Large Synoptic Survey Telescope

www.lsst.org

Photometric Redshift Calibration for LSST

S. J. Schmidt (UC Davis), J. A. Newman (U. Pittsburgh), J. A. Tyson (UCD), A. J. Connolly (U. Washington), D. M. Wittman (UCD), D. J. Matthews (Pitt), V. E. Margoniner (CSU Sacramento), A. Choi (UCD), I. Udaltsova (UCD) and the LSST Collaboration

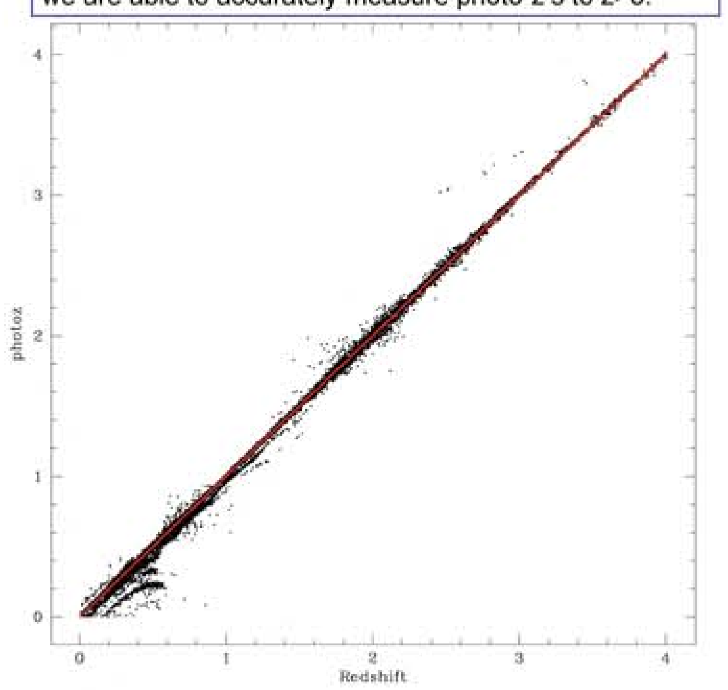
The proper calibration of photometric redshifts is of the utmost importance for the LSST, as cosmological measurements depend critically on knowledge of the underlying redshift distribution. We examine how the use of different photometric redshift estimators affects the prediction of the photometric redshift distribution. The great depth of LSST imaging will enable measurements over a significant portion of cosmic time, during which galaxies will undergo substantial evolution. We investigate how the inclusion of supplemental photometric and spectroscopic measurements can improve photo-z estimators with tighter constraints on galaxy distribution and evolution models. We also explore measuring the true galaxy redshift distribution by cross-correlating galaxies in photo-z bins with a bright subsample with known spectroscopic redshifts.

Tests With Observations

As a pure imaging survey LSST will rely on photo-z's for all redshift information. Some of the LSST science goals require extremely well calibrated photo-z's. For example, single technique probes of dark energy would need random and systematic errors less than 0.003-0.01 per redshift bin for dark energy parameter precision to degrade by less than 50%. However, joint WL and BAO results are less affected by photo-z systematics because of self-calibration (*see poster 460.05*). We are working on several fronts to develop better photometric redshift algorithms and validate calibration techniques to assure that we meet LSST calibration goals. We are now assembling a variety of datasets for this work. This involves both gathering larger spectroscopic samples in fields with LSST-like photometry, and obtaining LSST-like photometry in fields with spectroscopic samples. Spectroscopic redshifts can then be used to test and calibrate photo-z's.

LSST will reach magnitudes much too faint to observe large spectroscopic samples. Therefore, photo-z calibrations will be able to rely on spectroscopic redshifts only for brighter objects. We are now exploring several techniques to deal with this. One promising method is to obtain both deep spectroscopy and many-band, deep, multi-wavelength photometry (from UV to near-IR) in some small set of fields. Multi-wavelength photometric redshifts ("super-photo-zs") are more robust than those based solely on optical photometry, due to the presence of features (e.g. the Lyman break and 1.6 micron bump) which are strong in galaxies of almost all star-formation histories (see **Figure 1**).

Figure 1: Simulated spec-z vs photo-z plot for 17 band super-photo-z. By adding deep multi-wavelength data, we are able to accurately measure photo-z's to z>3.



Improving Photo-z Estimates

LSST will image galaxies in the distant past, where conditions are not the same as those seen in the local universe, and thus populations at high redshift can be markedly different than those in the local universe. Currently, photo-z algorithms assume that galaxy templates do not change with redshift or luminosity. We are working to improve photo-z algorithms in order to minimize bias and better identify catastrophic redshift failures. This includes methods for refinement of galaxy templates and filter curves (Margoniner *et al.* 2007), as well as incorporating evolution into the templates.

Galaxies of different types are not distributed uniformly in space, thus we can use additional information on galaxy type to infer more accurate redshifts in the form of Bayesian priors on our redshift likelihoods. These priors are particularly helpful in reducing the number of "catastrophic failures", where the redshift estimate is drastically wrong. While apparent magnitude priors are in common use currently (Benitez 2000), we are working to incorporate additional observables, such as surface brightness, concentration, and galaxy shape in order to further aid in reducing photo-z outliers. We can also identify areas of color space prone to degeneracies and remove them, a technique known as color tomography (Jain *et al.* 2006).

Characterizing redshifts using photometry in six broad bands means that, in practice, our redshift estimates can have a large uncertainty. Accurate estimates of these uncertainties are needed in order to minimize bias. Using the full probability density function (PDF), rather than a point estimate of redshift, allows for a far more accurate measurement of the overall redshift distribution and enables a more efficient identification of catastrophic outliers (Mandelbaum *et al.* 2008, Wittman *et al*, in prep, see **Figure 2**).

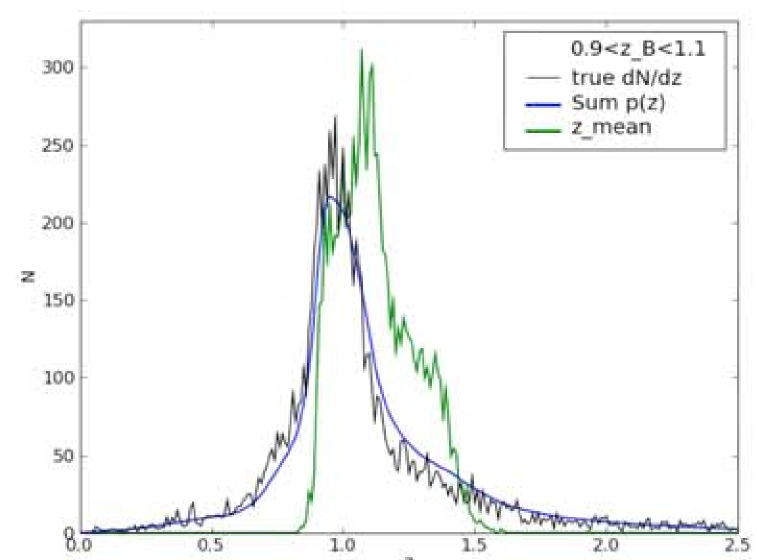


Figure 2: N(z) for a 4-band Deep Lens Survey photo-z bin selected with a point estimate of redshift. Black shows the true spec-z distribution, green shows a second point estimate photo-z, and blue gives the distribution recovered by summing the full PDF for each of the photo-z's. Using the full likelihood gives much more reliable measures of both the true width and bias of the redshift distribution.

Mock Galaxy Catalogs

In addition to supplemental observations, we are simulating mock galaxies in order to test our photometric redshift methods. We create catalogs based on light cones from the Millennium dark matter simulation (Croton *et al.* 2006, Kitzbichler & White, 2007, see **Figure 3**), which populate dark matter halos with galaxies using a semi-analytic model of galaxy formation, incorporating effects of star formation, stellar population synthesis, AGN feedback, and dust, amongst others, in a way that is consistent with the assembly history of their host dark matter halos. The galaxies in these mock catalogs exhibit realistic relationships between luminosities, colors, and redshift by incorporating the physics of galaxy evolution. See **Figure 4** for examples of the galaxy spectral energy distributions.

This representative mock dataset enables more realistic tests of super-photo-z's as secondary calibrators for LSST. We use the simulations to examine the effects of changing signal-to-noise ratios and adding photometric bands on the performance of our photo-z's, allowing us to find the combination of filters, depths, and spectroscopic training sets that optimize photo-z performance. We are also test strategies for identifying outlier populations in poorly constrained regions of parameter space (tomography).

Figure 3: An illustration of how semi-analytic galaxies (*red and blue dots*) are added to dark matter halos (*white*) in the Millennium Simulation (Springel *et al*, 2005 .)

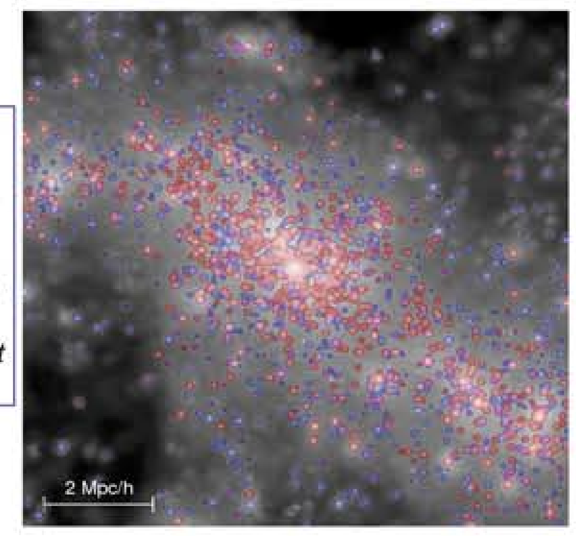
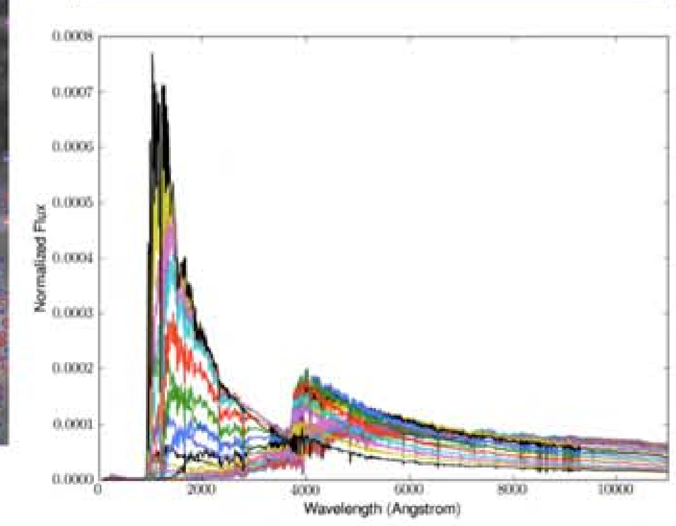


Figure 4: A subsample of the SEDs (vs rest wavelength) from our mock galaxy catalogs.



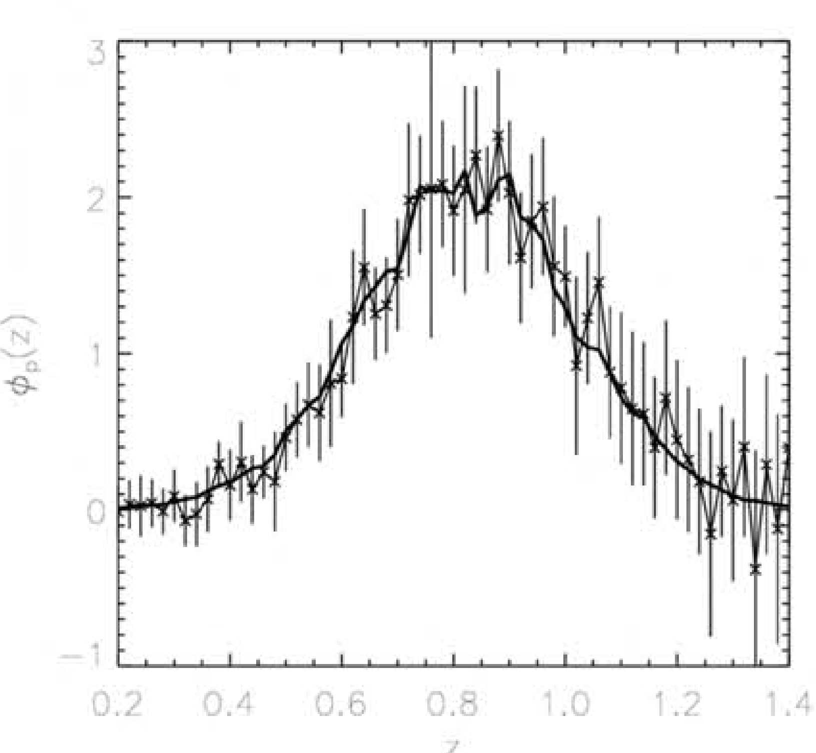
Large-Scale Structure Based Calibrations

Even at magnitudes much brighter than LSST will reach, spectroscopic training samples are systematically incomplete. This poses a significant problem for photo-z calibration, particularly if bright populations span a different range of SEDs than faint objects (as is true locally, and may be worse at high redshift, see Jimenez & Haiman 2006).

Calibrations using large-scale structure (LSS) information can avoid these problems. All populations of galaxies cluster with each other in three dimensions, and hence also in projection. Since the clustering is local, the observed angular correlation between two sets of galaxies will depend on the degree to which they overlap in redshift, in addition to the strength of their clustering in three dimensions (their 'bias'), thus we need only some spectroscopic sample that spans the expected redshift range. We estimate that a sample of 10^2 -10^4 galaxies per unit redshift is sufficient to reach various LSST calibration goals.

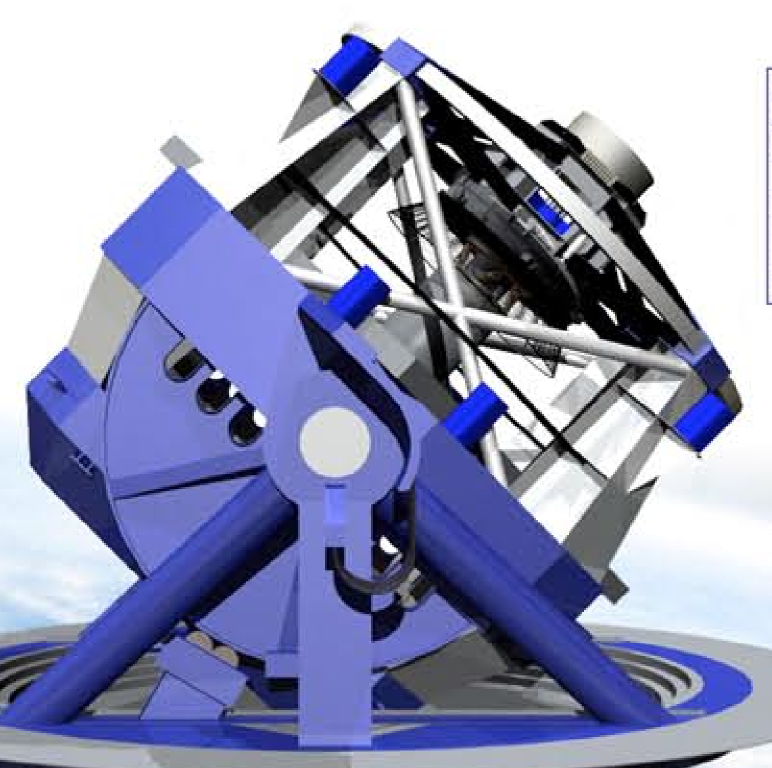
We are now testing cross-correlation techniques (Newman 2008) which can recover the true redshift distribution of any photometric sample using spectroscopy of only the brightest galaxies at each redshift (or any other sample, uniformly selected or not, see **Figure 5**). With realistic photometric and spectroscopic samples drawn from the Millennium Simulation mock catalogs described above, we find that cross-correlation techniques can, in fact, recover the redshift distribution of objects with strongly different properties, including different evolution in clustering strengths as a function of redshift, using mock spectroscopic samples comparable to existing redshift surveys.

Figure 5: Test of reconstruction of redshift distribution using cross-correlation. The solid line shows the true redshift distribution for a sample of mock galaxies drawn from the Millennium simulation. Points with error bars show the median and RMS of reconstructions from measuring cross-correlations with a sparse spectroscopic sample comparable to the DEEP2 Galaxy Redshift Survey (60% of R_{AB}<24.1 objects in four 0.5x2 degree fields). Covariance amongst bins is minimal (Newman 2009).



References:

Benitez, 2000, ApJ, 536, 571
Croton *et al.* 2006, MNRAS, 365, 11
Jain, Connolly, & Takada, 2007, JCAP, 03, 13
Jimenez & Haiman, 2006, Nature, 440, 501
Mandelbaum *et al*, 2008, MNRAS, 386, 781
Margoniner & Wittman, 2008, ApJ, 679, 31
Newman, 2008, ApJ, 684, 88
Newman, 2009, in prep.
Schmidt *et al.*, in prep
Wittman *et al.* in prep



LSST is a public-private partnership. Design and development activity is supported in part by the National Science Foundation. Additional funding comes from private gifts, grants to universities, and in-kind support at Department of Energy laboratories and other LSSTC Institutional Members.