CONSTRAINING DARK ENERGY WITH THE DARK ENERGY SURVEY: THEORETICAL CHALLENGES

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1. Introduction

The Dark Energy Survey (DES) will use a new imaging camera on the Blanco 4-m telescope at CTIO to image 5000 square degrees of sky in the South Galactic Cap in four optical bands, and to carry out repeat imaging over a smaller area to identify and measure lightcurves of Type Ia supernovae.[1] The main imaging area overlaps the planned Sunyaev-Zel'dovich survey of the South Pole Telescope. The idea behind DES is to use four distinct and largely independent methods to probe the properties of dark energy: baryon oscillations of the power spectrum, abundance and spatial distribution of clusters, weak gravitational lensing, and Type Ia supernovae. This white paper outlines, in broad terms, some of the theoretical issues associated with the first three of these probes (the issues for supernovae are mostly different in character), and with the general task of characterizing dark energy and distinguishing it from alternative explanations for cosmic acceleration. A companion white paper discusses the kind of numerical simulations and other theoretical tools that will be needed to address the these issues and to create mock catalogs that allow end-to-end tests of analysis procedures. Although we have been thinking about these problems in the specific context of DES, many of them are also relevant to other planned dark energy studies.

2. Baryon Oscillations

Oscillations of the coupled photon-baryon fluid in the early Universe imprint a "standard ruler" on the matter power spectrum. The length of this standard ruler can be calibrated using cosmic microwave background (CMB) anisotropy measurements, in particular from the Planck experiment. Measurements of the galaxy power spectrum in the transverse and line-of-sight directions then yield values of the angular diameter distance $d_A(z)$ and Hubble parameter $H(z)$, respectively.[2] This experiment can use the broad-band shape of the power spectrum in addition to the oscillation wavelengths themselves, at the price of somewhat stronger model dependence.

At a fundamental level, the critical issue for this approach to dark energy studies is the effect of non-linearity, redshift-space distortions, and complex galaxy bias on the galaxy power spectrum. Simulations that incorporate all of these effects show that the basic oscillation signal survives on large scales, and that the wavelengths of the oscillation peaks are close to those predicted by linear theory.[3] However, it is not yet clear that departures from linear theory are much smaller than the desired statistical errors. Work is needed to address this question at higher precision, and to understand the sensitivity of the observable baryon oscillation scale to the assumed galaxy formation physics, e.g., to the parameters of semi-analytic galaxy formation models used to place galaxies in dark matter simulations. These studies must also investigate the dependence of the observable oscillation scale on the cosmological model itself, since the non-linear and galaxy bias effects could vary with the dark energy parameters that one is trying to extract.

Including the broad-band shape of the power spectrum allows tighter dark energy constraints by making more complete use of the data, but the broad-band shape of the spectrum may be more susceptible than the baryon oscillation scales to weakly scale-dependent galaxy bias. Even if scale-dependent bias is present, it is possible that halo occupation modeling of small and intermediate scale clustering can pin down this scale-dependence, allowing recovery of the underlying linear theory power spectrum shape without reliance on a detailed model of galaxy formation. This approach requires development and testing to determine its efficacy and robustness.

At a more practical and survey-specific level, the key "theoretical" issue is how to best extract the desired signal from the data. In the case of DES, galaxy redshifts will be estimated photometrically, with expected errors of $\Delta z \sim 0.05 - 0.1$. A simple approach is to bin galaxies by photometric redshift and study just the angular power spectrum, but a more complete likelihood approach that uses the distribution of photometric redshift errors should, in principle, perform better by making more complete use of the available information. It is also important to understand the effects of drifts in photometric calibration zero-points and of systematic errors in photometric redshifts. In particular, it will be necessary not only to quantify the photometric bias and scatter, but also to control the *uncertainties* in the bias and scatter using careful calibration with large spectroscopic training sets.[1] There has already been a substantial effort to quantifying the potential impact of these effects in the case of DES,[4] but further work is needed on methods to identify such effects if they are present and to mitigate their effects if they are. The signal-extraction issue is also connected to the physics issues discussed above, since it may be possible to parameterize and marginalize over the most uncertain aspects of the predictions.[3]

3. Clusters

The cluster mass function (defined here as the number of clusters per unit mass per unit solid angle per unit redshift) depends on dark energy through the growth factor and the volume element. The primary method of constraining these with a cluster sample is to have some observable proxy for cluster mass and then to measure the mass (proxy) function over a range of redshifts to constrain dark energy. In DES, the main proxies will be the SZ decrement and optical richness; for other surveys, X-ray observables will also be crucial. With the deep imaging from DES, it is also possible to measure, via weak lensing, accurate cluster-mass correlation functions (i.e., population-averaged mass profiles) for ensembles of systems selected based on one of these proxies.[5]

The key theoretical issue is making predictions for the actual observables rather than for idealized mass functions. Doing so directly requires simulations that incorporate gravity, gas dynamics, radiative cooling, star formation, and feedback, all in a realistic cosmological context. The necessary physics is sufficiently complicated that we probably won't have convincing direct predictions of the mass-observable relations at the required level of accuracy (i.e., percent or better) in the near future. Rather, the best prospects for exploiting clusters arise from calibrating the mean mass-observable relations using observations.[6] This can be done either using observables from the primary sample, such as the clustering of the clusters themselves, the clustering of galaxies in the sample, or the cluster-mass correlations estimated from weak lensing, or it can be done using the properties of a moderate number of objects that have been studied very well with different techniques (adding, for example, galaxy spectroscopic data, X-ray data, or deeper SZ or weak lensing maps).

Simulations play two key roles in this process. First, they can be used to understand the magnitude and form of scatter about the mean relations and the expectations for redshift evolution and cosmology dependence. The inferences about dark energy have an important dependence on the scatter about mean relations,[6,7] but the dependence is less direct than that on the mean relation itself, and simulations can more reliably predict the variation from system to system and the effect of small parameter changes than the absolute values of observables. Calculations using different simulation techniques and different physical assumptions will be needed to understand the remaining uncertainties. The second essential role of simulations is to calibrate biases in observational analyses and to understand how the intrinsic mass-observable relation will propagate to observed quantities. Detailed simulations can be used to create mock sky surveys of clusters, including projection effects, beam smearing, and so forth, and to make accurate predictions in observable space that can be directly compared with data.

The relation between the weak lensing signal and the projected mass distribution is well understood. Accurate measurements of the tangential shear profiles of ensembles of clusters may therefore prove to be a robust way of constraining dark energy, since the only important observational biases are the effects of scatter in moving clusters into or out of the selected ensemble and of miscentering the clusters. This approach requires further investigation to understand its sensitivity to dark energy parameters and its likely systematic uncertainties; the latter is being explored in detail with lower redshift data from the Sloan Digital Sky Survey.

4. Weak Lensing

Cosmic shear depends on dark energy through the distance-redshift relation, space curvature, and the evolution of the linear growth factor. Because cosmic shear directly probes the mass distribution, which is dominated by dark matter, it is less sensitive to baryonic physics than the galaxy clustering or cluster abundance probes discussed above. However, while the baryon component is sub-dominant, baryonic effects on the mass power spectrum can be as large as the differences between interesting dark energy models on the small scales where the signal-to-noise ratio of the measurements will be high. A key physical issue for dark energy studies with cosmic shear is high precision calculation of the non-linear matter power spectrum, including the baryonic effects. Even for pure collisionless dark matter, numerical simulation predictions and analytical models have not reached the level of accuracy required for the next generation of surveys.[8] Fully assessing the baryonic effects requires simulations that include a dissipative baryonic component and star formation and feedback physics that yields a realistic mass fraction in galaxies.

A rapidly growing area of current theoretical research is the development of methods that use weak lensing measurements, including higher-order statistics and correlations with the galaxy distribution and the CMBR anisotropy, to separate the effects of geometry, curvature, and gravitational growth.[9] These new theoretical ideas will increase the robustness of weak lensing measurements of dark energy parameters, once they are reliably put into practice through simulation and real world observations.

The presence of intrinsic alignments in the galaxy population is a potential source of systematic bias in cosmic shear measurements,[10] and more work is needed on theoretical predictions and empirical estimates of these alignments and on data analysis methods that can mitigate their impact.

At a more practical level, much of the present "theoretical" effort is focused on finding the best ways of analyzing and calibrating the imaging data, to both reduce and estimate systematic uncertainties. For example, recent improvements in the method of tracking the anisotropy of the point-spread function have led to dramatic reductions in systematic errors (identifiable via "B-mode" shear polarization) from cosmic shear measurements using the BTC and Mosaic II imagers on the CTIO Blanco telescope. The estimation and correction of systematic errors is an area of much active research using both empirical and formal approaches.[11] Analysis methods have already progressed to the point that it is possible to create mock galaxy catalogs for lensing analysis that include gravitational shear as well as models of PSF patterns. With such catalogs, lensing measurement methods can be tested and the level of systematic error estimated in advance of the survey to refine observing strategy.

5. Characterizing Dark Energy and Alternatives

In the simplest cosmological models with dark energy, the universe is spatially flat, and the dark energy parameters to be constrained are $\Omega_{\rm DE} = 1 - \Omega_m$ and the equation of state parameter $w = p/\rho$. In the observational white paper on DES, we present error forecasts on w for each of the four probes: $\Delta w = 0.04$, 0.11, 0.02, and 0.02 from Type Ia supernovae, angular galaxy clustering, cluster abundances, and cosmic shear, respectively, assuming Planck priors (see reference [1], Table 1 for details). These forecasts assume that the measurements are limited by statistical rather than systematic errors, and much of the theoretical work described above is aimed at understanding and correcting the potential sources of systematic bias in each of the three structure probes. Consistency among the different estimates of w provides an external check for systematics, but the real goal is to test for systematics internally for each experiment and combine the results to obtain higher precision and to search for departures from the simplest models. The methods for combining results from different experiments are well understood in principle, but different issues arise depending on what parameters one is trying to constrain.

One would ideally like to test for the presence of spatial curvature rather than assume it to be zero, and in this case a multi-probe approach like DES becomes much more powerful, because curvature affects the distance-redshift relation but does not affect the expansion history or the growth of fluctuations. Another natural extension of the simplest models is a dependence of the equation of state parameter on redshift, which can be parameterized in various ways. The most general approach is to estimate $w(z)$ in bins and study the principal components of the constraints for the various experiments, individually or in combination.[12] Probing to redshifts $z \sim 1$ with high but not extraordinary (sub-percent) measurement precision, one can expect to get a good constraint on an effective value of w over the redshift range probed by the data, and a loose constraint on redshift evolution of w. One can take a similar approach using the Hubble parameter $H(z)$ or the energy density $\rho_{\rm DE}(z)$ in place of $w(z)$.

The most exciting prospect of combining multiple probes is the possibility of distinguishing dark energy from alternative explanations for cosmic acceleration, such modifications of General Relativity or local inhomogeneities on horizon scales that cause apparent accelerated expansion. Regardless of the specific model, the hypothesis that some form of dark energy drives cosmic acceleration entails particular connections between the expansion history, spatial geometry, and the growth of fluctuations, and hence between the observables measured by DES, by Planck, and their cross-correlation (the Integrated Sachs-Wolfe effect). These connections can be different in modified gravity models,[13] and perhaps in inhomogeneous universe models as well. Furthermore, even in some dark energy models the clustering of dark energy can have an impact on CMB anisotropies and matter clustering, and detecting these effects would give much greater insight into the dark energy physics. For each of these classes of models, more theoretical work is needed to identify quantitative predictions that distinguish them from simpler, uniform dark energy models and to develop the best ways of testing these predictions. The hope is that a quest for precise constraints on the dark energy equation of state will ultimately take us beyond w to a deeper understanding of the origin of cosmic acceleration.

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