Large Synoptic Survey Telescope

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# Multiple Probes of Dark Energy with LSST

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**The 27.6 *r* magnitude limit of the 20,000 square degree LSST image stack enables photometry of ten billion galaxies to low surface brightness and shape measurement of several billion galaxies. A number of independent cross checking probes of the nature of dark energy will result. Using many photometric redshift bins, the joint analysis of 2-D baryon acoustic oscillations and weak lensing cosmic shear is particularly powerful. The half-sky LSST six band survey will address dark energy physics by exploiting a diversity of simultaneous precision probes.**

**When combined with the CMB data these tests form interlocking checks on cosmological models and the physics of dark energy. The LSST wide angular coverage data is also capable of uncovering anisotropy in dark energy. LSST is being engineered to minimize and control systematics at a level ten times below the smallest signal of interest. Systematic error experiments using the Subaru telescope are incorporated. Reconstruction of galaxy images from fitting models to the full image stack can overcome residual PSF systematics. Full system simulations of LSST dark energy performance are shown.**

**Weak Lensing:** A big advantage for WL is the ability to do 3-D tomography. Examples of the shear power spectrum are given in Figure 1. WL tomography requires redshifts for the source galaxies, from which we can derive the mass distribution and cosmic geometry as a function of redshift. WL thus has sensitivity to the evolution of dark energy. LSST's multi-color deep imaging survey will provide photometric redshift information for galaxies to z = 3. A combination of spectroscopy and angular correlations of galaxies can produce a calibration of photometric redshifts to the precision required to perform lensing tomography. See related posters by Jee *et al.* and Schmidt *et al.*

**Baryon Acoustic Oscillations:** The low-z signature of the CMB sound horizon at decoupling is a set of peaks in the galaxy power spectrum. The LSST survey will provide a sample of four billion galaxies. Photometric redshifts will be used to collect these galaxies into redshift bins, and the galaxy angular power spectrum can then be computed as a function of redshift. Simulations of the quality of the data we expect are given in Figure 2. The BAO peaks are cleanly detected for redshifts ranging from z ~ 0.3–2.7. The corresponding angular diameter distance will be measured to ~0.4% accuracy, especially at higher redshift (Zhan, Knox, Tyson 2009 ApJ).

**Shear peaks:** Simulations show that LSST will detect ~100,000 giant shear peaks, potentially yielding constraints on $w_0$ at the 8 percent level (Fang & Haiman 2007). Like the supernova probe of dark energy, this technique has astrophysical systematics which will have to be understood if it is to be fully competitive with weak lensing and baryon acoustic oscillations.

**SNe:** Over a ten year run, an average ~15 minutes per night spent staring at fifty 10 square degree fields will yield SNe with a mean redshift of 0.75 and a distribution that extends to z > 1. A 3-5 day cadence will cycle among the five filters resident in the camera, following tens of thousands of SNe throughout their evolution with over 100 photometric points per light curve. Such detailed light curves will allow fitting for photometric redshifts from the SNe themselves. This large SN sample enables investigation of possible evolution in the "standard candle" by discovering correlations with other parameters.

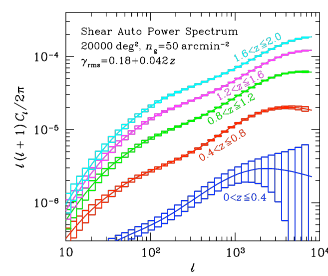



FIGURE 1: The lensing cosmic shear power spectra constructed from 5 redshift bins. Here, *l* is the multi-pole moment of the distribution on the sky, and the vertical scale is proportional to the rms fluctuation of the power spectrum per log interval in *l*. Only the 5 auto-power spectra of each redshift bin among the available 15 co-spectra are displayed, and the solid curves show the predictions for the concordance ΛCDM model. The boxes show the expected 1-σ measurement error due to the sample variance and intrinsic ellipticities (the sample variance is dominant at about *l* < 1000, while the intrinsic ellipticities are dominant at *l* > 1000). In fact, a larger number of redshift bins will be enabled by LSST leading to ~200 auto-and cross-spectra.

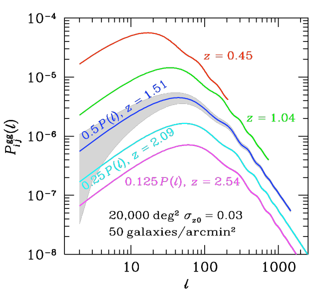



FIGURE 2: Angular galaxy auto power spectra in 5 redshift bins (shifted for clarity). Bin width increases from 0.1 to 0.22 for the bins shown. The BAO features are prominent at multipole *l* ~ several hundred. The grey area indicates the statistical error (cosmic variance and shot noise) per mode for the bin centered at z = 1.51. The truncation of the power spectra at high *l* is to reduce the impact of nonlinear evolution in our forecasts.

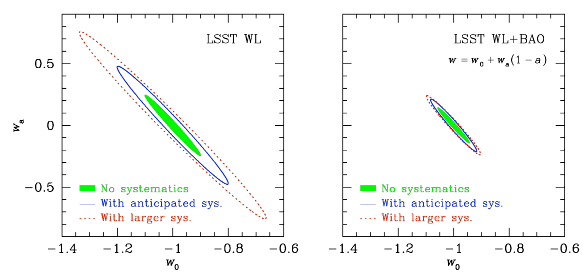



FIGURE 3: The joint WL and BAO results are less affected by the systematics because of the ability to self-calibrate. 1σ error contours of the dark energy parameters from LSST WL (*left panel*) and joint LSST WL and BAO (*right panel*). The shaded areas represent the results with statistical errors only. The solid contours correspond to those with the anticipated level of systematic errors, which include the uncertainty in the photo-z error distribution [ σ(photo-z bias) = 0.05$\sigma_z$, σ($\sigma_z$) = √2 0.05$\sigma_z$ ] and additive (noise power = $10^{-10}$) and multiplicative (0.5%) errors in the power spectra. These assumed photo-z systematics would require a redshift calibration sample of 2000 spectra per unit redshift interval if the photo-z error distribution was Gaussian. The dotted contours increase the shear additive error to $10^{-9}$ and relax the photo-z calibration requirement to 125 spectra per unit redshift. A much larger sample of 10,000 per unit *z* will be needed for realistic photo-zs.

The use of multiple probes may also allow us to discriminate whether dark energy is due to new physics in the stress-energy tensor or due to new gravitational physics. This is because these probes are sensitive to both the distance-redshift relation and the rate of growth of the large-scale density field. If the dynamical history of the Universe becomes well constrained by these measurements, we can use the growth of structure to constrain new gravity models.

Because of its uniquely high étendue, the LSST survey will produce all four complementary probes of dark energy from the same survey data. Combining these multiple probes with the CMB data will remove degeneracies and will make it possible to determine all parameters from the data, without external priors. The combination of BAO with WL is especially powerful. BAO+WL benefits from additional information in the density-shear correlation which is not captured in either technique alone. WL data can help BAO calibrate galaxy linear clustering bias (the relation between dark matter and galaxy density) which is degenerate with linear growth of structure. At the same time, galaxy auto and cross power spectra help calibrate the photo-z errors for WL. Figure 4 shows an estimate of the precision in 2-parameter dark energy model space for the LSST survey by combining four of its four probes in a global fit to 11 cosmological parameters. Curvature is fit with the data rather than assumed as a prior. The galaxy-mass bias is calibrated out via the WL data, thus removing a major degeneracy. More general dark energy models are constrained well (2008 Barnard, *et al.* PRD 78, 43528)

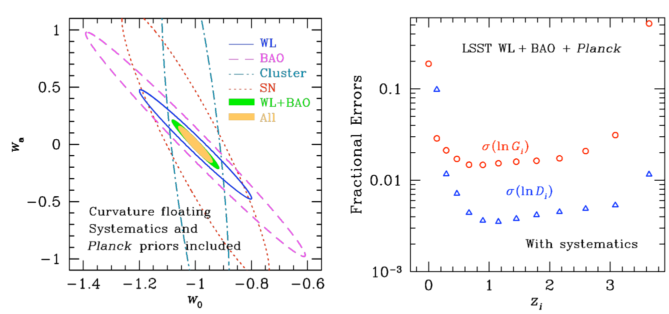
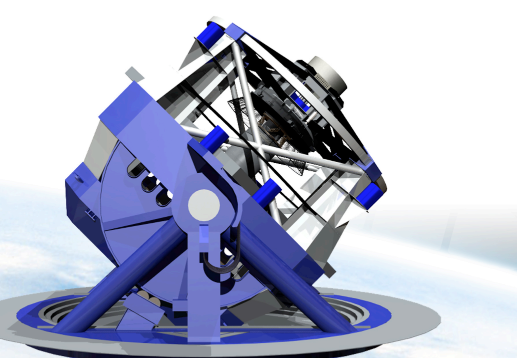



FIGURE 4: *Left panel*: Forecasts of LSST errors on the dark energy equation-of-state parameters $w_0$ and $w_a$ for BAO, WL, Cluster, SN, plus two and all four combined. The constraints are marginalized over 9 other cosmological parameters including the curvature and over 120 parameters that model the linear galaxy clustering bias, photometric redshift bias, and rms photometric redshift error (Zhan 2006). Different theoretical models of dark energy span this $w_0$ $w_a$ space, and smaller errors imply increased power of discrimination. Combining four probes has even higher power of discrimination for more general dark energy models:
*Right panel*: The precision in distance measurement (blue) and growth of structure measurement (red) opens the possibility of testing more general higher dimensional theories of acceleration. Schmidt PRD 78, 43002 (2008); Knox, *et al.* PRD 74, 23512 (2006).



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