Large Synoptic Survey Telescope

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LSST Probes of Dark Energy: New Energy vs New Gravity

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Is the late time acceleration of the universe due to new physics in the form of stress-energy or a departure from General Relativity? LSST will measure the shape, magnitude, and color of 4 billion galaxies to high S/N over 18,000 square degrees. These data will be used to separately measure the gravitational growth of mass structure and distance vs redshift to unprecedented precision by combining multiple probes in a joint analysis. Of the five LSST probes of dark energy, weak gravitational lensing (WL) and baryon acoustic oscillation (BAO) probes are particularly effective in combination.

By measuring the 2-D BAO scale in *ugrizy*-band photometric redshift selected samples, LSST will determine the angular diameter distance to a dozen redshifts with sub percent-level errors. Reconstruction of the WL shear power spectrum on linear and weakly non-linear scales, 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. Cross-correlation of the WL shear and BAO signal within redshift shells minimizes the sensitivity to systematics. LSST will also detect shear peaks, providing independent constraints. Tomographic study of the shear of background galaxies as a function of redshift allows a geometric test of dark energy.

Successful point-spread function (PSF) modeling will be the key to controlling the systematics for both BAO and WL in the survey, and is necessary to distinguish between the two forms of new physics. In order to account for PSF spatial variation on all scales, a CCD-by-CCD principal component analysis (PCA) technique is applied, and modeled PSFs are interpolated across the entire focal plane. Each galaxy model is convolved with the interpolated PSF and then a fit is performed using a powerful Bayesian forward-modeling algorithm called *Stack-Fit*.

Introduction

Is dark energy a cosmological constant? Is it isotropic and homogeneous? Could acceleration be caused by modified gravity? Given the wide range of possible explanations for the dark energy, there is strong justification for multiple tests, including purely geometrical ones such as distance vs. redshift relations, and probes of the growth of mass structure through weak lensing.

The LSST is optimally designed to answer these questions, and through the combination of multiple types of survey measurements, to provide answers and obtain unprecedented constraints on models of dark energy. One such combination in particular, weak lensing and angular BAO, probes the same large scale structure and thus has cross-calibrating systematic uncertainties. A joint analysis of both shear and galaxy overdensity can reduce sensitivity to shear systematic error.

Throughout its nominal 10 year survey, the LSST will achieve a galaxy number density of 60 galaxies per square arcminute at a limiting magnitude of r=27.5 mag. Through an appropriate shear noise-weighting technique, an effective density of 40 galaxies per square arcminute will be used for the WL analysis. Six band photometry across half of the sky will allow for more accurate photometric redshifts (photo-z's), thus providing increasingly lower statistical errors on dark energy model parameters, as Figure 1 illustrates below. The complete dataset provided by the survey classifies the LSST as a Stage 4 (or better) survey according to the Dark Energy Task Force.

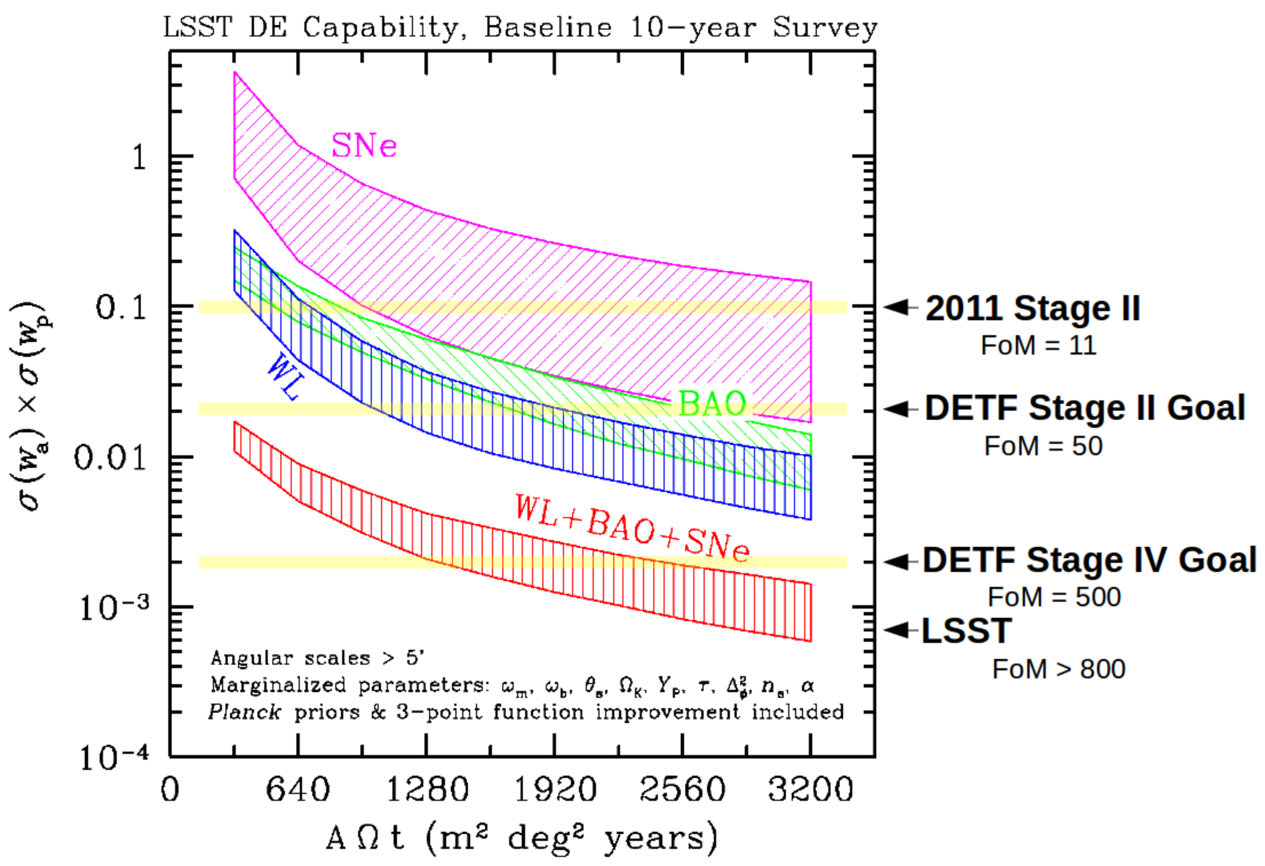

Figure 1: By jointly analyzing multiple probes of dark energy, the precision increases with time. Shown is the inverse of the Dark Energy Task Force figure of merit (FoM) as a function of time, for a baseline 10 year survey. The FoM is defined as the reciprocal of the product of the error on the equation of state w_p and the error on its evolution with cosmic scale factor w_a defined in the w_0-w_a plane (Fig 2).

Joint Analysis of WL and BAO

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 methods 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. However, when all the shear and galaxy cross-correlations are analyzed jointly, the constraints are much tighter and less susceptible to photo-z systematics.

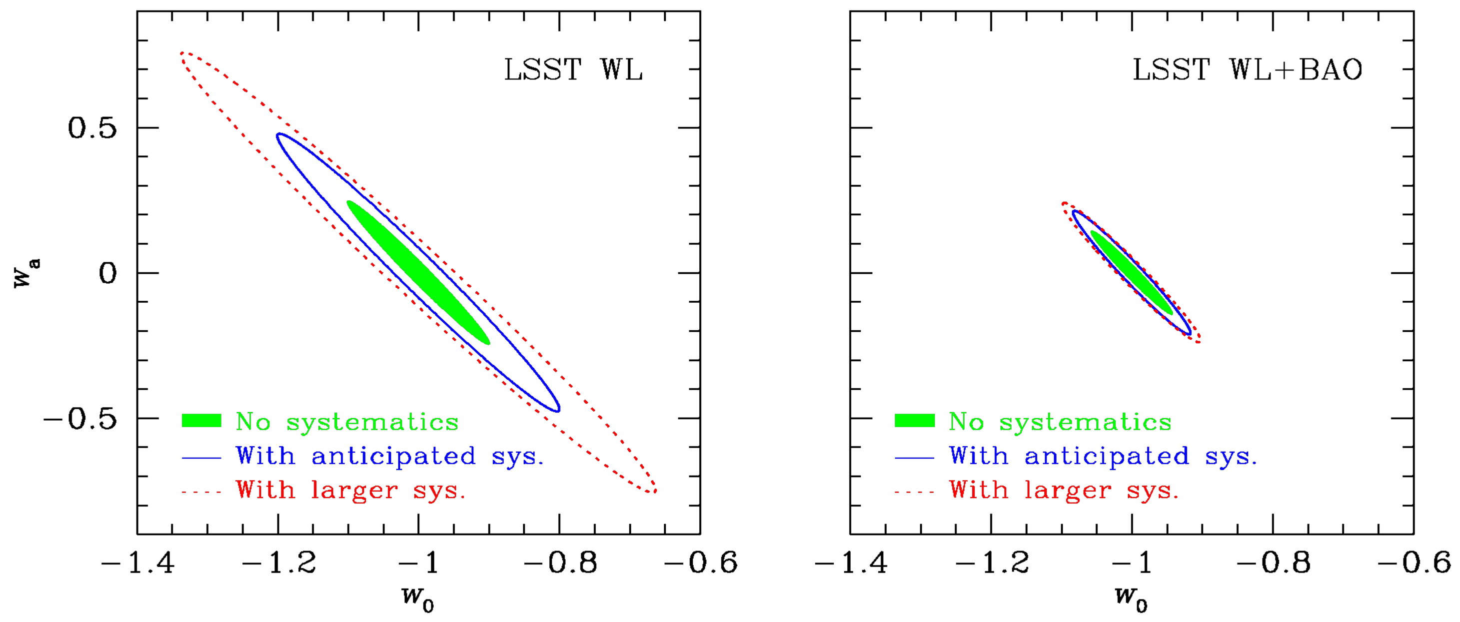

Figure 2: Jointly analyzing pairs of probes reduces sensitivity to systematic errors in each. These plots show the complementarity between WL (shear two-point correlations) and BAO (galaxy two-point correlations), parameterizing the EOS as $w(a) = w_0 + w_a(1-a)$. The dramatic improvement of the BAO+WL 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 parameterization. Three levels of photometric redshift systematic error were introduced in this simulation of LSST performance.

PSF and Shape Measurement

The shear of a typical background galaxy due to WL by foreground dark matter structures is very small, on the order of 1% to 0.1% at large angular scale. In addition, anisotropies of the point spread function (PSF) are on the order 1 - 5% from atmosphere + optics, and source galaxy images are intrinsically elliptical. In order to extract the dark energy signal, these foreground signals must be removed and intrinsic ellipticities averaged over. To remove the effects of the PSF in each CCD image, the stellar PSF field is first modeled using principal component analysis (PCA). Separately, a noise-weighted co-add of all dithered images is made, and a model (un-blurred) profile for the galaxy is estimated. Using the same weights as in the image co-add, the PSF components from each frame are also combined to obtain a co-added PSF map. This map is used to interpolate the PSF at each galaxy's position, so that the PSF may be convolved with the model galaxy shape and then compared with the data. This forward-modeling technique, called *Stack-Fit*, leads to a significant reduction in shear systematic error and an enhancement in the number of usable faint galaxies at high redshift.

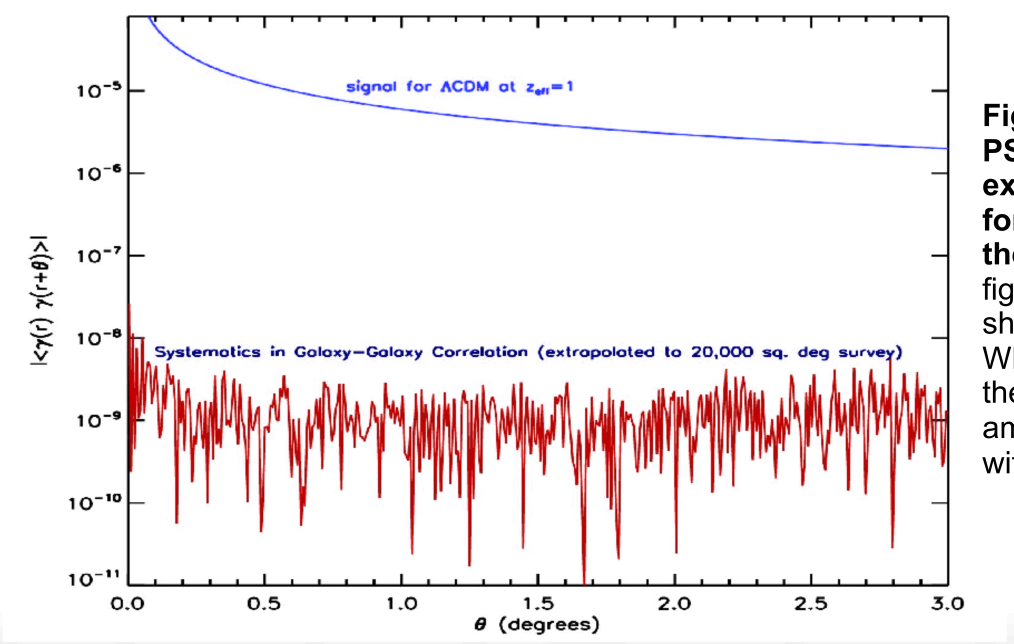

Figure 3: PCA analysis of the PSF on every CCD and every exposure can be used to correct for residual PSF systematics in the co-added deep image. This figure shows a simulation of galaxy shear-shear correlation with zero WL (Jee & Tyson 2011). Because there is no input shear, the residual amplitude should be consistent with the statistical noise as found.

LSST Precision on Dark Energy Parameters

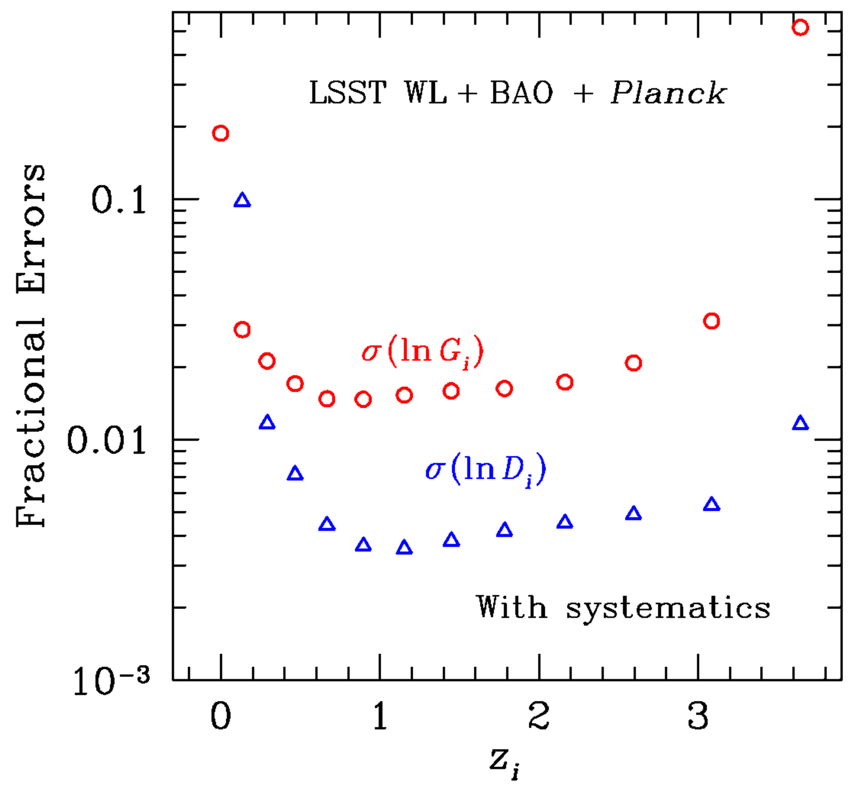

Figure 4: Theories of dark energy with more than 2 parameters can be confronted with the LSST data. Marginalized 1σ errors on the co-moving distance (blue triangles) and growth factor (red circles) from the joint analysis of LSST BAO and WL (galaxy–galaxy, galaxy–shear, and shear–shear power spectra) with a conservative level of systematic uncertainties in the photometric redshift error distribution and additive and multiplicative errors in the shear and galaxy power spectra. The precision in measurement opens up the possibility of measuring more general higher dimensional theories of acceleration (Zhan *et al.* 2009).

Conclusions

The combination of only two LSST probes (BAO and WL) removes degeneracies and yields high precision tests of dark energy models. This combination is much more powerful than the simple weighted mean. Joint analysis of five LSST probes of distance and growth is even more powerful. Multiple cross calibrations and checks will then allow for further reduction in systematic errors, making LSST data maximally sensitive to new physics. Finally, time domain lens tomography of flickering sources, and two independent probes of the anisotropy, enable tests of radical models of the physics of "dark energy."

Primary LSST probes	
Weak Lens shear cross correlation tomography	✓
2-D Baryon Acoustic Oscillations	✓
Supernovae	✓
Shear peak statistics	✓
Galaxy cluster counts	✓
Secondary LSST probes	
Time domain tomography of QSOs and AGNs	✓
Anisotropy of WL+BAO and SN signals	✓
New Energy or New Gravity?	✓

References

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