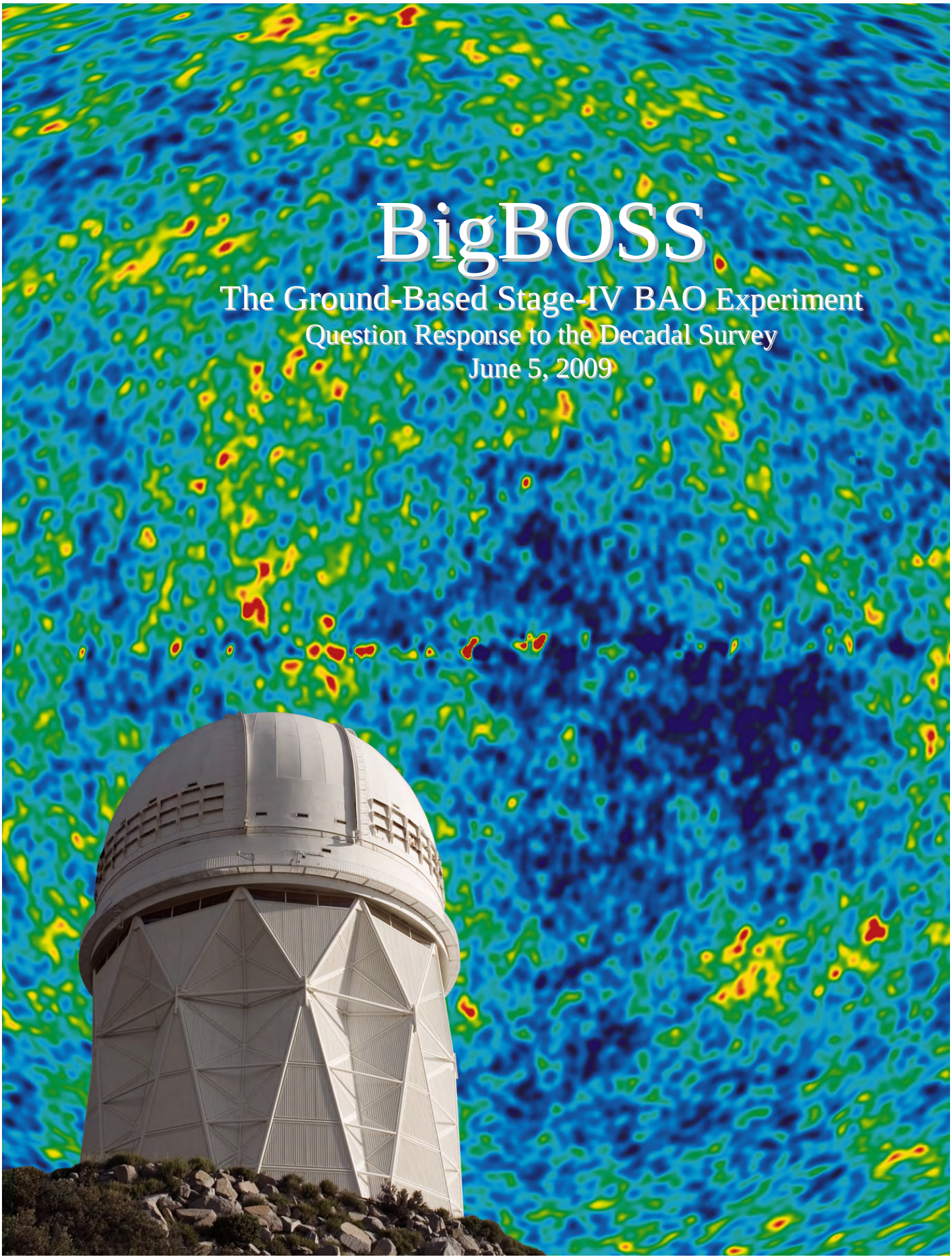
BigBOSS

The Ground-Based Stage-IV BAO Experiment

Question Response to the Decadal Survey

June 5, 2009



BigBOSS: The Ground-Based Stage IV BAO Experiment

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Question 1a:
What fraction of the observing time do you expect to be devoted to the BigBOSS survey during its operation?

The full BigBOSS experiment uses 6 years of dark time on a 4-m telescope to obtain its complete sample of 30 million galaxies to z = 2 in the Northern sky. An additional 4 years of dark time on a Southern telescope would complete the 50 million galaxy sample over 24,000 deg^2. This time assumes 50% loss of time due to weather, and a 60% observing speed relative to good conditions, i.e. 30% of all dark time. The time lost to reconfiguration is minimal for the fiber positioner, and calibration exposures need not be obtained on every exposure due to the stability of the bench-mounted spectrograph design.

The full experiment achieves a Dark Energy Task Force Figure-of-Merit (FoM) comparable to the JDEM BAO experiment described in the JDEM Science Coordination Group Final Report. BigBOSS achieves this with the lower cost and risk of a ground-based program. A compelling experiment can also be performed with less time with a sacrifice of redshift range. An experiment with redshift range reduced from z = 2 to z = 1.6 has greatly increased survey speed and could be performed with 100 nights per year (equivalent to the DES utilization of CTIO) for 10 years (North+South) yet still obtain 50 million galaxies and a 15% smaller Figure of Merit (FoM). The instrument could be built without the HgCdTe detectors at a savings of $10M. The target list would be derived from *grz* imaging rather than *ugr* imaging, removing the need for a large-area *u*-band survey deeper than SDSS. The required integration time is reduced by more than a factor of two, such that they program could be completed with an equivalent time allocation as for DES.

This descope option may be the most sensible approach programmatically. After completion of the Northern-sky z<1.6 survey, the decision could be made to either pursue the higher-z program (by adding NIR detectors) or extend the sky area with the Southern-sky survey.

Question 1b:
What information do you have on the likelihood that the US community will approve of devoting a huge fraction of the 4-m dark time for BigBOSS from 2015-2021?

There are seven 4-m class facilities in the US OIR System: Palomar 5-m, SOAR 4.2-m, KPNO 4-m, CTIO 4-m, WIYN 3.5-m, ARC 3.5-m, and Shane 3.0-m. The Lowell 4.2-m will come on-line within the next 2 years.

The BigBOSS experiment uses the Kitt Peak 4-m and CTIO 4-m telescopes as the baseline design, although it is not formally committed to these particular telescopes. We are systematically exploring optical designs of 14 astronomical telescopes in the 3.5 to 4.2 m aperture range. Of the 5 telescopes studied to date, the Kitt Peak 4-m, CTIO 4-m, and Calar Alto 3.5-m are suitable to conversion to a 3-degree field. In what follows, we assume for the purposes of this discussion that BigBOSS will seek implementation initially on the KPNO 4-m Mayall Telescope.

NOAO has developed a plan for current and future needs of telescope access on apertures smaller than 6-m through its ReSTAR committee (Renewing Small Telescopes for Astronomical Research). This committee's findings show that the science from small- and mid-sized telescopes remains compelling. Their recommendations call for the specialization of the 2–4 meter class telescopes: "Specialization will provide a more limited set of observing capabilities on each telescope but should preserve a breadth of capability across the ReSTAR System." The BigBOSS instrument would be the most ambitious low- and mid-resolution spectrograph ever fielded on a 4-m class telescope, with 5000 fibers spanning the full 340–1150 nm wavelength range.

The current suite of Kitt Peak 4-m instrumentation includes the NOAO CCD Mosaic, the NEWFIRM infrared imager (shared between KPNO and CTIO as a bright-time instrument), and the RC single-slit spectrograph. After the arrival of the WIYN One Degree Imager in 2011, the Mosaic will be much less competitive. The ReSTAR report presented a prioritized list of near-term capabilities, and "Moderate resolution optical spectroscopy" was listed as the second most desired capability by the user community. In addition, the committee noted that "…spectroscopy should receive the highest priority for new instrumentation, since instrumentation for imaging is in a somewhat better state." NOAO has responded to this directive by proposing for incremental funding from the NSF to upgrade the current 4-m spectrographs by 2011. The BigBOSS instrument would be the ideal follow-on to this, resulting in a much higher multiplex (by a factor of 100) and a larger field of view (by a factor of 30) over the planned spectrographs. Within that broader context, BigBOSS offers unique and compelling new capability for the US community.

At the NOAO 4-m telescopes, the community would have direct access to this capability in four ways. First, through the traditional NOAO TAC process the community could directly apply for nights with the instrument. Second, again through the TAC, the community could propose for fibers to be used during normal survey operations. After all, BigBOSS plans to cover a significant fraction of the extragalactic sky, and request for specific targets (QSOs, bright galaxies, clusters, rare objects, inter alia.) could easily be accommodated as part of the regular survey operations. Third, the BigBOSS survey, like the preceding SDSS surveys, will reach out the community for participation and input in planning associated surveys and / or to increase the legacy value of the survey data. For example, it would be natural for the BigBOSS survey data to be used for various studies related to extragalactic astrophysics. We will work with NOAO in order to form a community-based science team (or teams) to undertake these science programs and to help with the survey planning and implementation. Fourth, like the SDSS program, we anticipate that the BigBOSS project will have significant participation by US and international university partners. Fifth, we note that we expect all the survey data to be archived and become publicly available to the astronomical community.

Question 1c:
What is the process for approving this allocation of resources?

The Dark Energy Survey (DES) blazed a path for obtaining significant amount of 4-m telescope time through NOAO. NOAO initiated a call for large proposals for the CTIO 4-m and the DES was reviewed and selected for its imaging survey using 100

nights per year for 5 years. This process was monitored by NSF at each step, including the final decision. One possible avenue for BigBOSS would be a response to a similar NOAO call for large proposals on the Kitt Peak 4-m.

Following DES, we assume that 100 nights per year is a likely constraint. However, two factors could allow that number to grow. First, funding could be provided to NOAO to purchase nights on other 4-m class telescopes. The ReSTAR committee has already recommended that option as a means to obtaining access to new capabilities. Second, we note that the over-subscription rate on the KPNO 4-m has dropped to less than 2, while in the past NOAO has considered 3–4 acceptable and a sign of scientific vigor. As long as over-subscription stays in that range, it is possible that more nights could be allocated to the BigBOSS survey.

Question 2:

Can you provide a detailed cost estimate, including operations? What is included in the operations cost estimate? Which parts of the path from data to science are not included, and where will that funding come from?

The costing for BigBOSS relies heavily on the BOSS experiment, expected to be operational later this year. This includes detailed, as-built expenses for the spectrographs, detectors, electronics, fibers, computing, and operations. New costs are based engineering designs and vendor quotations. Instrument and telescope operations costs were provided by KPNO and by scaling of BOSS operation costs. Though we expect to have significant reuse of the data pipelines from BOSS, we have included significant funds for pipeline development. Operation of these pipelines is modeled on the BOSS experiment. We have included significant costs for data reduction and for creation and export of the data catalogs to the community. We have not included, however, the cost for scientific analyses. We expect this to be borne by our collaborating faculty through their academic support.

Table 1 shows the total cost in FY09 dollars for the entire BigBOSS project. WBS items 1.0 through 5.0 comprise the construction phase from project initiation through the start of operations and science data taking. WBS item 6.0 applies to the data reduction development and operations, and operation of the instrument and telescope.

Hardware Construction Cost:

WBS item 1.0 provides project management and systems engineering for the construction phase of the BigBOSS project (management activities during the operations is included in WBS 6.0). The estimated cost is based on a comparison with similar sized projects – DES (at FNAL), Daya Bay (at LBNL) and BOSS. The schedule specifies a four year development from the project initiation to the start of operations. A full time Project Manager and 1.0 FTE of administrative support is budgeted. Because of the greater engineering complexity compared to BOSS, a full time Systems Engineer and 2.0 FTE's of additional engineering support are required through the construction period.

WBS 2.0 includes all costs associated with the design and fabrication of the 10 spectrograph assemblies. The spectrograph design is identical to that of the BOSS spectrographs except for the addition of a third arm. The cost of the optics and structure is taken from the final as-built costs of the BOSS systems with the addition of optics and

structure for the third arm as is the cost of the dewar assemblies. Detectors and front end electronics costs are from recent quotes from the relevant detector manufacturers obtained by the SNAP project. Costs for the digital electronics system necessary to gather data from the spectrographs and transfer it to the science data analysis pipeline, as well as to control the positioners and other instrument functions, are based on a modification of the electronics developed for the SNAP instrument.

Table 1 BigBOSS Cost by WBS Item (FY09$M)

WBS Level 2	3	4	Description	Total	Basis of Estimate
1			**Construction Project Management and System Engineering**	**5.1**	
1	1		Project Management (includes Administrative Support)	1.9	DES and Daya Bay, LBNL Labor Rates
1	2		Systems Engineering and Quality Assurance	3.2	DES and Daya Bay, LBNL Labor Rates
2			**Spectrographs and Instrument Control Electronics**	**30.9**	
2	1		Spectrograph Optics and Structure (x10)	10.7	
2	1	1	Management	0.68	
2	1	2	Systems Engineering	1.67	
2	1	3	Structure	0.68	
2	1	4	Slithead	0.14	
2	1	5	Collimator Assembly	0.56	WFMOS Spectrograph Proposal and BOSS actuals
2	1	6	Hartmann Doors and Shutter	0.12	
2	1	7	Central Optics	1.62	
2	1	8	Blue Camera	1.46	
2	1	9	Visible Camera	1.29	
2	1	A	Red Camera	1.29	
2	1	B	Controller	0.47	
2	1	C	Integration and Test	0.72	
2	3		Detector Assy 1	4.00	
2	3	1	Dewar and Vacuum System	2.30	Engineering Estimate, BOSS actual
2	3	2	Detector [4kx4kx15u e2v]x10	1.30	Vendor Quote from e2v
2	3	3	Front End Electronics [CRIC 5.0 - CLIC 5.0]	0.40	Engineering Estimate, SNAP Prototype Build
2	4		Detector Assy 2	2.60	
2	4	1	Dewar and Vacuum System	1.00	Engineering Estimate
2	4	2	Detector [4kx4kx15u LBNL]x10	1.20	Vendor Quote from MSL
2	4	3	Front End Electronics [JDEM CCD F/E module]	0.40	Engineering Estimate, SNAP Prototype Build
2	5		Detector Assemblies 3	11.80	
2	5	1	Dewar and Vacuum System	0.50	Engineering Estimate
2	5	2	Detectors [2 each 2kx2kx18u Teledyne +2 each 4kx4kx15u LBNL]x10	10.80	Vendor Quotes from Teledyne and MSL
2	5	3	Front End Electronics [JDEM SIDECAR module]	0.50	Vendor Quote from Teledyne
2	6		Digital Electronics System	1.80	
2	6	1	Positioner Control Elect. with Camera Interface	0.10	Engineering Estimate

2 6 2	Science Data Processing and Control Electronics	0.20	Engineering Estimate, SNAP Prototype Build
2 6 3	Software	1.50	Engineering Estimate, BOSS actual
3	**Fiber System with Positioners**	**5.4**	
3 1	Fiber Assembly [block w/ 500 150u fibers]x10	1.2	Vendor quote (catalog item), BOSS actual
3 2	Positioner Assemblies	3.8	Engineering Estimate, Prototype Build Invoices
3 3	Fiber Support Tray System	0.4	Engineering Estimate
4	**Optic**	**8.4**	
4 1	Upper Mechanical Structure	0.9	Engineering Estimate from KPNO
4 2	Secondary Mirror	3.5	Quote from U. Arizona Optical Sci.
4 3	Fiber Position Camera Assembly	0.1	Fairchild Off-the-Shelf Product
4 4	Lower Mechanical Structure	0.9	Engineering Estimate from KPNO
4 5	Cassegrain Cell Assembly	0.8	Engineering Estimate from KPNO
4 6	ADC Assembly	0.8	Engineering Estimate from KPNO
4 7	Focal Plane Assembly	1.4	Engineering Estimate
4 7 1	Mounting Plate and Structure		Engineering Estimate
4 7 2	Guider Modules		Semi-custom designs & built around a
4 7 3	Auto Focus Modules		standard CCD
5	**Contingency**	**15.0**	Based on 30% on all construction costs. Contingency on Ops included in 7.0
6	**Pipeline and Operations**	**20.1**	
6 1	Instrument Operations	**10.5**	KPNO estimates
6 1 1	Spectrograph Operations (including dewars, detectors)	3.0	
6 1 2	Associated Computers	1.5	
6 1 3	Non-Spectrograph Hardware	1.5	
6 1 4	Telescope Operations	3.0	NSF/NOAO
6 1 5	Management/Admin Support	1.5	
6 2	Data Management Budget	**4.5**	SDSS running costs
6 2 1	Science Archive Servers and Mirror	0.8	
6 2 2	Maintenance and Facility Support	1.4	
6 2 3	Data Archivist and Coordinator	0.8	
6 2 4	Catalog Archive Administrators and Licensing	0.6	
6 2 5	Software Development	0.9	
6 3	Data Reduction	**5.1**	Estimate, based on BOSS projected
6 3 1	Project Management	0.6	
6 3 2	Data Reduction and Packaging	1.0	
6 3 3	Code Development	2.2	
6 3 4	Target Selection	0.8	
6 3 5	Computing Hardware, Support and Licensing	0.5	
	Total for Project:	**84.9**	**(FY09 $M)**

WBS 3.0 includes the 5000 fiber positioner assemblies and the fiber. The cost for the fiber was determined following a visit to the 4 meter KPNO telescope to make an estimate of the length of the fiber run, along with the catalog price of the fiber from Polymicro. The costs for the fiber assembly with ferrules (on the focal plane) and v-groove blocks (on the spectrograph end) are based upon the BOSS cost for similar assemblies from C Technologies. The cost of the positioners is based on invoiced costs for the prototype constructed at the LBNL, modified by quoted quantity discounts for the drive components, the machined parts and the electrical control circuits. Labor represents approximately 40% of the positioner costs as estimated by the LBNL engineering division (included in estimate).

WBS 4.0 includes all optics assemblies to be installed into the KNPO telescope, including the new secondary mirror and its mounting and interface assembly, the fiber positioner camera assembly, the Cassegrain cell equipment, and the focal plane plate with its associated mounting components. The cost of the secondary mirror is from a quote for machining a light weighted 2.0 meter blank from an existing DOE-owned Zerodur boule and figuring it to form the convex BigBOSS mirror. Cost for the fiber position camera is based on a quote for an off-the-shelf CCD assembly made by Fairchild Imaging Systems. Cost estimates for the Cassegrain cell assembly and the ADC including their associated structure, and the structure for mounting the secondary mirror to the telescope were made by the KPNO engineering team based on past modifications they have made to the 4-m telescope. Estimates for the focal plane assembly and the guider and autofocus detector modules are based by the SNAP engineering team for similar parts designed for the SNAP instrument and telescope.

WBS item 5.0 includes contingency over the estimated cost of 30% for all activities during the construction phase. Contingency for the operations phase is included in WBS 6.0

WBS 6.0 includes costs incurred during the 4 year construction phase for setting up and testing the data pipeline to be used during the following Science Operations phase. The costs are based on a 0.5 FTE effort during that period along with a cost of $500K for computer hardware.

Operations Cost

WBS 6.0 includes all program costs for operations and data reduction pipeline (North, 6 year plan only). The telescope operations budget was obtained from the Kitt Peak Director. These reflect the current operations cost for telescope operators (6.1.4) and associated management and administrative support (6.1.5). Additional personnel will be necessary for instrument support (included in estimate).

The data reduction effort is estimated at the same level as for the BOSS project, with an additional year of effort before the start of operations. The BOSS pipeline is a major modification of the existing SDSS spectroscopic pipeline. The BigBOSS pipeline will be a modification of the final BOSS pipeline. Software project management has been added to this budget at the level of 0.5 FTE for four years.

The data management budget is based upon the SDSS-III budget for the same running time. This includes the development and support of a flat-file data archive and an SQL database. The data flow and data integrity is ensured by the Data Archivist. The database is administered by a Database Administrator. All data operations are mirrored,

with additional archiving provided by NERSC. These estimates were made in consultation with the SDSS-III Data Coordinator.

Pipeline and data operations are funded until the final data release, 6 months after the end of operations. Long-term stewardship of the data is not included in the budget.

Science Costs

This budget does not include data analysis beyond the reduction of the data to 1-D spectra, redshifts and object classification. The highly successful SDSS-I, SDSS-II and SDSS-III models will be followed, whereby the collaboration members carried out these analyses. In practice, member universities have typically committed funds for both the project buy-in and science postdocs.

Agency Costs

We have developed a provisional concept for the international collaboration and are focused on adopting a funding model that was used successfully for SDSS-III/BOSS. For BigBOSS our expectation is that DOE along with international partners and university in-kind contributions would be the principal funding mechanism for the instrument. Operations costs would be provided by NSF and university funds at our collaborating institutions. We have included the NOAO costs of the telescope operations in this estimate; alternatively NOAO could assume these costs. Table 2 shows this breakdown for our nominal project ($z<2.0$) and Table 3 shows a descoped version ($z<1.6$) where the NIR system is removed. The latter still obtains 50,000,000 galaxies over a ten year period with a telescope allocation similar to that of DES.

The agency, international, and in-kind contributions given in both of these tables are notional. Operations costs are given for just the North; extension to the full 10 year program is proportional. The optical design of the secondary for use at CTIO requires no change in the prescription, so installation costs of the instrument in the South are modest.

Table 2

BigBOSS Cost Breakdown					
			Offsets		
WBS	Description	Cost by WBS	Major in kind contributions		University Contributions
1.0	Project Management & System Engineering	5.1			5.0
2.0	Spectrographs and Instrument Electronics	30.9	10.6	France	
3.0	Fiber System with Positioners	5.4	4.8	China	
4.0	Optics	8.4			
5.0	Contingency	15.0			
6.1	Instrument Operations (6 years)	10.5			5.0
6.2	Data Operations (7.5 years)	9.6			
	Total Project Cost -- Construction + Ops:	**84.9**			
	Total Contributions:	25.4			
	Total DOE Cost -- Construction only:	**44.4**			
	Total DOE Cost -- Ops. only:	**15.1**			

Table 3

BigBOSS Cost Breakdown -- with Descope of NIR Detectors					
WBS	Description	Cost by WBS	Offsets		
			Major in kind contributions		University Contributions
1.0	Project Management & System Engineering	5.1			5.0
2.0	Spectrographs and Instrument Electronics	20.9	10.6	France	
3.0	Fiber System with Positioners	5.4	4.8	China	
4.0	Optics	8.4			
5.0	Contingency	12.0			
6.1	Instrument Operations (5 years)	8.8			5.0
6.2	Data Operations (6.5 years)	8.2			
	Total Project Cost -- Construction + Ops:	**68.8**			
	Total Contributions:	25.4			
	Total DOE Cost -- Construction only:	**31.4**			
	Total DOE Cost -- Ops. only:	**12.0**			

Question 3a:

What line flux sensitivity do you expect as a function of wavelength in a one-hour exposure (for all redshifts in the survey)?

The notional BigBOSS design draws heavily on the spectrograph design of the SDSS-III / BOSS spectrographs. To first order, one can scale the flux sensitivities in BOSS with aperture area, fiber size, and resolution to the design of BigBOSS. Figure 1 shows the extracted line flux sensitivity for S/N=8 in a standard BigBOSS half-hour exposure with the current design parameters. The plotted wavelengths correspond to the spectrograph arms that will obtain Lyα absorbed QSOs and LRGs to $z < 0.5$. Note that the sensitivity is degraded below 4000Å due to falling efficiencies in the detector and gratings, absorption in the fibers, and atmospheric absorption through Rayleigh scattering. Observations at wavelengths longer than 8000Å will encounter bright sky lines that will degrade the S/N for specific wavelengths. The sky lines will have the largest impact on the detection, extraction, and redshift measurement of the [OII] emission line doublet from $1 < z < 2$. BigBOSS mitigates this impact with a spectrograph design that has high resolution (R ~5000) and throughput, characterized monochromatic spots, and minimal scattered light. Figure 2 shows the optimal extraction of the single [OII]λ3726 emission line over the redshift range covered by the red spectrograph arm. We expect that there will be small redshift ranges ($\Delta z < 0.001$) where the single-line MDLF cannot be achieved due to background sky noise from bright OH sky lines. However, the split [OII] doublet allows us to identify and measure the other doublet line, recovering the redshift measurement with the weighted signal between both emission lines.

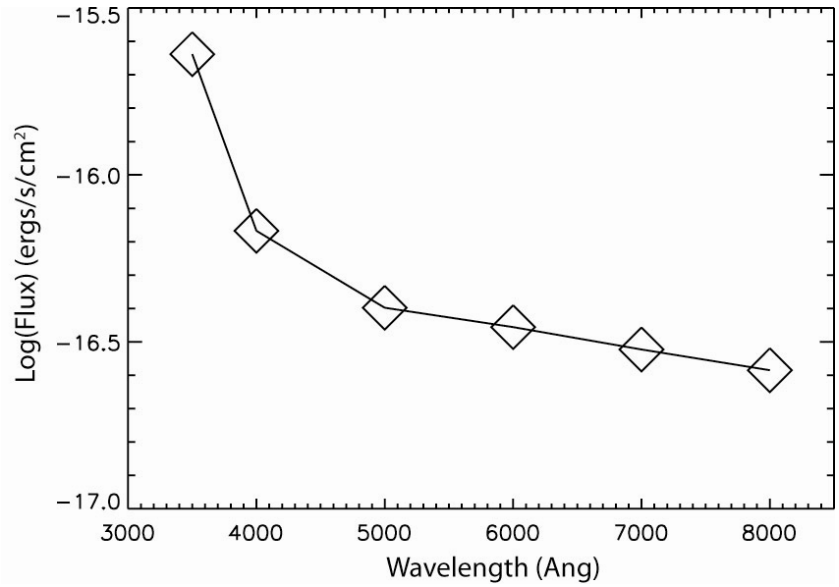

Figure 1. The line flux sensitivity (for emission-lines with 60 km/s dispersion) in the BigBOSS blue and visible spectrograph arms.

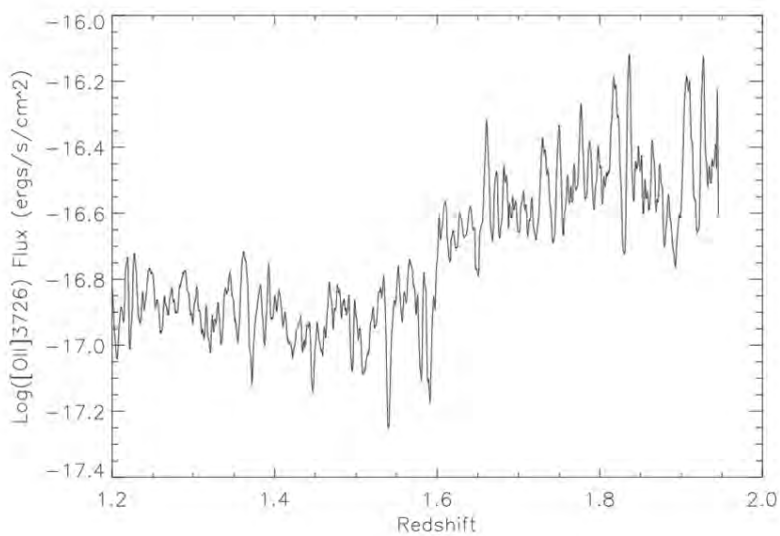

Figure 2. The optimal extracted line flux sensitivity for S/N=8 [OII]λ3726 in the BigBOSS Red spectrograph arm (8000-11000Å). The sensitivity has been smoothed by 10Å to show the larger variations due to night sky lines. Note the systematic decrease for z > 1.6 corresponds to a higher noise background from the NIR detectors.

Question 3b:

What comoving number density of galaxies as a function of redshift will the survey sample?

The BigBOSS science goal is to measure redshifts of split [OII] line emission from star-forming galaxies (SFGs) between 0.7 < z < 2 at a source density of

2000 $dn/(dz\text{-deg}^2)$, or a comoving number density of approximately of 3.4×10^{-4} $(h/Mpc)^3$. These top level requirements translate to a single-line minimal detectable line flux (MDLF) of 2.5×10^{-17} erg/s/cm^2 for the spectrograph measurement (see Question 5/Figure 9, for the density of selected [OII] galaxies as a function of redshift). LRGs will also be selected with this same number density out to z = 1 and will be better BAO tracers since their dark matter halo mass bias is a factor of two larger than the SFGs. The QSO target density will be sparsely sampled in the manner of BOSS, but the 4-m aperture of BigBOSS will allow us to sample 1 million sightlines from $2 < z < 3.5$.

Question 4:
How technically risky is the 3 degree field? If it is not achievable, what is the descope option and how does it modify the science achievements?

To accommodate a 5,000 automatic fiber positioner system our conceptual design requires a 2.5º field-of-view including space for the telescope guiding system. Consequently, we do not require a 3º field-of-view, but we are designing to this dimension to provide design margin on the positioner system to allow trades of fiber count versus telescope time and to allow an increase in the number of fibers that can be provided for community access. The 3º field of view has not proved to be a technical challenge within the telescope constraints such as optics, telescope mechanics, baffling, or vignetting.

The light is delivered to a flat telecentric focal plane at *f*/5. This allows us to feed bare fibers without the light losses inherent to systems with microlens couplers. This is the same design choice made by SDSS and BOSS.

Modification of the Mayall telescope requires a new secondary mirror and corrector assembly. Mayall is a fairly slow Ritchey Chretien telescope, which reduces the optical challenge of the design and allows the 3º field. The secondary mirror magnifies the prime focus. The corrector assembly does not, so chromatic aberration is not a strong driver in its design. All three elements can be made from fused silica; no opto-mechanically challenging materials (such as calcium fluoride) are necessary for color correction. Figure 3 shows the layout of the modified Mayall telescope.

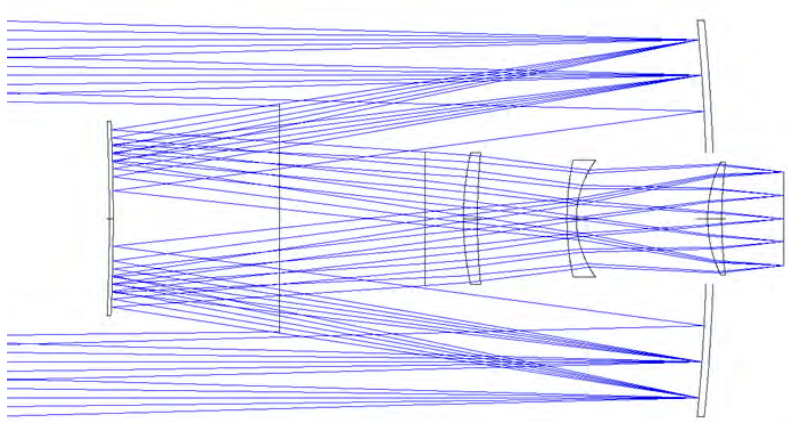

Figure 3. Modified Mayall telescope optics.

Manufacturing feasibility of the secondary mirror and the corrector elements were verified by the University of Arizona College of Optical Sciences. Using profilometry and interferometry, all elements are less challenging than previous optics made there. Parameters of the optics delivering a 3º field-of-view are shown in Table 4.

Table 4.

Element		Diameter (m)	Material	Radius (m)	Aspheric departure (m)
Secondary		2.0	ULE or Zerodur	22.3	52
C1	$S_{urf}1$	1.5	Fused silica	4.8	(sphere)
	$S_{urf}2$			13.0	(sphere)
C2	$S_{urf}1$	1.2	Fused silica	2.8	(sphere)
	$S_{urf}2$			1.0	95
C3	$S_{urf}1$	1.3	Fused silica	1.4	1810
	$S_{urf}2$			6.2	(sphere)

The telescope can be descoped by reducing the field of view, which moderately reduces the diameters of the corrector lenses. For a 2.5º FOV, the diameters of C1, C2 and C3 are 1.4, 1.1 and 1.1 m, respectively. Another possible descope is reduction in the size of the secondary mirror. The 2-m mirror is currently properly sized with a 37% obscuration and no field-dependent vignetting. If the secondary mirror size is reduced from 2 m to 1.5 m diameter, the vignetting becomes field-dependent with the same 37% obscuration in the center, increasing to a 55% effective obscuration at the edges.

Manufacturing of the secondary mirror and fused silica corrector elements are well within the existing capabilities of the University of Arizona Optics department. None of the optical elements present great risk, but the design could be descoped by reducing the FOV or the diameter of the secondary mirror.

Question 5:

Please present a detailed estimate and justification of the accuracy of photometric redshifts in the 1.3 < z < 2 range and the predicted [OII] flux, and how it translates to object pre-selection efficiency.

We do not require photometric redshifts in order to create a target selection list. Color cuts will be made to select targets within the redshift range of interest much as the DEEP2 survey did.

The spectroscopic BigBOSS survey will require a target selection method that will efficiently select bright [OII] line emitting galaxies from $0.7 < z < 2.0$. A few photometric color selection methods have been suggested in the literature, but during the next decade, the optical *ugriz* bands are the most likely bands to be measured at the BigBOSS required depths and sky coverage. The zCOSMOS galaxy SEDs demonstrate that the *grz* and *ugr* color planes efficiently select [OII] line emitters from the total galaxy population between $0.7 < z < 1.5$ and $1.5 < z < 2$, respectively. We describe the selection process in the sections below; the speed reader can skip to Figure 9 for the result.

The [OII] luminosity function

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

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

where L is $L_{[\mathrm{OII}]}$ in erg/s, and $\alpha \sim -3.0$ and $\beta \sim 3.6$ are fit parameters for our redshift range of interest. For z > 1.5, we use the same α and β values derived from the highest DEEP2 redshifts, which should conservatively estimate an evolving [OII] luminosity function. To achieve a projected sky density of 2000 $dn/(dz\text{-}deg^2)$ in a ΛCDM universe, BigBOSS will require a galaxy space density of $10^{-3.76}$ dex^{-1}-Mpc^{-3} at z = 2 and therefore must measure a minimum single-line [OII] luminosity of ~$10^{42.6}$ erg/s. The second source of data comes from the zCOSMOS fit galaxy template catalog and calibrated [OII] line emission from VVDS spectra (Ilbert et al., 2008). The zCOSMOS catalog contains more than 500,000 galaxies with $i < 26$ over a 1.3 deg^2 field of view and photometric redshifts with $\Delta z < 0.01$. zCOSMOS measures [O II] flux directly at z<1.5, and estimates that flux at z>1.5 using the M(UV)-[OII] calibration (Kennicutt, 1998). Figure 4 compares the MDLF derived from the Zhu et al. luminosity function and the Ilbert et al. catalog with M(UV)–[OII] line flux calibration. Both data sources are in good agreement over the redshift range 1 < z < 2, keeping in mind that the [OII] line fluxes beyond z > 1.5 have been extrapolated from the available low redshift data. At z = 2, we calculate that BigBOSS will be required to measure a MDLF ~1×10^{-16} erg/s/cm^2 for an unresolved [OII] emission line, or 5×10^{-17} erg/s/cm^2 for the resolved doublet. However, it is often the case that such luminosity functions can vary from different data sources by more than a factor of two since the data over this redshift range are limited in both depth and area. Therefore, we conservatively estimate a MDLF of the split [OII] doublet to be 5×10^{-17} erg/s/cm^2 from 1.1 < z < 1.5 and 2.5×10^{-17} erg/s/cm^2 from 1.5 < z < 2.0.

Target Selection

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

For z > 1.5, we will select targets based on the Lyα absorption feature of these high-redshift galaxies using *ugr* colors. Color selection based on the Lyman-break can extend out to z < 3, but we will restrict our color space to z < 2, trading exposure time on faint objects for a larger survey area.

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

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

Selection Efficiencies

For both color selections, the selection efficiency of SFG targets within a $\Delta z \sim 0.5$ window will depend on the photometric error delivered by large area surveys at our magnitude limits. At present, we consider the sources in Table 5 for photometry in the Northern Hemisphere: the Palomar Transient Factory (PTF), Pan-STARRS and an example *u*-band survey that could be carried out on CFHT. Figure 7 shows the calculated magnitude errors for each of these surveys. Our target selection boxes can be successfully applied to the zCOSMOS catalog degraded to the projected photometric errors of these imaging surveys (Figure 8).

Table 5. The bandpass sensitivity and sky brightness for possible photometric selection sources in the Northern Hemisphere.

Survey	Band	Limiting magnitude	Sky Brightness (mag/arcsec)	Integration time (s)	Seeing (arcsec)
CFHT	u	25.77	21.3	400	1.2
PTF	g'	24.02	22.11	10800	1.8
PTF	R	25.27	21.06	10800	1.8
PanSTARRS-1	i	25	20.15	1200	1.0
PanSTARRS-1	z	24.63	19.26	1200	1.0

The redshift distributions of both colors cuts are presented in Figure 9. The *ugr* and *grz* color selections are > 85% efficient at selecting objects with bright [OII] emission above the BigBOSS MDLF. These cuts also deliver the desired BAO target

number density of 2000 $dn/(dz\text{-}deg^2)$, with a redshift distribution that is essentially flat and constrained to the $1 < z < 1.5$ and $1.5 < z < 2$ windows. Interestingly, the *ugr* color selection alone provides a well sculpted redshift distribution over the entire $1 < z < 2$ range as lower redshift interlopers are scattered into the selection box. However, we note that the specific selection criterion for [OII] emission using best-fit galaxy templates should be further tested, and we are in the process of collecting available *ugr* data to test with [OII] spectra near 1 µm.

Q5 References

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Ilbert, O., et al., 2008, COSMOS Photometric Redshifts with 30-bands for 2-deg^2, [arxiv:0809.2101v1].

Kennicutt, R. 1998, Galaxies: Interactions and Induced Star Formation, Saas-Fee Advanced Course 26. Lecture Notes 1996. Swiss Society for Astrophysics and Astronomy, XIV, Edited by R. C. Kennicutt, Jr. F. Schweizer, J. E. Barnes, D. Friedli, L. Martinet, and D. Pfenniger. ISBN: 3-540-63569-6, 1998.

Zhu, G., et al., 2008, The [OII] lambda 3727 Luminosity Function at z ~ 1 [arxiv:0811.3035].

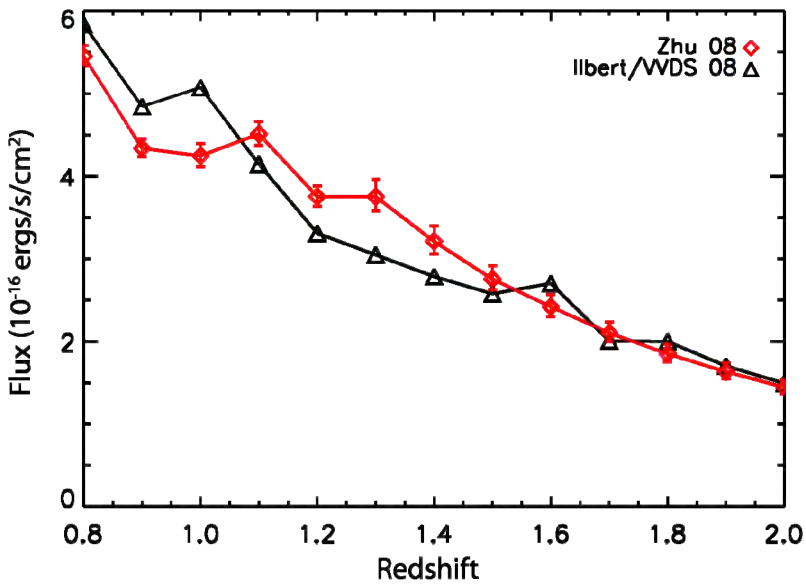

Figure 4. Comparison of the MDLF required to achieve the BigBOSS goal source density (Zhu et al, 2008, Ilbert et al, 2008). The plotted line fluxes are for the unresolved [OII] doublet line flux.

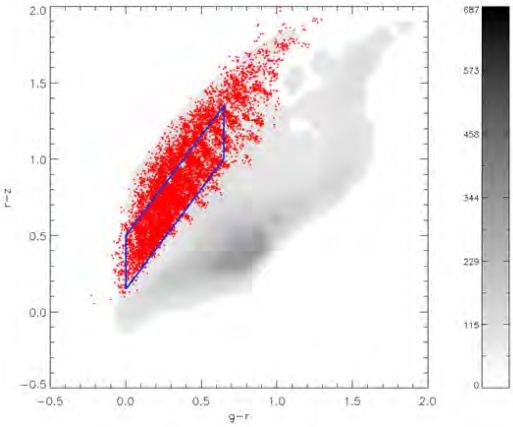

Figure 5. Colors of the zCOSMOS fit galaxy template SEDs in the *grz* color plane. The gray contours correspond to all galaxies with r < 23.5 and the red crosses correspond to the BigBOSS galaxy targets from $1.1 \leq z \leq 1.5$ and split line flux F[OII] > 5×10^{-17} erg/s/cm^2. The blue box shows an example color selection criterion that could be used for these objects.

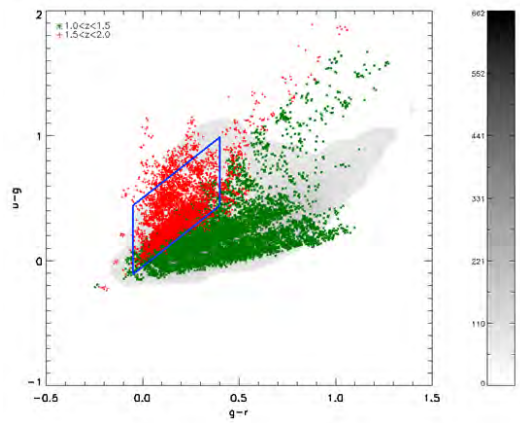

Figure 6. Colors of the zCOSMOS fit galaxy template SEDs in the *ugr* color plane. The gray contours correspond to all galaxies with r < 24.0, the red crosses correspond to the BigBOSS galaxy targets from $1.5 \leq z \leq 2.0$ and split line flux F[OII] > 2.5×10^{-17} erg/s/cm^2, and the green stars have the same flux cut for $1.0 \leq z \leq 1.5$. The blue box shows an example color selection criterion that could be used for these objects.

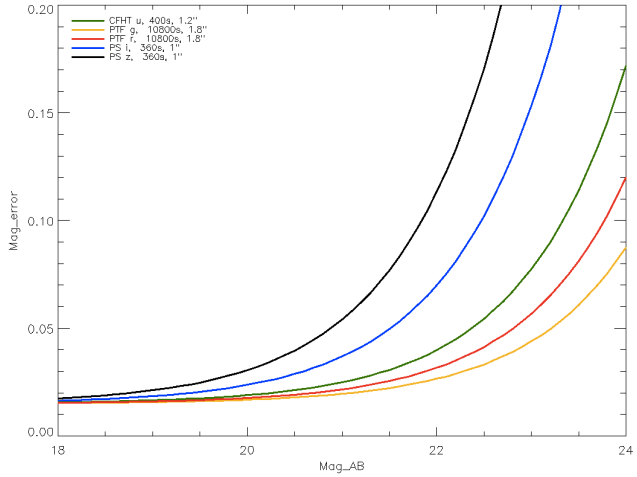

Figure 7. Assumed magnitude errors for the Palomar Transient Factory, Pan-STARRS, and an example CFHT *u*-band survey.

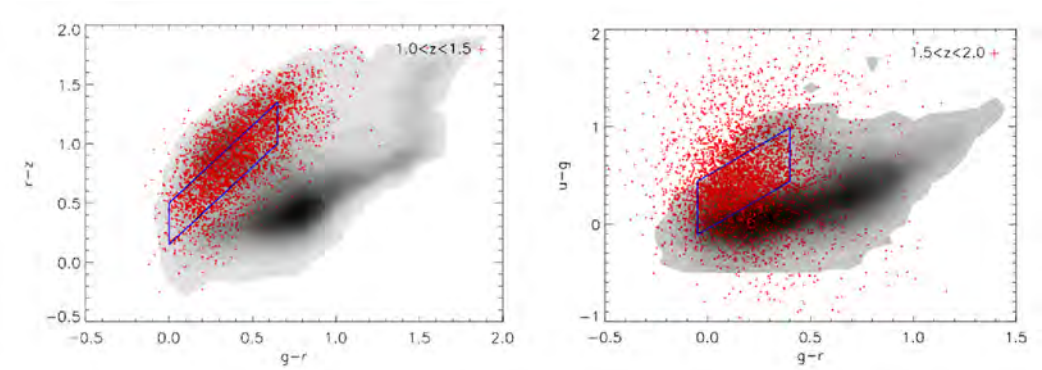

Figure 8. The *grz* and *ugr* color space for synthetic magnitudes and associated photometric errors from PTF, Pan-STARRS, and CFHT surveys. The selection boxes are reproduced from ideal cuts made in Figure **5 and** Figure **6.**

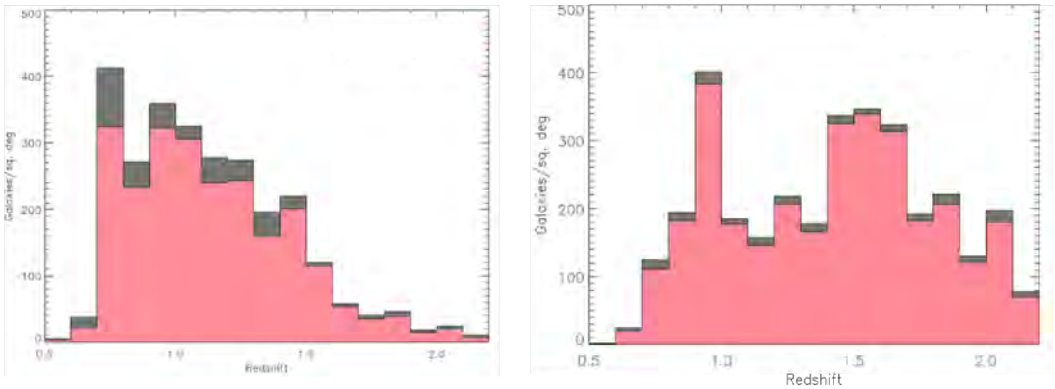

Figure 9. Both panels show a galaxy redshift distribution (in gray) with our color and magnitude cuts applied to the zCOSMOS catalog, *r* < 23.5 for z < 1.5 and *r* < 24.0 for z < 2.0. The histograms in pink show the *grz* (left panel) and *ugr* (right panel) color selected galaxies to our nominal line detection limit. The color cuts are > 85% efficient at selecting bright [OII] emitters and also deliver the target number density of 2000 *dn*/(*dz-deg*^{2}).