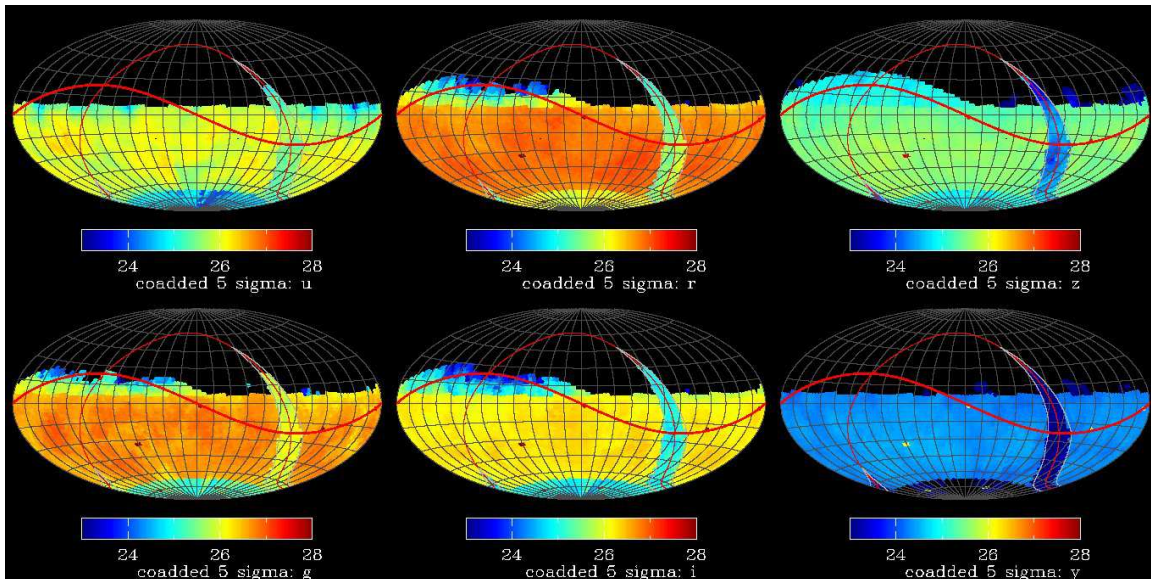


Exploring Dark Energy with Next-Generation Photometric Redshift Surveys

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Summary

The coming decade will be an exciting period for dark energy research, during which astronomers will address the question of **what drives the accelerated cosmic expansion** as first revealed by type Ia supernova (SN) distances [1], and confirmed by later observations.

The mystery of dark energy poses a challenge of such magnitude that, as stated by the Dark Energy Task Force (DETF), “*nothing short of a revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration*” [2]. The lack of multiple complementary precision observations is a major obstacle in developing lines of attack for dark energy theory. This lack is precisely what next-generation surveys will address via the powerful techniques of weak lensing (WL) and baryon acoustic oscillations (BAO) – galaxy correlations more generally – in addition to SNe, cluster counts, and other probes of geometry and growth of structure. Because of their unprecedented statistical power, these surveys demand an accurate understanding of the observables and tight control of systematics.

This white paper highlights the opportunities, approaches, prospects, and challenges relevant to dark energy studies with wide-deep multiwavelength photometric redshift (photo- z) surveys. Quantitative predictions are presented for a 20000 deg² ground-based 6-band (*ugrizy*) survey with 5σ depth of $r \sim 27.5$ [3], i.e., a Stage 4 survey as defined by the DETF.

Exploring Dark Energy with Multiple Probes

Cross-checks and confirmations by multiple lines of evidence are extremely important in cosmology. This is especially true for dark energy investigations, as the properties of dark energy can only be inferred from often subtle effects. In fact, most future surveys are designed to enable multiple techniques using a single, uniform data set and allow for cross-correlating with other types of observations, so that they can form interlocking cross-checks on the accelerated expansion and maximize the science output. For example, WL has a stringent requirement on image quality, so a wide-area WL survey is readily suitable for angular BAO, cluster counting, strong lensing, and, with a proper design of survey programs, SNe as well.

These techniques probe the cosmic acceleration through its effect on the growth of structure and/or geometry of the Universe. They have different parameter degeneracies and vary in sensitivity over redshift. By comparing results of the same quantity (such as distance) from multiple probes, one can detect and possibly rectify unexpected systematics of each probe. By combining them, one can break individual degeneracies and achieve stronger constraints on dark energy properties. Moreover, a multi-probe approach allows one to test the consistency of dark energy models and constrain (or explore) new physics [e.g., 4].

Correlations can be significant between some probes. If they are not properly accounted for, the combined constraining power will be over-estimated. However, correlations can provide useful information as well. In the case of BAO and WL, a joint analysis of the shear and galaxy overdensities for the same set of galaxies involves galaxy–galaxy, galaxy–shear, and shear–shear correlations, which enable some calibration of systematics that would otherwise adversely impact each probe [5]. Figure 1 demonstrates that while the WL constraints on the dark energy equation of state (EOS, $w = p/\rho$) parameters, w_0 and w_a , as defined by $w = w_0 + w_a(1 - a)$, are sensitive to systematic uncertainties in the photo- z error distribution, the joint BAO and WL results remain fairly immune to these systematics.

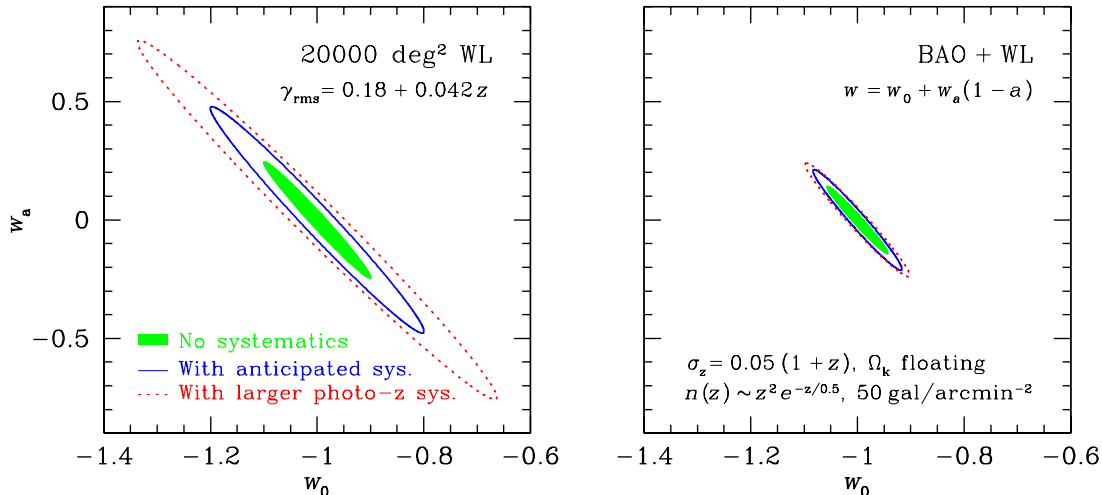


Figure 1: Complementarity between WL and BAO. The dramatic improvement of the BAO+WL results (right) over the WL-alone results (left) is due to the cross-calibration of galaxy bias and photo- z uncertainties and is independent of the dark energy EOS parametrization. The results are marginalized over 9 other cosmological parameters and over 140 parameters for the galaxy bias, photo- z bias, photo- z rms, and additive and multiplicative errors of the power spectra [5, 8, 9, 10].

The w_0 - w_a parametrization in Fig. 1 does not capture the complexity of all dark energy models. It also significantly underestimates the full capabilities of Stage 4 surveys [6]. More generally, one may allow the EOS to vary independently at different redshifts and let the data determine the EOS eigenmodes and their errors, which can then be used to constrain dark energy models. Stage 4 surveys can measure at least 5 EOS eigenmodes with errors better than 10% each, and may completely eliminate some quintessence models [e.g., 7].

We emphasize that the projection in Fig. 1 assumes not only progress in observation and theory but also a facility designed and engineered to deliver superb image quality with high throughput. Billions of galaxies are required. We also note that a very-deep-and-wide survey has the unique capability of exploring very-large-scale properties of the Universe; this topic is discussed in detail in a separate Wide-Field Cosmology white paper by Scranton *et al.*

Dark Energy Study Prospects

Precision Measurements of Distance, Growth, and Curvature

Dark energy properties are derived from variants of the distance-redshift and growth-redshift relations. Different dark energy models feature different parameters, and various phenomenological parametrizations may be used for the same quantity such as the EOS. In contrast, distance and growth measurements are model-independent, as long as dark energy does not alter the matter power spectrum directly. Hence, it is desirable for future surveys to provide results of the distance and growth of structure, so that different theoretical models can be easily and uniformly confronted with the data.

Figure 2 demonstrates for the fiducial survey that joint BAO and WL can achieve $\sim 0.5\%$ precision on the distance and $\sim 2\%$ on the growth factor from $z = 0.5$ to 3 in each interval of $\Delta z \sim 0.3$ [10]. Such measurements can test the consistency of dark energy or modified gravity models [e.g., 11, 12].

The mean curvature of the Universe has a significant impact on dark energy measurements. Allowing the curvature parameter Ω_k to float greatly weakens the ability of SNe to constrain w_a [13, 14]. For the fiducial survey, BAO and WL can determine Ω_k to $\sim 10^{-3}$ separately and $< 10^{-3}$ jointly, and their results on w_0 and w_a are not affected in practice by the freedom of Ω_k [5, 14]. Given its large area, the fiducial survey can place a tight upper limit on curvature fluctuations, which are expected to be small ($\sim 10^{-5}$) at the horizon scale in standard inflation models.

Is Dark Energy A Cosmological Constant?

The results of current observations are consistent with a cosmological constant, Λ , as the cause of the cosmic acceleration. However, the magnitude of Λ as observed is completely inconsistent with any theoretical expectation. This situation has driven the development of other explanations for cosmic acceleration, although none so far are compelling. It is imperative that observations be able to distinguish between a cosmological constant and a dynamical origin for the dark energy. Either result may be the starting point for a revolution in our understanding of fundamental physics.

The cosmological constant, with $w = -1$, must be constant in space-time and admit no interaction with matter or fields. Therefore, detection of $w \neq -1$, time evolution of w , anisotropy or inhomogeneity, or nonstandard gravitational effects will indicate non- Λ dark energy or new physics (see below).

Is Dark Energy Isotropic and Homogeneous?

The easiest test of the isotropy of dark energy is to measure its properties in different directions on the sky with a *highly uniform survey*. For example, one can determine the dark energy EOS in thousands of pixels across the sky with each containing a few hundred SNe. Then one can examine the distribution, mean, and rms value of w over all the pixels to see if dark energy appears isotropic in space from our vantage point. This approach can potentially provide a high-resolution map of the dark energy EOS on the sky, but for a given survey one has to trade resolution with the precision of the EOS in each pixel. A wide-deep BAO+WL survey of billions of galaxies is even more powerful (see the Wide-Field Cosmology white paper).

To examine the homogeneity, we can attempt to measure the clustering of dark energy, as parameterized by the sound speed (c_s) of the dark energy fluid. For $c_s \geq 1$, dark energy will remain smooth as the clustering scale for the fluid keeps pace with the expanding sound horizon of the universe. If $c_s < 1$, then eventually the horizon will catch up to the clustering scale of dark energy, at which point it will begin to fall into the largest gravitational potentials. Since our current measurements are consistent with a very smooth dark energy [15], we would expect to see the signature of clustering dark energy most directly in the

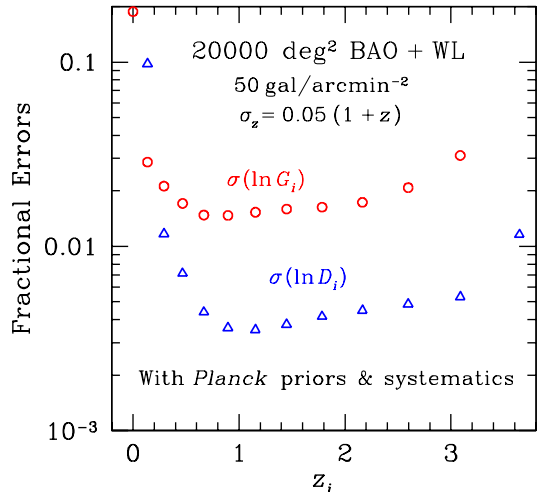


Figure 2: Joint BAO and WL constraints on the comoving distance (open triangles) and growth factor (open circles) from the fiducial survey [10].

integrated Sachs-Wolfe (ISW) effect through CMB–galaxy correlations. The ISW effect on CMB photons is generated by the decay of gravitational potentials due to the expansion of the universe exceeding the clustering rate of dark matter. For a flat universe, detecting an ISW signal is a strong indicator of the existence of dark energy. However, if $c_s < 1$, then dark energy will begin falling into the largest potentials at very late times, suppressing the ISW signal on those scales. For a $w = -0.8$ cosmology that is otherwise consistent with Λ CDM, our fiducial survey together with *Planck* would be able to constrain the smoothness of dark energy on scales of 1 Gpc to better than 10% [16]. The sensitivity of detection is a strong function of the exact value of w and c_s , but this measurement offers the best possible chance at detecting dark energy inhomogeneities.

Is Acceleration Caused by Modified Gravity Instead?

Alternative explanations for the apparent cosmic acceleration (e.g., modified gravity or the effect of an inhomogeneous background metric) are being actively investigated. For demonstration purposes, we show here how well the fiducial survey can distinguish modified gravity from a dark energy that presumably preserves the framework of General Relativity (GR).

Like dark energy, modified gravity alters the distance–redshift and growth–redshift relations, so multiple dark energy probes are also probes of modified gravity. While it is always possible to find an EOS for dark energy that allows the expansion history to be accounted for within GR: $w(a) = -(1/3)d \ln[\Omega_m^{-1}(a) - 1]/d \ln a$, where $\Omega_m(a)$ is the matter fraction, the growth of structure generally differs in different models. Thus, growth measurements are crucial for finding evidence for beyond-Einstein gravity (see the Wide-Field Cosmology white paper for a discussion of other tests).

In the convenient minimal modified gravity parametrization, the deviation from GR is captured in a growth index γ [17]. In the standard GR cosmological model, $\gamma \simeq 0.55$, whereas in modified gravity theories it deviates from this value. For a strawman example, the flat DGP braneworld model [18] has $\gamma \simeq 0.68$ on scales much smaller than those where cosmological acceleration is apparent [19].

Measurements of the growth factor (e.g., Fig. 2) can be used to determine the growth index γ and constrain modified gravity models. In terms of model selection, one may compare a dark energy model that has a fixed GR value for γ with a modified gravity model whose γ is determined by the data and ask “do the data require the additional parameter and therefore signal the presence of new physics if the new physics is actually the true underlying model?” This question may be answered with the Bayesian evidence, B , which is the ratio of probabilities of two or more

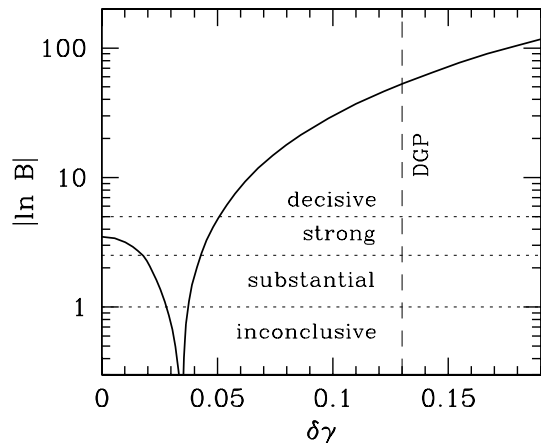


Figure 3: Bayesian evidence B for GR as a function of the true deviation of the growth index from GR, $\delta\gamma = \gamma - 0.55$, for a Stage 4 WL survey comparable to our fiducial survey in combination with *Planck* [12]. The larger the B value, the greater the statistical power of this survey to distinguish the models. If modified gravity is the true model, GR will be favored by the data to the left of the cusp ($B > 1$), and increasingly disfavored to the right ($B < 1$). The Jeffreys scale of evidence [20] is as labeled. Joint BAO and WL will place stronger constraints.

models, given some data.

Figure 3 shows how the Bayesian evidence for GR changes with increasing true deviation of γ from its GR value for a combination of a Stage 4 WL survey (comparable to our fiducial survey) and *Planck* [12]. It is assumed that the expansion history in the modified gravity model is still well described by the w_0 - w_a parametrization. The combination of WL and *Planck* could strongly distinguish between GR and minimally-modified gravity models whose growth index deviates from the GR value by as little as $\delta\gamma = 0.048$. Even with the WL data alone, one should be able to decisively distinguish GR from the DGP model at $\ln B \simeq 11.8$, or, in the frequentist view, 5.4σ [12]. Joint BAO and WL will place even stronger constraints.

Enabling Next-Generation Dark Energy Studies

Unprecedented prospects will face unprecedented challenges. Three key issues must be faced to fully realize the science potential.

Breakthrough Facility

As emphasized by DETF, a next generation facility is required for this science mission. Deep multiwavelength coverage of half the sky is required for these tests of dark energy, together with uniform good image quality. The Large Synoptic Survey Telescope (LSST) [3] with active optics is designed for this application. Variants of JDEM are synergistic, providing near-IR photometry.

Controlling Systematics

Photo- z errors are one of the most critical systematics for an imaging survey, as redshift errors directly affect the interpretation of the distance-redshift and growth-redshift relations. The effects of photo- z errors are twofold: they randomize galaxy positions in the line-of-sight direction, causing a loss of information, and the uncertainty in the error distribution leads to uncertain predictions of the observables (or biases in the analysis, if the uncertainty is underestimated).

Currently, photo- z s from ground-based observations have rms errors of $\sigma_z \sim 0.05(1+z)$ per galaxy for $0 < z < 3$. Future surveys will do better with deeper imaging, more precise photometric calibration, and larger spectroscopic training samples. Adding very deep near-infrared photometry, which can be obtained if JDEM covers the same survey area in *JHK*, will reduce the photo- z errors, particularly at $1.5 < z < 2.5$ [21]. A more important task is to calibrate the photo- z error distribution and model it realistically in parameter estimation. Direct calibration with spectroscopy is impractical for the faintest galaxies in the photometric catalog. Indirect methods that utilize cross-correlations between spatially overlapping spectroscopic and photometric samples [22] or those between different photometric samples [5, 23] do not require deep spectroscopic sampling and hold promise for application to future surveys.

For WL, shear measurement errors are another source of systematics. They are characterized by a multiplicative factor (or shear calibration bias), and an additive component, which is caused mainly by imperfect correction of the anisotropic point spread function. Current methods consistently achieve smaller than 2% shear calibration bias [24]. We project that it can be reduced to 0.5% in ~ 5 years. The additive error is correlated over small angles,

which is potentially problematic, but the impact on dark energy measurements will be small if its amplitude is sufficiently low [8]. Extensive ray-tracing simulations, in which photons travel through turbulent atmospheric layers and realistic optics with conservative margins of fabrication errors (e.g., chip tilt), show that the shear additive error will be several orders of magnitude lower than cosmic shear on scales of interest for next-generation WL surveys [25]. This is supported by a study with Subaru observations [26].

Predicting the Observables

Predicting the properties of the observables given a cosmological model is crucial for data interpretation and statistical inference. Uncertainties in the predictions, if not resolved satisfactorily, will undermine the tremendous statistical power of future surveys. Computational cosmology and cross-calibration with different observations are indispensable and *complementary* tools for meeting this challenge.

The key requirements for cosmological simulations are (1) to cover sufficiently large volumes with appropriate mass and spatial resolution set by the survey, (2) to include the relevant physics – gravity and astrophysical processes, and (3) to return results with accuracies that match the survey requirements. The accuracy targets are demanding, being $\lesssim 1\%$ around $k = 1 h^{-1}\text{Mpc}$ for the matter power spectrum [27].

In the gravity-only case, the challenge will likely be met over the next few years since simulation accuracy, parametric reach, and simulation size requirements are well within the capabilities of petascale supercomputers [28]. The addition of gas physics is problematic not only from the point of view of numerical accuracy and complexity, but also because of our lack of detailed knowledge about basic processes (e.g., star formation). For instance, hydrodynamical simulations show that baryonic effects may be significant on scales of interest for some WL surveys [29, 30], but the results differ considerably. Nevertheless, the baryonic effects on the matter power spectrum can be modeled by a modification to halo profiles [31], which will be measured accurately with the same WL survey through galaxy and cluster lensing on scales from well within to beyond the virial radius [32].

A theoretical uncertainty for WL is the intrinsic alignment of galaxy shapes with local tidal fields and/or the larger scale cosmic web. Low-redshift observations suggest that intrinsic alignments may systematically contaminate the cosmic shear power spectrum by a few percent at $\ell \sim 500$ for Stage 4 WL surveys [33], comparable to the statistical errors. Therefore, these alignments must be removed from the data. Several promising schemes to remove these alignments [34] exist that, with the addition of prior information to be available in the next few years [35], allow for reduction of the intrinsic alignment contamination without too much loss of information. Finally, other observations, such as galaxy-galaxy lensing, three-point functions, and shear B-modes, can reduce the effects of intrinsic alignments [36].

Mining Huge, Complex Datasets

As learned from CMB experiments, we need support for development of data analysis methods capable of tackling the challenge of extracting the influence of subtle effects: observables affected by dark energy are also affected by other “nuisance” parameters. Depending on how the analysis is done, these other parameters number anywhere from tens to hundreds. Some of the nuisance parameters are cosmological, such as the density of dark matter today, and some are astrophysical/phenomenological; e.g., those that govern the photo- z distributions.

In order to reach conclusions about the dark energy parameters we need to run numerical simulations of the data and we require analysis methods that make the most efficient use of these simulations. The simulations are necessary not only for understanding how the statistics derived from the data (such as the shear power spectra) depend on the parameters, but also for understanding the uncertainties in those statistics.

Conclusion

Exciting science opportunities are on the horizon. To realize these opportunities, the community needs to invest in facilities such as the LSST and in research programs that will improve our understanding of the systematics, our knowledge of the observables, and our ability to analyze the data. Science frontiers are often opened by unexpected discoveries. The LSST is designed and optimized not only for the known science drivers such as dark energy but also for the capacity to discover new science. We are optimistic that the challenges associated with the opportunities will be met in the next few years.

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