warren, S. J., Hewett, P. C., Irwin, M. J., McMahon, R. G., & Bridgeland, M. T. 1987, Nature, 325, 131
White, M., Myers, A. D., Ross, N. P., et al. 2012, MNRAS, 424, 933
White, R. L., Becker, R. H., Gregg, M. D., et al. 2000, ApJS, 126, 133
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Yan, L., Donoso, E., Tsai, C.-W., et al. 2013, AJ, 145, 55
York, D. G., Adelman, J., Anderson, Jr., J. E., et al. 2000, AJ, 120, 1579
York, D. G., Khare, P., Vanden Berk, D., et al. 2006, MNRAS, 367, 945