NOAO Observing Proposal *Survey proposal* **Panel:** *For office use.*
Date: March 31, 2014 **Category:** Cosmology

The DECam Legacy Survey of the SDSS Equatorial Sky

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Abstract of Scientific Justification *(will be made publicly available for accepted proposals)***:**
We propose to create a public optical imaging survey to complement the vast spectroscopic database of ∼2.5 million extragalactic targets created by the SDSS, SDSS-II and SDSS-III/BOSS surveys and the start of the SDSS-IV/eBOSS survey. Using DECam, we will image 6700 $\deg^2$ of the SDSS/BOSS extragalactic footprint that lies in the region $-20 < \delta < +30°$ to depths of $g = 24.7$, $r = 23.9$, and $z = 23.0$ AB mag (5-σ point-source). The goal is to create a high quality multicolor imaging dataset that will be significantly deeper and have better image quality than SDSS or Pan-STARRS. Our survey will enable transformational studies of the dark and baryonic matter distribution in galaxy halos, focusing on the key issues of feedback and halo growth in the evolution of galaxies and AGN. The data will also be useful for studies of the halo and satellites of the Milky Way. In addition to providing a legacy dataset that will greatly enhance the value of the existing SDSS spectroscopy, our proposed survey will enable target selection within this footprint for the future Dark Energy Spectroscopic Instrument survey, which aims to provide spectra of additional tens of millions of galaxies and QSOs. Given its present and future scientific uses, this survey will be among the highest impact projects if approved by the NOAO Survey Program.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-4m	DECam	8	all	Jul - Dec	2014B
2	CT-4m	DECam	14	all	Jan - Jun	2015A
3	CT-4m	DECam	8	all	Jul - Dec	2015B
4	CT-4m	DECam	14	all	Jan - Jun	2016A
5	CT-4m	DECam	7	all	Jul - Dec	2016B
6	CT-4m	DECam	13	all	Jan - Jun	2017A

Scheduling constraints and non-usable dates *(up to four lines).*

None. We require 18 dark nights (for g-band), 18 dark-grey nights (for r-band), and 28 grey-bright nights (for z-band). One-third of the footprint is in the Fall semester, two-thirds in the Spring.

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

SDSS has demonstrated the great leverage that the combination of wide-field spectroscopic and imaging surveys has on a wide range of astrophysical problems. Unfortunately, for the current generation of surveys, the footprints of imaging and spectroscopy are amazingly disjoint, with the majority of wide-field spectroscopy lying in the northern+equatorial sky (Fig. 1). We therefore propose to create a public imaging survey to complement the expansive SDSS spectroscopy in a large equatorial footprint, greatly enhancing the science reach of the existing spectroscopy.

The SDSS Spectroscopic Legacy: The SDSS-I,II,III/BOSS surveys contain ∼2.8 million spectra, including 300,000 unique stars, 700,000 galaxies at $z < 0.2$, 500,000 galaxies at $0.2 < z < 0.5$, 1 million galaxies at $z > 0.5$, 100,000 QSOs at $z < 2$, and 200,000 QSOs at $z > 2$ (`http://sdss3.org`). The median extragalactic redshift is now 0.5! SDSS-IV/eBOSS (2014-2020) will add another 600,000 galaxies at $0.6 < z < 1$ and 750,000 QSOs at $z > 0.9$. SDSS-III will be fully public by the end of 2014; SDSS-IV will continue with periodic data releases. While the bulk of SDSS-I spectroscopy was of nearby galaxies ($r < 17.77$; i.e., 4-5 magnitudes brighter than the imaging detection limit), BOSS pushed much fainter, targeting galaxies to $i = 19.9$ and QSOs to $g = 22$, near the limits of the original SDSS imaging (Dawson et al. 2013); eBOSS goes even fainter. While adequate for the study of large-scale structure, the full science impact of these data is limited by the depth and quality of the existing imaging. We no longer have precise photometry, well-resolved size measurements, detailed morphologies, or environmental measures for the bulk of the sample.

DECam can remedy this situation by imaging two-thirds of the BOSS footprint to magnitudes suitable for the study of the $z > 0.5$ Universe. By imaging 1.5–2 magnitudes fainter in three optical bands, we can increase the number of $z > 0.5$ ($z > 1$) galaxies by a factor of 30 (600) over SDSS (Fig. 3b). Measuring $g - r$ vs. $r - z$ colors cleanly isolates $z > 0.5$ galaxies; the optical photometry coupled with *WISE* measures stellar masses and AGN activity. The improved image quality (FWHM≈1″) and depth will resolve morphologies and structural parameters for all SDSS spectroscopic galaxies.

Spectroscopy complements deep imaging; it provides: robust redshifts; a crisp 3-d view of large-scale structure; dynamical information through velocity dispersions; spectral diagnostics of stellar populations, star formation rates, and nuclear activity; and probes of the intergalactic medium through absorption line studies. Here, we describe a few of the many projects that this combination of data sets enables, focusing on key issues in galaxy formation: feedback and halo growth.

Halo Gas Through Cosmic Time: Galaxy formation is regulated by the outflows and inflows between the luminous galaxies and the tenuous gas resevoirs surrounding them. This circumgalactic medium is best probed by absorption along lines of sight to background quasars. By connecting the absorber systems to their host galaxies, we can investigate gas accretion and outflows around galaxies of different types. SDSS spectra have already yielded >50,000 MgII absorption line systems

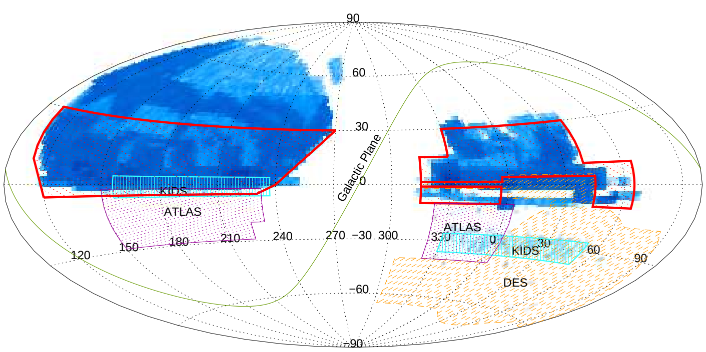

Figure 1: The 6200 deg^2 equatorial footprint for this proposed survey, shown as the red boxes, overlaps 2/3 of the space volume of all existing extragalactic spectroscopy (blue scale, showing the logarithmic density of spectroscopic redshifts $z > 0.3$ from SDSS-I, SDSS-II, SDSS-III/BOSS, 2dF and WiggleZ). The Dark Energy Survey footprint (orange hashed region) will provide an additional 500 deg^2 of overlap with the blue region. KIDS-N overlaps 780 deg^2 of the proposed footprint, but ATLAS and KIDS-S lie outside.

at $0.4 < z < 2.5$ toward background QSOs (Zhu & Menard 2013), and eBOSS will increase the number of sightlines to nearly a million. By cross-correlating 2,000 absorbers at $z \sim 0.5$ with SDSS photometric galaxies, Lan et al. (2014) extracted new relations between galaxy properties and their surrounding gas (Fig. 2a). We will dramatically improve this type of analysis by extending its reach from $z{\sim}0.5$ to $z{\sim}2$, sampling the full range of ~100,000 identified absorbers. This will map the cosmic evolution of halo gas as a function of redshift, making it possible to understand its dpendence on galaxy type, orientation, luminosity, star-formation rate, environment, etc.

Galaxy Halos Through Cosmic Time: The relationship between the physical properties of galaxies and the dark matter halos in which they reside is a key problem in galaxy evolution. The contents (and shapes) of galaxy dark matter halos can be revealed from the cross-correlation of spectroscopic and imaging maps (e.g., Eisenstein et al. 2005, Tal et al. 2014) and from galaxy-galaxy weak lensing (e.g., Mandelbaum et al. 2013). These methodologies benefit substantially from deeper imaging; the precision typically scales as $\sqrt{N_{gal}}$. Higher precision is crucial: variations in clustering as a function of galaxy properties are often only of order 10%, so distinguishing between models requires percent-level clustering measurements. Our proposed depth of $z = 23$ (e.g., $\sim 0.5L^*$ at z=0.7) will increase these samples by factors of 30 or more (Fig. 3b).

Cross-correlation studies use angular correlations to tie deep photometric catalogs to overlapping spectroscopic maps, measuring the mean environments and clustering of galaxies and AGN with great accuracy. SDSS has provided high-precision results at lower redshift using these techniques, e.g., measuring the mean environment of galaxies as a function of luminosity, color, and scale (Hogg et al. 2003, Eisenstein et al. 2005, Masjedi et al. 2006, Jiang et al. 2012) and interpreting this to constrain halo populations and merger rates (Zheng et al. 2009, Watson et al. 2012). The proposed survey will extend this to far larger (>10-100×) spectroscopic and photometric samples at high redshift, measuring the satellite distributions around the central galaxies as a function of redshift, luminosity, stellar mass, color, major axis orientation, velocity dispersion, [OII] emission line equivalent width, etc. Cross-correlation also enables more robust clustering measurements around rare spectroscopic populations (e.g., E+A galaxies - Hogg et al. 2006; quasars - Fig. 2b), and the ability to calibrate galaxy redshift distributions from imaging data. This latter can significantly improve the calibration of photometric redshifts (Newman et al. 2008, Ménard et al. 2013).

Counts of galaxies (selected in photo-z bins) around galaxies of known redshifts provide direct estimates of the environments of the spectroscopic samples. One can then study the mean stellar populations of galaxies as a function of environment by stacking spectra (Eisenstein et al. 2003, Choi et al. 2014). With over a million $z > 0.5$ massive galaxy spectra, the available S/N in stacked spectra is amazingly high ($\gg 300$ per pixel), even when divided into many subpopulations, allowing one to probe subtle changes in the stellar populations with environment.

Finally, deep imaging data can directly measure galaxy halo masses for galaxies with spectroscopic redshifts using galaxy-galaxy weak lensing (Mandelbaum et al. 2006). Secure lens redshifts (and hence rest-frame properties) are key to using weak lensing data and detailed imaging for galaxy evolution studies. This study benefits from the spec-z and photometric overlap; mismatched samples where the lens photo-z is bootstrapped from calibration fields can be significantly biased (e.g., Nakajima et al. 2012).

The Evolution of Galaxy Clusters: SDSS has obtained redshifts of 1.5 million massive galaxies. These are often the central and brightest galaxies in groups and clusters; however, current imaging often cannot detect their satellites. The proposed imaging will significantly improve stellar mass models for these galaxies and enable a sensitive search for cluster members around them. We will construct volume-limited cluster catalogs out to $z \approx 0.7$, with richer systems detected to yet higher redshifts. Extrapolating from the 1700 clusters found in the SDSS Stripe 82 imaging

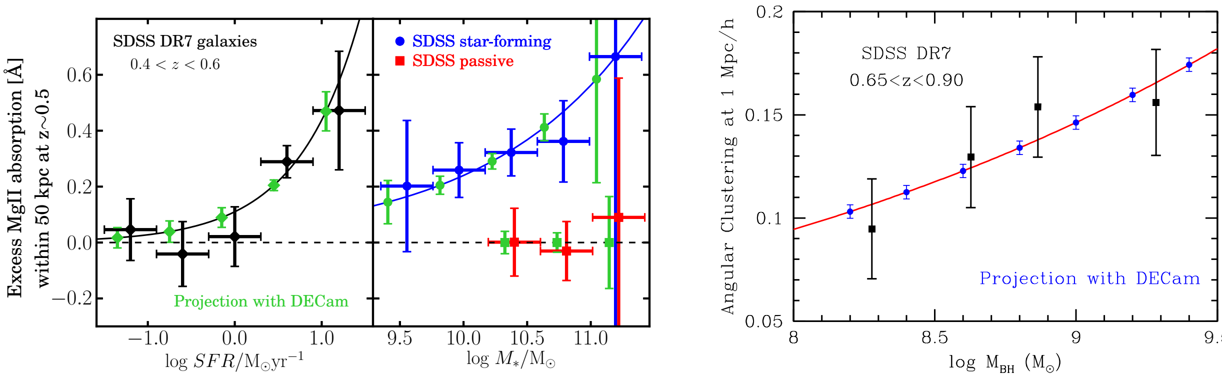

Figure 2: ***Left:*** Excess MgII absorption measured within 50 kpc of $z \sim 0.5$ galaxies, as a function of star formation rate and stellar mass (Lan et al. 2014). These relations come from 2000 pairings of MgII absorbtion sytems with galaxies from SDSS imaging. Deeper DECam imaging will dramatically improve on these measurements, using MgII absorption over a much wider redshift range and reaching to less luminous galactic counterparts. We will thereby probe the galaxy-gas connection as a function of cosmic time and relate it to the star formation history of the Universe. ***Right:*** The angular clustering at $1h^{-1}$ Mpc scale of galaxies around 4000 SDSS DR7 QSOs at $0.65 < z < 0.9$ (black points, Krolewski & Eisenstein, in prep), as a function of the QSO black hole mass determined from Hβ line widths (Shen & Liu 2012). The tentative (2σ) positive slope suggests a correlation between halo mass and black hole mass. This relied on a sample of 850K galaxies selected by color to be at $z > 0.6$. With the proposed DECam data, we can extend this analysis to $z > 1$ QSOs and fainter galaxies, gaining a 100-fold increase in pairs and making it possible to study detailed trends as a function of QSO properties (blue points) and redshift.

(Rykoff et al. 2013), we expect to identify ∼50,000 clusters, nearly all of which will have spectroscopic redshifts available from SDSS. Spectroscopy provides three key benefits not available to photometric-only surveys: 1) one can calibrate cluster masses by stacked velocity dispersion measurements (e.g., Becker et al. 2007), 2) one can test general relativity by the comparison of the velocity field around clusters to the weak lensing shear mass profile (Lam et al. 2012, Zu et al. 2013), and 3) the galaxy and quasar spectroscopic data enables calibration of cluster masses by detecting the weak-lensing magnification of the luminosity function of background sources (Menard et al. 2010, Coupon et al. 2013). Magnification-based methods have systematics uncertainties that are completely independent from the shape and photo-z systematics expected to dominate the error budget of photometric-only surveys like DES or LSST, thereby enabling a critical consistency test with these surveys.

The Evolution of AGN: The evolution of galaxies is tightly linked to the evolution of their central super-massive black holes. The most luminous AGN may represent a short-lived but crucial evolutionary phase in the formation of the present-day massive galaxies (Hopkins et al. 2006). A comprehensive investigation of this relationship requires large statistical samples of AGN and galaxies that span the same redshift range and for which robust and accurate dark halo masses are available (through cross-clustering and/or galaxy-galaxy lensing measurements). Spectroscopy is key, as it provides estimates of accretion rates, black hole masses, and galaxy properties such as stellar luminosities and star-formation rates. This proposed survey will create such a sample over a wide range of redshift, AGN type, and AGN/galaxy luminosity, using the million spectroscopic AGN from SDSS-I to IV. It also leverages the upcoming eROSITA all-sky survey, which will make a near-complete catalog of X-ray bright AGN over the last 8 Gyr. At the proposed depths, we will identify ∼ 97% of AGN (∼ 95% type 2 AGN; see Brusa et al. 2010) dramatically improving our ability to: (i) characterize the rarest AGN populations (high- z QSOs, super-Eddington accretors, Compton thick AGN, etc.); (ii) compile cross-identification of AGN across wide parts of the electromagnetic spectrum; (iii) study how the overall spectral energy distribution (SED) of AGN, and thus the physical conditions in the vicinity of SMBH, changes with redshift, luminosity, host galaxy properties and environment (e.g., Aird et al. 2012).

The Milky Way Halo and Environs: The SDSS revolutionized the study of the Milky Way, finding numerous stellar halo streams (e.g. Newberg et al. 2002; Yanny et al. 2003; Grillmair 2009) and doubling the number of dwarf galaxies to 25 (Willman 2010). Pan-STARRS survey is expected to find several more (Laevens et al. 2014). This DECam proposal combined with DES will map twice as far out into the galactic halo over 11,000 deg^2, increasing the volume of the MW explored by a factor of $\sim$4 relative to SDSS+Pan-STARRS.

We will test the predictions that stellar halo substructure dramatically increases with distance (Bell et al. 2008; Helmi et al. 2011). Our photometric parallax-based maps will extend to $\sim$ 40 kpc using main sequence stars (Ivezic et al. 2008; Juric et al. 2008), $\sim$ 80 kpc using gr-selected main sequence turnoff stars (Bell et al. 2008), and $\sim$ 150 kpc using ugr-identified BHB stars where u-band is available (Ruhland et al. 2011). The deeper data on known streams (e.g. Pal 5, Odenkirchen et al. 2003; Grillmair & Dionatos 2006) will be used to test for the presence of "missing satellites" via their signatures in these streams (Carlberg 2009; Yoon et al. 2011). We expect to find $4-10$ new dwarf galaxies in these data. Each dwarf galaxy discovery immediately adds years of Fermi integration to the search for dark matter detection via gamma rays (Fermi-LAT 2014).

Given the 10-year time baseline between SDSS and DECam, proper motions will be measured to accuracies of a few milliarcsec per year for stars 2 mag fainter than the GAIA limits.

A WISE Legacy: Our dataset will provide a critical improvement in the utility of the mid-IR imaging data from the WISE satellite by providing deep z-band template images for matched photometry using the "Tractor" package (described in Exp. Des.). By optimally matching WISE to deep optical imaging, one can partially deblend the images and improve S/N in colors. Using SDSS r-band templates already shows substantial improvement, but DECam z-band will allow extraction of higher redshift sources. The WISE mission was recently extended and will quadruple the exposure time in the 3.4 and 4.6 μm bands in the next three years. With DECam, we will produce matched WISE photometry for hundreds of millions of z-band sources. Properly matched optical to mid-IR photometry will allow more robust estimation of stellar masses and improve photometric redshifts. It also allows high-fidelity selection of massive galaxies to $z \sim 1.5-2$ and nearly all luminous quasars.

A Legacy for the Present ... and Future: We are capable of making this high-impact dataset immediately public for general use. The survey proposed here will not only create the deepest survey of the equatorial SDSS footprint, but also be sufficient for identifying the primary LRG, ELG and QSO targets for the Dark Energy Spectroscopic Instrument (DESI) Key Project and for any possible public access time on the instrument. DESI, a 5000-fiber spectrograph destined for the Mayall telescope, will undertake a spectroscopic survey an order of magnitude larger than SDSS, measuring spectra and redshifts for 20 million emission line galaxies (ELGs), 4 million luminous red galaxies (LRGs) and 2 million QSOs. The survey is designed to probe the expansion history at $0 < z < 3.5$ using the baryon acoustic oscillation scale, and to map the dark matter and gravitational growth through redshift space distortions (Schlegel et al. 2011). DESI will have revolutionary capabilities for broad investigations on the origin and evolution of galaxies, Galactic structure, rare-object discovery, and result in one of the most complete high-z AGN catalogs to date (Pilachowski et al. 2012).

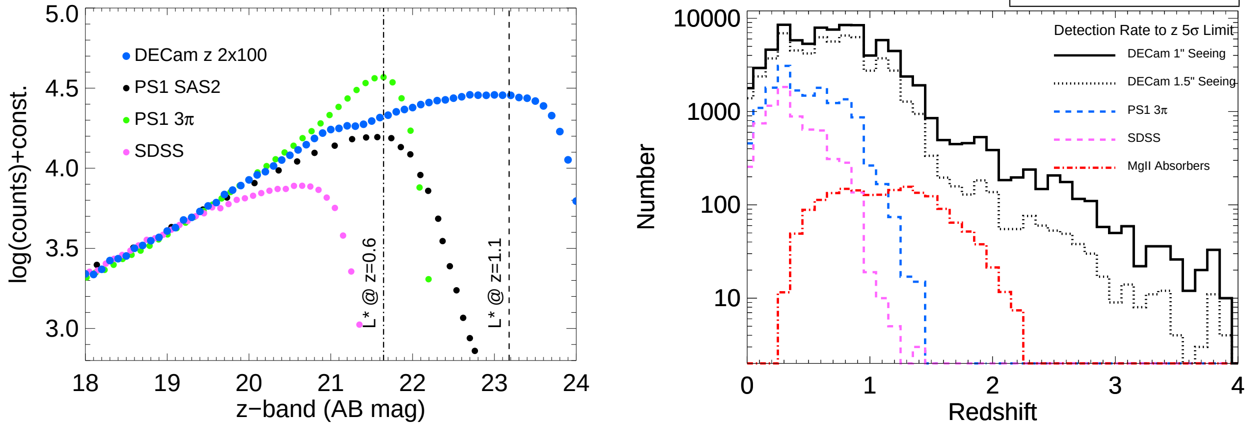

Figure 3: ***Left:*** z-band number counts of sources as a function of magnitude for the existing DECam data from our pilot study in 2013A (blue points). The flattening at $z \sim 21$ is due to the shallower slope of star counts as we look out of the Galactic disk. Counts from SDSS, Pan-STARRS 3π Survey (Schlafly; filled green circles), and the deeper SAS2 pointing of Pan-STARRS (Metcalfe et al. 2013; tied to Stripe 82; filled black circles) are also shown. The excess seen in the 3π counts results from a persistent false-detection problem in the stand-alone single-band Pan-STARRS data, which is mitigated by requiring multi-band detections. The proposed DECam imaging reaches the depth of sub-L^* galaxies at $z = 1$. ***Right:*** The observed redshift distribution $N(z)$ (based on zCOSMOS catalog) for galaxies selected to the z-band limit of our proposed DECam survey. The black solid- and dashed-lines shows the $N(z)$ for two values of the seeing and our proposed exposure time. Also shown is the distribution of MgII absorbers from the JHU-SDSS Metal Absorption Line Catalog (Zhu & Menard 2013), which is clearly not matched by the depths of the shallower Pan-STARRS 3π and SDSS imaging.

Experimental Design *Describe the survey experimental design and the observations planned in detail. Justify choice of telescope, instrument, and sensitivity goals in terms of the survey science goals. A key part of the survey proposal process is to justify the total duration of the program both in terms of the number of nights and the number and distribution of observing runs required. Please show explicitly how on-target exposure time, setup, and calibration requirements determine these parameters. Please do not include any allowance for bad weather. Based on a clear understanding of your observational strategy as outlined in this section, we will evaluate the need for augmenting the allocation to allow for bad weather.*

Survey Design Our goal is to create a public imaging dataset to greatly extend the science reach of the SDSS spectroscopic database. We propose to complete DECam imaging over the entire SDSS/BOSS/eBOSS footprint at $-20°\delta < +30°$. 6200 deg^2 of this 6700 deg^2 footprint will be observed; the remaining 500 deg^2 will be observed by DES to greater depth (Figure 1).

We will image in 3 bands (grz); this is the minimum number required to color-select galaxies by redshift and type and to reject galaxies at $z < 0.5$. The proposed depth provides: (i) good ($> 10\sigma$) detections of low-luminosity ($\sim 0.5L^*$) galaxies in the vicinity of galaxies at $z = 0.7$ and higher luminosity galaxies around QSOs at $z > 1$ (for cluster-finding, cross-clustering, and MgII analyses); (ii) good ($> 10\sigma$) detections of background galaxies for galaxy-galaxy lensing analyses; (iii) high signal-to-noise data for the measurement of structural parameters of galaxies with known redshifts (i.e., $> 10\sigma$/pixel) on the faintest $z = 20$ mag eBOSS targets; (iv) detections of nearly 100% of the *WISE* sources; (v) detections of 97% of the *eROSITA*-detected AGN. These requirements are met with depths of $g, r, z \approx 25.0, 24.0, 23.0$ AB mag (see Fig. 3a). The DECam median seeing of $\approx 1''$ will be a significant improvement (2×) over the existing SDSS data.

Exposure Times and Tiling Strategy: Our observing would be spread over all seasons and lunations: $g/r/z$ in dark/grey/bright time. Assuming an average airmass of 1.4 and slightly worse than the median seeing, the g, r, z depths require minimum total exposure times of 100, 100, and

200 seconds (see Table 1). Survey photometric uniformity requires a 3-pass tiling strategy with individual exposure times of $[t_g, t_r, t_z]$=[50,50, 100] sec (see Observational Details section). This requires a total of 64 clear nights (18 in g, 18 in r and 28 in z). The footprint covers 4000 deg^2 in the NGC and 2200 deg^2 in the SGC, requiring a time split of 41 A- and 23 B-semester nights.

"Tractor" Photometry: Galaxy photometry using optical and *WISE* mid-IR data is susceptible to large systematic errors in color due to differences in PSF and pixel sampling. Developed by Co-I Dustin Lang, the "Tractor" photometric formalism mitigates systematic error through a forward-modeling approach and global calibration (PSF and astrometry) at the pixel level of each dataset. "Tractor" photometry has been used for the bulk of targets in eBOSS, using SDSS+*WISE* data. We have begun a similar analysis using DECam+*WISE* data from our 2013A pilot survey, recovering substantially redder and fainter galaxies (especially faint LRGs).

Why DECam? The 3 deg^2 field-of-view and enhanced red sensitivity of DECam are unparalleled properties that are uniquely suited for the proposed program. Only the KPNO MOSAIC and CFHT Megacam imagers have the potential for a similar large-area survey in z-band, and both these instruments would be 5-10 times slower than DECam. We have confirmed that it is indeed possible to use DECam to δ=+30. Even at our northern limit, the extinction in g is only 20% worse than at zenith and the image quality will still be superior to SDSS. The ATLAS Survey lies mainly in the South and only goes to SDSS depths. The KIDS survey only covers 780 deg^2 of our footprint and will provide a useful u- and i-band complement, but lacks the area to accomplish our scientific goals.

The Need for Deeper Imaging: The Pan-STARRS 3π survey has imaged the sky north of $\delta > -30°$, including our whole footprint. However, as recently documented by Metcalfe et al. (2013), even the best seeing PanSTARRS data are only slightly deeper than SDSS in g and r. As show in in Table 1, the proposed DECam data will be 1-1.5 magnitudes deeper than Pan-STARRS 3π *in all three bands*. This is crucial for the science cases presented, e.g., to reach faint galaxy populations at $z > 0.5$. Pan-STARRS data will provide useful photometric calibration and important temporal comparisons for variability and proper motion studies, but are not sufficient for our proposed science.

TABLE 1: 5σ Point Source Depths (AB mag)

	Proposed Survey			Other Surveys		
	Exp.Time[1] (sec)	**DECam seeing 1"**	**DECam seeing 1.5"**	SDSS (DR8)	PS1 SAS2[2] (Best case)	DES
g-band[3]	**100**	**25.1**	**24.7**	23.1	23.4	26.5
r-band[4]	**100**	**24.3**	**23.9**	22.7	23.4	26.0
z-band[5]	**200**	**23.4**	**23.0**	20.7	22.4	24.7
Spectro area (deg^2)		**6,200**	**6,200**	10,000	10,000	500

[1] Exposure times and depths quoted are for two passes. 62% of the area will have *three* passes and hence 0.4 mag deeper. [2] 3π depths are likely to be ∼0.3 mag brighter, as the SAS2 test field has substantially better than median seeing (Metcalfe et al. 2013). [3] Assumes dark moon phase. [4] Assumes 7-day day moon. [5] Assumes 11-day moon.

Management Plan *Describe the overall organizational plan for conducting the proposed survey, including data reduction and analysis, preparation of survey deliverables, and staffing requirements. List the roles and responsibilities of the Co-Is with their anticipated time commitments directed to achieving the goals of the survey. You may also wish to detail external sources of support that will be used in the program. Please detail any use of non-NOAO observational facilities that are required to achieve the overall goals of the survey program.*

The project will be managed by the PIs David Schlegel and Arjun Dey, with leadership roles for Dustin Lang and Peter Nugent. The project team includes key people from the SDSS-III/BOSS, SDSS-IV/eBOSS, DES, eROSITA, and DESI collaborations who are: (a) experienced in successfully carrying out large survey programs; (b) knowledgeable about the DECam instrument and operational software; (c) experienced in the creation of pipelines and in reducing, analyzing and calibrating imaging data; (d) have a proven track record of delivering publicly useful data products in a timely manner; (e) experienced observers; and (f) outstanding scientists experienced in doing research with large and multiwavelength datasets.

Time Commitments: PIs Schlegel and Dey will each devote 1/2 of their research time to this project to manage the execution and data analysis. K. Honscheid & A. Walker are experts on DECam operations. F. Valdes is an expert on the NOAO DECam pipeline and is responsible for the NOAO pipeline reductions and public release of the data. P. Nugent is reponsible for the catalog reductions. D. Lang is responsible for the further development and implementation of the Tractor code for DECam data. All members of the team will participate with observing, data analyses, catalog creation, or research aspects of this proposal (see Co-Investigator List in addenda).

Observing: The observing will be done by team members, many of whom are already experienced DECam and CTIO users. Two observers will be on site for each night. LBNL will fund travel.

Data reduction: Key to the success of this survey is to process and assess the data quality as the survey progresses, and to create and distribute the calibrated images and catalogs.

(1) Catalog Reductions: These reductions (managed by P. Nugent) will make use of the existing DECam pipelines already implemented by LBNL and NOAO. The calibrations will be tied to SDSS (since the footprints overlap). The SDSS calibrations have recently been improved to subpercent precision (Schlafly et al. 2012; Finkbeiner et al. 2014). The image pre-processing and image stacking for large dithers will be implemented by the NOAO members of the team, Dey, Dickinson & Valdes. The sextractor-based catalog reductions of these images will be performed at LBNL using the current code for the DECam transient detection pipeline. These reductions will be released as they are produced, on timescales of $\approx$2 months from the time the data are taken; they will be of sufficient quality for the vast majority of the science cases in this proposal.

(2) Longer-Term Tractor Reductions: D. Schlegel and D. Lang will manage the longer-term pipeline necessary for the Tractor-based multi-wavelength forced-photometric catalogs. This will produce PSF-matched photometric catalogs that include joint photometry with the *WISE* data, and implementation of an internally-consistent photometric calibration (uber-calibration). Although interim versions of these reductions are expected, the final calibrated dataset will only be possible with the completion of the observations. These matched catalogs will be released periodically, within 1 year of the data being taken.

Use of Other Facilities or Resources *(1) Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program. (2) Do you currently have a grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?"*

This proposal will enhance a wide range of other wide-field data sets. Beyond the obvious synergy with SDSS, the survey will have strong synergy with multi-wavelength wide-field imaging from WISE, GALEX, Planck, Herschel, and the UHS & VHS NIR imaging surveys. Identifications of eROSITA X-ray sources will be carried out using this data and will be released by the eROSITA team. Spectroscopy of these sources are planned with SDSS-IV, and this proposal would provide the deeper imaging to enhance the legacy value of eROSITA.

Funding and Other Support: All data will be processed at the National Energy Research Scientific Computing Center (NERSC). Our team has an accepted proposal to provide both the computational time and the storage space necessary to handle the processing of these observations as well as all data sets where we will perform joint photometry. These data will form the basis for equatorial target selection for the future DESI spectroscopic survey. As a result, support will be provided by the DESI Project Director Michael Levi at Berkeley Lab.

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Release of Data *Describe the data products (reduced observations, single or stacked images, spectra, object catalogues, and so on) to be releases, as well as the timeline and mechanism of their release to the community. Please differentiate between intermediate products developed during the execution of the survey versus the final products likely to be produced after the full observations have been obtained.*

Our proposed survey will be public with no proprietary period. The NOAO pipeline reduced images will available as they are processed through the NOAO Science Archive. The calibrated reductions using the LBNL-implementation of the DECam pipeline will be available on timescales of every 3 months during the period of the survey. These catalogs will include our early version of the Tractor-based WISE photometry as currently implemented. The final Tractor-based data release will be no more than 1 year after completion of the observing.

We will make public not only the photometric catalogs resulting from the DECam observations, but also matched catalogs of the spectroscopic data from the SDSS I-IV surveys, and mid-IR data from our new analyses of the *WISE* data within the proposed footprint.

We will release the calibrated images and catalogs both through NERSC and the NOAO Science Archive. Data will be distributed to the public from NERSC's Science Gateway Nodes, which provide a simple web-based interface to raw and processed data as well as the corresponding catalogs from DECam, WISE, and SDSS. The Science Gateways are a key part of NERSC's ability to allow users to adhere to the "America Competes Act" for full public disclosure of their data and simulations (see: http://www.nersc.gov/users/science-gateways). The reduction and release of data will be funded by LBNL.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

The PI was assigned 4 nights in March/April 2013 to obtain z-band imaging of 1000 sq deg of the equatorial sky. These nights were during bright/grey time, 2.5 were clear and were used to image 800 square degrees with a two-pass strategy in z-band. The 3-pass strategy now proposed is superior for photometric uniformity and completeness, and will fold in these earlier data where appropriate. All data have been reduced and are being "Tractor"-ed with *WISE* survey data to produce catalogs. We have reduced our time request by 2 nights since we will fold in these data.

Observing Run Details for Run 1: CT-4m/DECam

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for queue and Gemini runs).*

Tiling Strategy - Optimizing Photometry: Large-scale surveys require uniform completeness for statistical analyses that minimize selection effects. Our tiling strategy is designed to maximize the data uniformity and facilitate photometric calibration. Hence, although our depth requirement is met by two passes, in order to achieve this uniformly requires a minimum of 3 passes. Our strategy is to use triplets of exposures offset by ∼1/3 the focal plane diameter + a small random offset, splitting the observations into 3 tilings of the sky: the "A" pointings will only be observed under photometric observations. The offset "B" and "C" pointings will ∼double the depth, fill the remaining gaps, and offer additional tie-downs in the photometric solutions for that fraction that happen to be photometric. We will tile the 6200 $\deg^2$ (500 more will be covered by DES) with 3 passes with large dithers; given the CCD gaps and 2 non-working CCDs, this will ensure that ∼99% of the footprint will be covered by a minimum of 2 passes. Because of gaps in the DECam focal plane, the tiling strategy will result in 99.5% of the footprint with at least 1 covering, 94% with at least 2 coverings, and 62% with 3 coverings.

This simple strategy has been found to be near optimal for uniform coverage (Holmes, Hogg & Rix, 2012) and will result in photometry with the highest level of relative calibration possible given the sparse sampling. This "uber-calibration" strategy was implemented in the final SDSS data release (Padmanabhan, Schlegel et al 2008) and achieved 0.7%, 0.7%, 1.4% RMS error in g,r,z bands, ultimately limited by site transparency variations in the single epoch observations.

Exposure Times and Time Request: This study requires a minimum of 100, 100, 200 second observations in the g,r,z-bands to reach the proposed depths (5σ in 1.5" seeing) of $g = 24.7$, $r = 23.9$ and $z = 23.0$. As described above, to achieve this uniformly across the entire survey footprint requires a minimum tiling of 3 passes per filter. We therefore set the individual exposure times to be 50sec, 50sec and 100 sec in g, r and z bands respectively. With a 25 second readout/exposure and 10 sec dither overhead, a total of 915 sec is necessary to obtain the three band imaging on each sky position. The three-pass strategy therefore requires a total of 64 clear nights (18 in g, 18 in r and 28 in z).

Given the overlap, only 1/3 of the time need be photometric for the calibration strategy to be successful. The proposed observations span the lunar cycle; we will undertake g, r, z observations during dark, grey and bright time respectively.

Instrument Configuration

Filters: g, r, z	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

R.A. range of principal targets (hours): 0 to 24

Dec. range of principal targets (degrees): -20 to +30

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

GLOSSARY

BOSS = Baryon Oscillation Spectroscopic Survey (2008-2014; part of SDSS-III), using the Sloan Telecope to spectroscopically map $1.5h^{-3}Mpc^3$ 1.5 million luminous red galaxies and the Lyman-alpha forest towards 160,000 quasars. Two-thirds of these data are public, with the remainder going public in December 2014.

DES = Dark Energy Survey, currently running at the Blanco 4m telescope at CTIO. The project will image 5000 deg^2 of the southern sky to 10σ point-source depths of $[grizy]$ $\approx$[25.2,24.8,24.0,23.4,21.7] AB mag. The bulk of the survey lies at $\delta < -25$, but it has an extension to the equator to cover Stripe 82 and the region $0 > \delta > -25$,$0 < \alpha < 45$.

DESI = Dark Energy Spectroscopic Instrument, destined for the Mayall 4m telescope at KPNO, will measure redshifts of more than 20 million galaxies and quasars and result in sub-percent measurements on the expansion history of the universe at $0.5 < z < 3$. DESI is constructing its first spectrograh in 2013-2015, will undergo CD-1 review in summer 2014, and expects first light in 2018.

eBOSS = Extended BOSS (part of SDSS-IV), which will target an additional 375,000 luminous red galaxies, 260,000 emission line galaxies and 740,000 quasars, and extend the redshift range over which the BAO signal will be measured. eBOSS begins in July 2014.

eROSITA = The extended ROentgen Survey with an Imaging Telescope Array is the primary instrument on the Spectrum-Roentgen-Gamma satellite to be launched in 2015. The eROSITA All-Sky X-ray Survey (eRASS) will begin in early in 2016 (Merloni et al. 2012) and map the entire sky eight times over 4 years. eRASS will provide a full census of AGN and cluster of galaxies in the 0.2-8 keV band, reaching about a factor $30\times$ deeper than any existing wide-area surveys at these energies.

Fermi = The Fermi Gamma X-Ray Telescope has been mapping the diffuse sky and high-energy sources on the full sky since 2008.

Pan-STARRS = Panoramic Survey Telescope and Rapid Response System has completed a survey of the $\delta > -30$ sky to 5σ depths $[grizy] \approx [23.0, 22.8, 22.5, 21.7, 20.8]$ AB mag (Metcalfe et al. 2013). A data release is scheduled for March 2015, including stacked images and catalogs.

WISE = Wide-Field Infrared Survey Explorer that carried out an all-sky survey in 4 mid-IR bands (3.4,4.6,12,22μm) from 2010-2011. The all-sky data have been released.

CO-INVESTIGATOR LIST

Name	Task	Research Interest
Stephen Bailey	Reduction pipeline	Cosmology; DESI target selection
Dmitry Bizyaev	Stellar photometry	New Dwarf Galaxy Candidates
Eric Bell	Observing, Photometry	Milky Way/Local Group science
Michael Blanton	SDSS-IV data products	Deep photometry of MaNGA galaxies
Adam S. Bolton	SDSS-IV data products	cosmology, massive galaxies
Mark Brodwin	photometric redshifts	High-z galaxy clusters; galaxy evolution
Kevin Bundy	Large galaxy photometry	MaNGA
Raymond Carlberg	Photometry; target selection	Galactic structure; cosmology
Francisco Castander	Photometric redshifts	Cosmology
Johan Comparat	eBOSS and DESI target selection	Galaxy evolution; cosmology
Kyle Dawson	eBOSS and DESI target selection	Cosmology
Timothee Delubac		Lyman-alpha cross-correlation, cosmology
Mark Dickinson	Data processing, archiving	Galaxy evolution; large-scale structure
Tom Dwelly	X-ray source identification	X-ray selected AGN
Peter Eisenhardt	WISE coordination	Galaxy clusters; galaxy/AGN evolution
Daniel Eisenstein	QA through correlations	Cross-correlations; Cosmology
Xiaohui Fan	Quasar photometry	High-z quasars
Enrique Fernandez	Photometric redshifts	Cosmology
Doug Finkbeiner	Data analyses; photometry	Milky Way stars; 3D dust maps
Pablo Fosalba	Photometric redshifts	Cosmology
Sébastien Foucaud	Multi-band photometry; photo-z's	High redshift galaxies and quasars
Juan Garcia-Bellido	Photometric redshifts	Cosmology
E.Gaztanaga	clustering analysis	angular crosscorrelations
Marla Geha	MW substructure analysis, photometry	Milky Way satellites
Anthony Gonzalez	Observing, Cluster finding	High-z galaxy clusters
Or Graur		supernovae in dwarf galaxies
Nathan Hetherington	Observing	Galactic structure; cosmology
Klaus Honscheid	DECam operations	Large-scale structure; cosmology
Eric Huff	Observing, Image Processing	Lensing
Zeljko Ivezic		3-D Milky Way structure
J.-P. Kneib	lensing measurements	Mass mapping
Richard Kron	Observing	DESI target selection, cosmology
Ting-Wen Lan	Observing	Galaxy-absorber correlations
Dustin Lang	Astrometry; Multi-λ Photometry	cosmology
Michael Levi	Observing	DESI Targeting, Cosmology
Brice Menard	Absorber-Galaxy cross-corr	Redshift distribution estimators
Andrea Merloni	eROSITA matching	X-ray luminous AGN
Ramon Miquel	Photometric redshifts	High-precision photo-z cosmology
Joe Mohr	Observing; photometric calibration	X-ray luminous galaxy clusters
David Monet	Astrometry	Proper motions and MW structure
John Moustakas	Data analysis; photometry	DESI targeting; galaxy clusters
Adam Myers	Observing	AGN Clustering, obscured quasars

Kirpal Nandra	X-ray, multi-λ data	AGN+galaxy co-evolution, clusters
Jeffrey Newman	Selecting LRG samples	LRG clustering and evolution
Brian Nord	Observing; calibration	clusters, clustering, cosmology
Peder Norberg	Selection function characterization	Large Scale Structure; cross-correlations
Peter Nugent	Reduction pipeline	QSO selection,Cosmology
Eran Ofek	Astrometry, photometric calibration	Supernova
Cristobal Padilla		High-precision photo-z cosmology
N. Palanque-Delabrouille	Multi-epoch photometry	Quasar variability
Peter Predehl	eROSITA matching	X-ray selected AGN
Carlos Allende Prieto	Comparison with Gaia	Kinematics of halo stars
Kevin Reil	DECam operations	
Constance Rockosi	Proper motions	Milky Way satellites
Nicholas Ross	Observing	AGN
Eduardo Rozo	Cluster finding	Clusters; cross-correlations
Gregory Rudnick	Observing	High-z Galaxy Clusters; environment
Eli Rykoff	Cluster finding	Clusters; cross-correlations
Mara Salvato	AGN multi-λ associations, photo-z's	Galaxy+AGN coevolution
Eusebio Sanchez		High-precision photo-z cosmology
Eddie Schlafly	Data analyses; photometry	Milky Way stars; 3D dust maps
Uros Seljak	Lensing measures	Galaxy-galaxy lensing
Adam Stanford	DECam/WISE faint sources	Galaxy clusters; galaxy/AGN evolution
Rollin Thomas	Reduction pipeline	
Frank Valdes	Reduction pipeline	Moving objects
Alistair Walker	DECam Characteristics & Operations	Milky Way Satellites
Risa Wechsler	Simulations,cross-correlations	Galaxy-halo connection
Martin White		Quasar triggering mechanisms
Guangtun Zhu	Observing; data analysis	MgII Absorbers - Galaxy connection