Probing Dark Energy with Weak Lensing with LSST

Ian P. Dell'Antonio[1], D. Wittman[2], B. Jain[3], J. Bosch[2], D. Clowe[4], M. Jarvis[3], M. Jee[2], J. Tyson[2], H. Zhan[5], LSST Weak Lensing Science Collaboration
[1]Brown University, [2]UC Davis, [3]University of Pennsylvania, [4]Ohio University, [5]National Astronomical Observatories of China

LSST will measure the shape, magnitude, and colors of more than 3×10^9 galaxies over 20,000 square degrees. Reconstruction of the shear power spectrum on linear and non-linear scales l≤2000, and of the cross-correlation of shear measured in different photometric redshift bins, provides a constraint on the evolution of dark energy that is complementary to the purely geometric measures provided by supernovae and BAO. Combining weak lensing and BAO measurements breaks degeneracies and results in tighter constraints on dark energy than each method can provide individually. Cross-correlation of the shear and galaxy number density signal within redshift shells minimizes the impact of photo-z errors on dark energy constraints. Measurements of the shear bispectrum provide complementary constraints on dark energy and allow an independent test of theories of gravity. In addition to the galaxy shape correlations, LSST will detect ~ 50,000 shear peaks with significance greater than 4σ, and ~ 10,000 securely detected clusters of galaxies with line-of-sight velocity dispersions greater than 700 km/s. These allow independent constraints on the dark energy signature in the growth of structure. Tomographic study of the shear of background galaxies as a function of redshift allows a geometric test of dark energy. Finally, lensing signatures beyond the shear (magnification and flexion) will be accessible with LSST with unprecedented statistical power. .

Introduction

Weak Gravitational lensing has long been identified as a prime technique for measuring dark energy (Albrecht et al. 2006). As light from distant galaxies travels to Earth, distortions are imprinted in their shapes and sizes according to the pattern of mass overdensities. This distortion depends both on the evolution of mass clustering and on the angular diameter distances involved, both of which are affected by the dark energy density (and its evolution) directly and in different ways.

Because the distortion of the vast majority of distant galaxies is very small compared to the intrinsic observed ellipticity of the sources, the weak gravitational measurements depend on the statistical measurement over many sources. By mapping 20,000 square degrees of the sky repeatedly, LSST will measure shapes and magnitudes in 5 bands for more than 40 galaxies per square arcminute and construct a sample of more than 3 billion galaxies for weak lensing analyses.

Shear correlation functions

The single most important weak lensing measurement from LSST will be the measurement of the shear-shear correlation functions as a function of source redshift. If we describe the ellipticity in terms of the shear components γ_+ and $\gamma_\times$, and we bin the galaxies into tight and non-overlapping redshift bins, we can define the two point correlations between redshift bins i and j :

$\xi_+(\theta) = \langle \gamma_{i+}(\boldsymbol{\theta}_1)\gamma_{j+}(\boldsymbol{\theta}_2)\rangle$ and $\xi_\times(\theta) = \langle \gamma_{i\times}(\boldsymbol{\theta}_1)\gamma_{j\times}(\boldsymbol{\theta}_2)\rangle$

Using the cross-correlations, we can define their Fourier transforms as the shear-shear power spectra $C_{\gamma i \gamma j}(l)$. These shear power spectra are directly related to the mass power spectrum and to the cosmological scale factors:

$$C_{\gamma_i\gamma_j}(\ell) = \int_0^\infty dz\, \frac{W_i(z)\, W_j(z)}{\chi(z)^2\, H(z)}\, P_\delta\left(\frac{\ell}{\chi(z)}, z\right)$$

Each cross-correlation is a direct test of the dark energy. LSST will map about 20x more galaxies than any previous survey, and cover a factor of 4 more area than any previous survey, resulting in tighter constraints at all redshifts. Given the expected photometric redshift uncertainty Δz~0.04/(1+z), LSST will measure correlation functions in 10 independent redshift bins. Because clustering is non-linear, the shear power spectra are not independent at each wavenumber. Careful modeling is necessary to extract the uncertainty in cosmological constraints from the shear power spectrum (Jain et al. 2011).

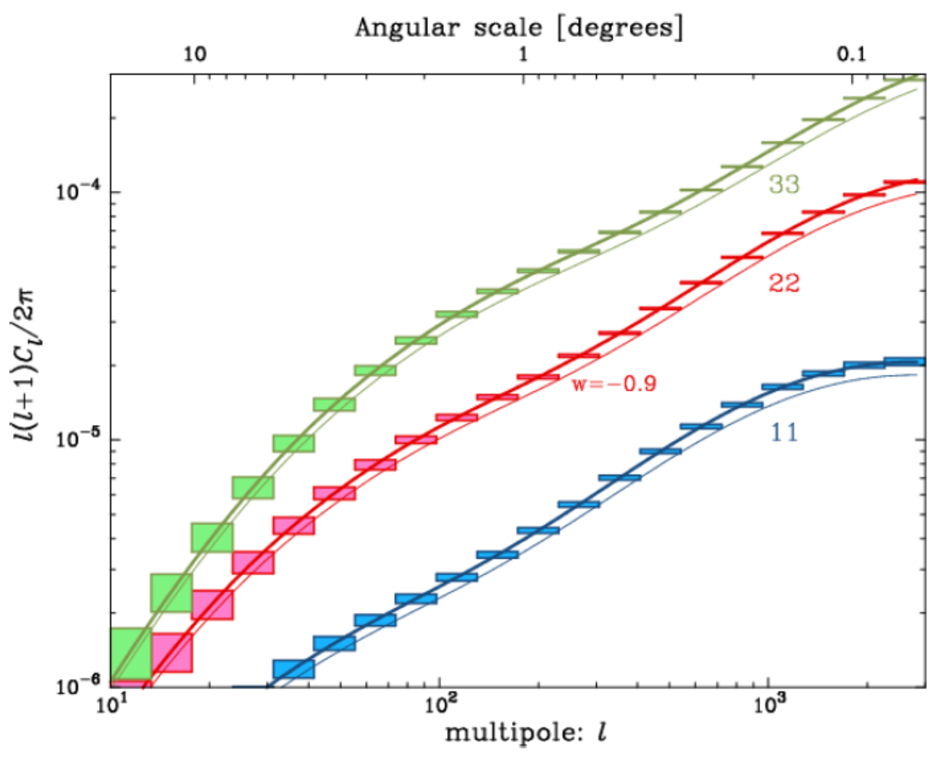


Figure 1: The lensing power spectra constructed from galaxies split into three broad redshift bins: z < 0.7, 0.7 < z < 1.2, and 1.2 < z < 3. The solid curves are predictions for the fiducial CDM model and include nonlinear evolution. The boxes show the expected measurement error due to the sample variance and intrinsic ellipticity errors.
The thin curves are the predictions for a dark energy model with w = −0.9. LSST will be able to construct 10 separate redshift bins, leading to about 100 auto- and cross-power spectra.
Source: LSST science Book V2 (2009)

Higher order correlations—the bispectrum

The shear power spectrum does not encode all of the cosmological information contained in the shear correlation functions. Because of non-linear clustering, the three point correlation function, or its fourier transform, the bispectrum, contains significant signal. Because the bispectrum depends on the geometry of the Universe in a different way than the shear power spectrum (Takada & Jain 2004), measurement of the bispectrum improves the cosmological constraints and reduces the effect of systematic errors in shape measurements compared to just using the shear correlations.

Galaxy-shear cross-correlations

In addition to shear-shear cross-correlations, LSST will measure the galaxy-shear and galaxy-galaxy cross-correlations. Because these statistics together can calibrate important systematic errors for either shear or galaxy method alone, combining the measurements greatly improves the cosmological constraints from both methods. Figure 2 shows that systematic uncertainties in the photo-z error distribution can weaken the WL (shear-shear correlations) constraints on the dark energy equation-of-state (EOS) parameters considerably. When all the shear and galaxy cross-correlations are analyzed jointly, the constraints are much tighter and less susceptible to photo-z systematics.

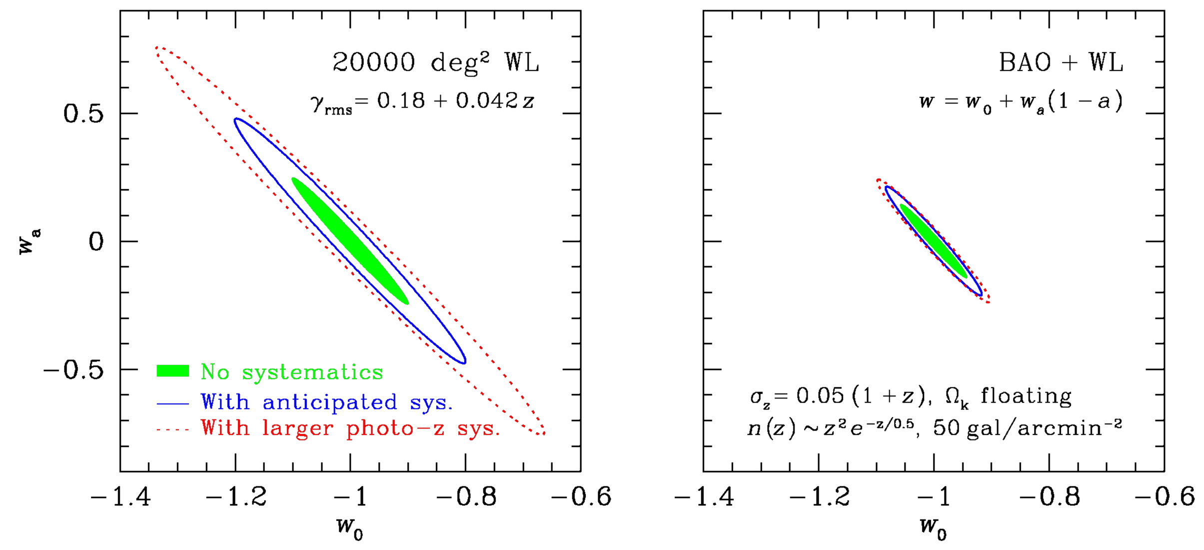


Figure 2: Complementarity between WL (shear two-point correlations) and BAO (galaxy two-point correlations). The dramatic improvement of the BAO+WL results (right) over the WL-alone results (left) is due to the cross-calibration of galaxy bias and photo-z uncertainties and is independent of the dark energy EOS parametrization. The assumed photometric redshift systematics would require a redshift calibration sample of 3000 spectra per unit redshift interval if the photometric redshift error distribution were Gaussian. The dotted contours relax the requirement to 188 spectra per unit redshift.

Galaxy Clusters—cluster mass function

Because galaxy clusters are the largest virialized structures in the Universe, the evolution of the cluster mass function with redshift is a powerful constraint on the growth of structure (and dark energy). Because the cluster number counts measure the growth of structure in the highly non-linear regime, they provide constraints on dark energy that are almost independent of the shear cross-correlation constraints (Takada & Bridle 2007). Based on the results obtained so far (Wittman et al. 2006, Miyazaki et al. 2007), LSST will detect 10,000-15,000 clusters of galaxies in the redshift range 0.2<z<0.7 with sufficient S/N for their mass to be determined to better than 20% random uncertainty.

Shear peak statistics

Because the redshift kernel in the weak gravitational lensing sensitivity is so broad, weak lensing measurements of clusters will be subject to contamination by structures along the line of sight. This introduces an irreducible uncertainty of ~30% on individual cluster mass measurements (Hoekstra et al. 2010). Superpositions of smaller groups along the line of sight will also be detected as a single shear ``peak". However, even these superpositions encode information about the growth of structure (Marian et al. 2009), and thus constrain dark energy (Wang, Haiman & May, 2009).

Cluster Tomography

The distortion of background galaxies behind an individual cluster of galaxies depends only on the ratio of angular diameter distances. Therefore, the cosmological expansion of the Universe is mapped by the amplitude of the distortion as a function of background galaxy redshift. In practice, we average the tomographic signal over many clusters to obtain a cosmological constraint (Jain & Taylor 2003). LSST will allow measurement of the tomographic signal for a sample 100 times larger than any studied so far, yielding a dark energy measure that is competitive with that due to the shear correlations.

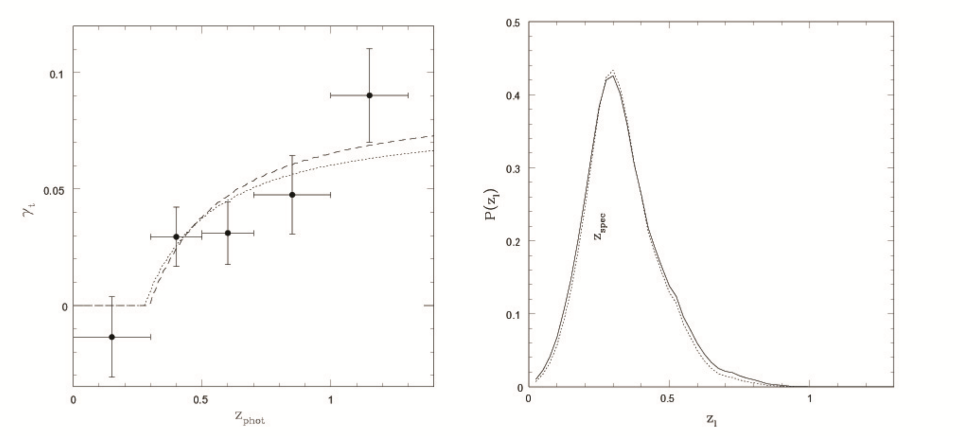


Figure 3. Left panel: the tangential shear as a function of redshift behind the galaxy cluster DLS1054-0305 (Wittman et al. 2003). The lines represent different cosmological models. LSST will measure the tangential shear with error bars 2x smaller than this for more than 10,000 clusters. Right: the probability distribution of the cluster redshift derived from the shear tomography alone.

Tests of Theories of Gravity

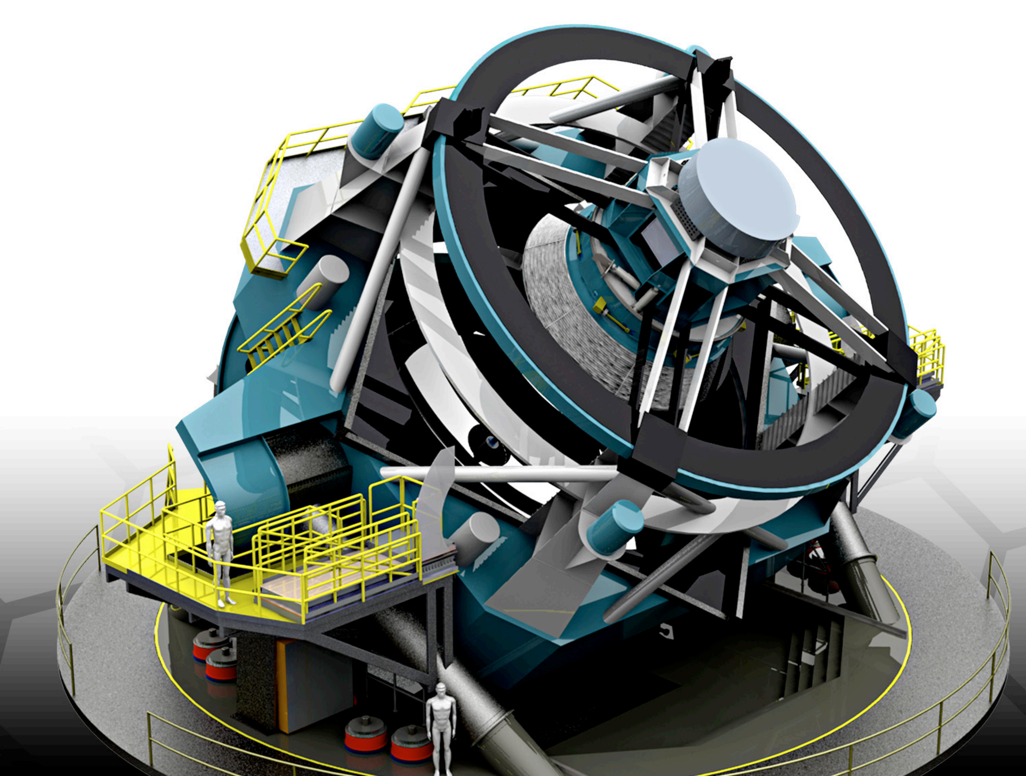
We will combine the weak lensing results with those from techniques that measure the geometry of the universe (supernovae or BAO) to test the nature of gravity. General relativity and alternate gravity theories (such as f(R) gravity) make different predictions for the relation between the geometry and the growth of structure. Demanding consistency between the different measurements of dark energy can therefore act as independent test of general relativity. (Wang et al. 2004)

Ellipticity Systematics

Although the combination of different gravitational lensing techniques and the cross-correlation with the galaxy power spectrum provides numerous cross-checks on the effect of shape systematics, LSST will still be in the regime where the largest contribution to the uncertainty in the dark energy parameters arises from systematic errors; see Jee et al. and Chang et al. in this poster session.

References

Albrecht et al. , 2006, DETF report
Hoekstra, H., et al., 2010, arXiv1011.1084
Jain, B, et al., 2011, in preparation.
LSST Science Book v2., 2009—arXiv0912.0201
Marian, L. et al., 2009, ApJL, 698, 33
Mathews, D.J., & Newman, J.A., 2010, ApJ, 721, 456
Miyazaki, S., et al., 2007, ApJ, 669, 714
Takada, M., & Bridle, S., 2007, NJPh, 9, 446
Takada, M., & Jain, B., 2004, MNRAS, 348, 897
Wang, S., et al., 2004, PhRvD, 70, 12308
Wang , S., Haiman, Z. & May, M., 2009, ApJ, 691, 547
Wittman, D. et al., 2003, ApJ, 597, 218
Wittman, D. et al., 2006, ApJ, 643, 128



January 2011

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.