Large Synoptic Survey Telescope

Four LSST Probes of Dark Energy

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The half-sky LSST six band survey of four billion galaxies will address dark energy physics by exploiting a diversity of precision probes:

- **Weak lensing tomography (WL) of galaxies vs. redshift, which probes both distances and the evolution of structure vs. redshift, setting multiple independent constraints on dark energy.**
- **Spatial correlations of galaxies (Baryon Acoustic Oscillations, BAO) vs. redshift utilizes the "standard ruler" of the peak in the correlation of dark matter revealed in the temperature anisotropies in the cosmic microwave background (CMB).**
- **The redshift distribution of shear peaks due to large structures of dark matter (via WL combined with the optical data) are a potentially sensitive probe of dark energy.**
- **Tens of thousands of supernovae are complementary for probing the recent cosmic era when dark energy becomes dominant.**

When combined with the CMB data these tests form interlocking checks on cosmological models and the physics of dark energy. The combination of BAO with WL is especially powerful. Astrophysical observations are susceptible to systematics, so the LSST is being specifically designed and 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 in these estimates. These diverse probes are complementary, removing degeneracies.

WL: 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 *etal.* and Schmidt *etal.*

BAO: 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 and Knox 2006).

Shear peaks: Simulations show that LSST will detect ~100,000 giant shear peaks, potentially yielding constraints on w_0 at the several percent level (Wang et al 2005). 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 WL and BAO.

SNe: Over a ten year run, an average ~15 minutes per night spent staring at several 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.

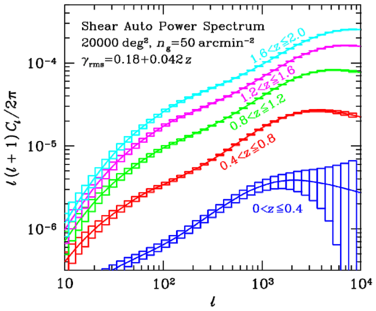


FIGURE 1: The lensing cosmic shear power spectra constructed from 5 redshift bins. Here, *l* is the multi-pole moment of the distribution on the sky, and the vertical scale is proportional to the power spectrum. Only the 5 auto-power spectra of each redshift bin among the available 15 co-spectra are 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.

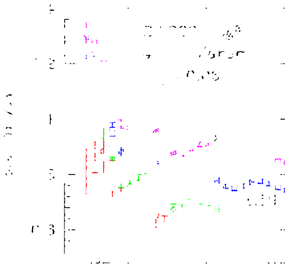


FIGURE 2: Simulations of the ratio of the measured galaxy power spectrum to a featureless reference power spectrum in various redshift bins (shifted vertically for clarity), for the full LSST survey using very conservative photo-z errors. The several peaks visible in each curve are the signature of baryon acoustic oscillations.

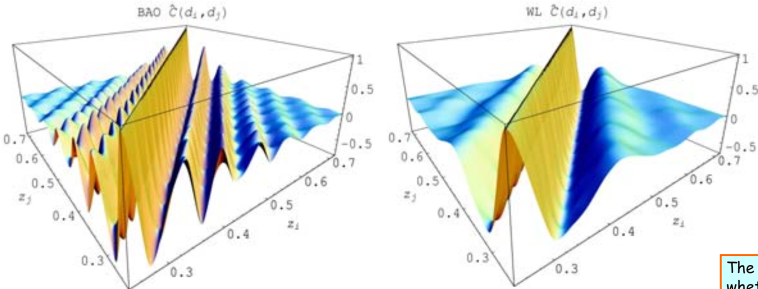


FIGURE 3: *Left panel*: Normalized covariance of the "reconstructed" distances from LSST BAO. Each element of the covariance matrix is scaled by the geometric mean of the corresponding diagonal elements, i.e., $\hat{C}_{ij} = C_{ij}\,(C_{ii}\,C_{jj})^{-1/2}$. The distance parameters are logarithmically spaced in (1+z) from z = 0.02 to 5. Only 18 distance parameters between z = 0.24 to 0.72 are presented here. The covariance matrix has been smoothly interpolated to show the underlying structure, and the discrete elements of the covariance matrix are identifiable with the peaks and troughs. *Right panel*: The same as the left panel, but for LSST WL. The WL technique renders a smoother distance covariance than the BAO technique, because the lensing kernel is much broader than the BAO (i.e., galaxy power spectrum) kernel. Dark energy constraints can be derived from the distance constraints. The stark difference between the two distance covariances means that the WL and BAO techniques have different degeneracies and can be very complementary to each other.

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 the cosmic shear is sensitive to both the distance-redshift relation and the rate of growth of the large-scale density field. In linear theory, the growth of structure depends on the gravitational force law and can be simply described. If the dynamical history of the Universe becomes well constrained by SN and BAO measurements, we can use the growth of structure diagnostics to constrain new gravity models (Knox et al. 2006; PRD 74, 3512).

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. *See also photo-z calibration poster by Sam Schmidt etal.* Figure 4 shows an estimate of the precision in 2-parameter dark energy model-space for the LSST survey by combining two 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. The effect of combining three or four of the LSST probes of dark energy constrains models even more sharply.

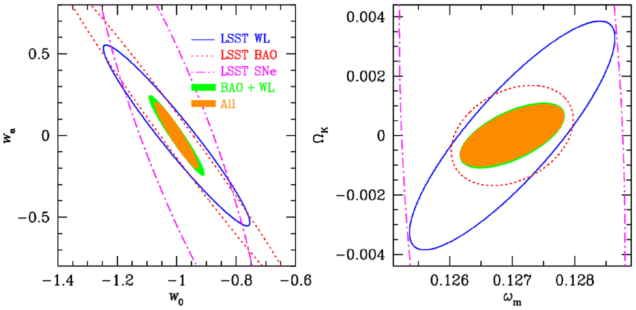
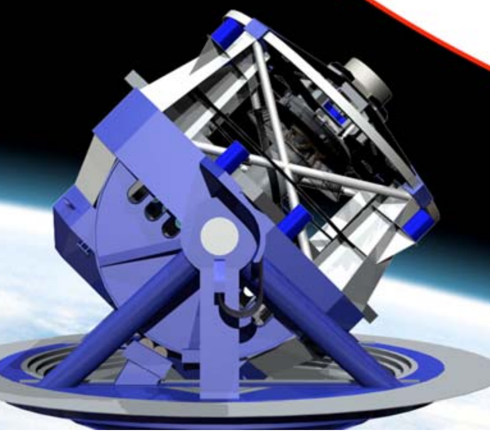


FIGURE 4: *Left panel*: Forecasts of LSST errors on the dark energy equation-of-state parameters w_0 and w_a for BAO, WL, SN, plus two and three combined. The constraints are marginalized over 9 other cosmological parameters including the curvature and over 120 parameters that model the linear galaxy clustering bias, photometric redshift bias, and rms photometric redshift error (Zhan 2006). *Right panel*: The same as the left panel, but for the matter density ω_m and curvature term Ω_k. Note that CMB alone can constrain ω_m to 1% (it does poorly on the curvature). Cluster counting (or, more robustly, shear peak statistics) and cluster power spectrum can potentially place strong constraints as well. Different theoretical models of dark energy span this w_0 w_a space, and smaller errors imply increased power of discrimination.



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