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Exploiting cross correlations and joint analyses

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1. Overview

The nature of the dark energy thought to be causing the accelerating expansion of the Universe is one of the most compelling questions in all of science. Any of the explanations for the accelerated expansion, whether a new field, a negative pressure fluid, or a modification to General Relativity will signal new physics and have a profound effect on our understanding of the Universe. The current observational constraints on dark energy and modifications to gravity still allow for a large range of models and theoretical explanations. Given the importance of dark energy, we must attack the problem from a variety of angles, taking advantage of **cross-correlations** between and **joint analyses** of different probes, missions, wavelengths, and surveys, to enable the most stringent cosmological constraints.

Dark energy has two observational consequences. The first is an accelerated expansion history as encoded in the redshift-distance relationship. This is indeed the way that dark energy was discovered in the 1990s. Of the primary observational probes of dark energy, Type Ia Supernovae and the baryonic acoustic oscillations (BAO) signal in large scale structure are best suited to measure the expansion history of the Universe [1]. The second effect of dark energy is that the growth of large-scale structure is inhibited as the attractive force of gravity works against the repulsive nature of dark energy. Weak gravitational lensing, galaxy clusters, and

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redshift space distortions (RSD) are all well-suited for measuring the growth of structure [2].

The theme of this paper is that combining these probes allows for more accurate (less contaminated by systematics) and more precise (statistically since there is information in the cross-correlations) measurements of dark energy. We explore ways in which disparate surveys can significantly enhance our knowledge of dark energy and our ability to control systematics and other errors. We also present arguments for inter-agency cooperation to fully empower the community to make use of the data that will be available in the coming decades.

We present a mix of work in progress and suggestions for future scientific efforts. The paper is organized as follows. In Section 2, we describe the general framework of cross-correlation measurements and the basic information provided by each probe of dark energy. We then (Section 3) describe the ways in which the multiple dark energy probes provided by imaging-based (also referred to as "photometric") dark energy experiments are correlated, and how these correlations may be profitably exploited. Then, in Section 4, we explore new opportunities for cross-correlation studies that are possible when information from spectroscopic and imaging experiments are combined. Section 5 broadens the horizon to discuss observations at other wavelengths that will help extend the reach of the optical surveys. A brief discussion of the benefits of joint analysis of data is provided in Section 6.

2. Cross-correlations

The canonical attack on dark energy features four independent probes: Type Ia supernovae, weak gravitational lensing, the BAO/RSD signatures in the observed Large-Scale Structure, and galaxy clusters [2,1]. If the probes were uncorrelated with one another, each could be studied independently with its own set of systematics; the results of the probes could be combined (after checking for consistency) by multiplying the individual likelihoods together. Inconsistency in the probes would signal a defect in the model used to fit the data (assuming systematics had been properly accounted for), whereas consistency and the ensuing joint likelihood would lead to much tighter constraints on the dark energy parameters than could be delivered by a single method. In general, each technique will yield its strongest constraints on different degeneracy directions in parameter space, so that a large range of models will be ruled out by one measurement or another, yielding tight limits in combination. An example of the power of combining results in this way can be seen in Fig. 6, discussed below.

Treating all likelihoods from each method as independent is appropriate only if the probes are not correlated with one another. The reality is different, largely because all the major probes are affected by the distribution of matter in the regions studied. This effect is weakest for Type Ia supernovae, whose apparent brightness will be affected by gravitational lensing by matter along the line of sight at a modest level. For other probes, this dependence is more fundamental. Each probe either relies on using galaxies as a direct tracer of mass in the universe (for BAO, large-scale-structure power spectrum measurements, and galaxy clusters), or else measures the gravitational impact of matter and uses that to constrain cosmological models (for weak lensing and RSD).

As a result, the values of cosmological observables obtained via different methods from the same region of sky will exhibit covariance; for instance, in an area where the density of galaxies is high at some redshift, the distortion of background objects by gravitational lensing will also be greater. In general, we can measure the degree of covariance between a cosmological observable at one location and a second observable at a different location, as a function of the separation between those positions: these **cross-correlation** functions can provide information not given by each observable on its own.

This language originates in studies of large-scale structure, where measurements of the two-point cross-correlation function (the excess probability of finding an object in one class at a given separation from an object in a second class, compared to random distributions) have been used to study the relationship of different populations of galaxies to the underlying dark matter distribution. On sufficiently large scales, the two-point correlation statistics (the power spectrum or correlation function) used to measure clustering should be related to the corresponding statistic for the underlying matter distribution via a constant "bias" parameter that describes the relative overdensities of galaxies compared to dark matter; cross-correlations between probes can be critical for determining the strength of the bias.

Cross-correlation measurements can be used to recover information that each probe misses on its own. For instance, understanding the nature of the large-scale structure bias is key for many cosmological applications of large-scale structure (particularly power-spectrum measurements and RSD – the impact on BAO is minimal), since theories make clean predictions only for the statistics of the matter distribution, but we observe the clustering of visible objects. Weak gravitational lensing measurements can help by constraining weighted integrals of the clustering of dark matter. The combination of information on the observed clustering of galaxies, the integrated weak lensing signal, and the cross-correlation between the two can break the degeneracy between bias and dark matter clustering in the linear regime to provide strong constraints on the growth of structure.

In turn, while the strength of weak lensing depends on the clustering of dark matter, the observed signal is difficult to interpret without information on the redshifts of the sources of the lensing effect as well as of background objects. Cross-correlations between the lensing signal and the positions of galaxies whose redshifts are measured in the course of large-scale-structure studies can break degeneracies and allow more powerful constraints than from lensing alone.

The use of galaxy clusters as a probe of dark energy benefits from lensing measurements – which can enable direct measurement of average masses of clusters selected based on other properties – as well as large-scale-structure measurements, as determination of the bias of clusters by cross-correlation with other populations can provide another constraint on mass with different weighting [3]. Lensing magnification effects on Type Ia Supernovae are subtle, but knowledge of which lines of sight should have more or less lensing allows them to be measured more readily, mitigating their impact on supernova cosmology studies.

In the sections following, we consider a few of the most important applications of cross-correlations and synergies between multiple probes in more detail.

3. Photometric experiments

Large photometric (imaging-based) experiments are a key ingredient in the assault on dark energy [4]. Data from these projects will be used to provide multiple, complementary constraints on dark energy. They will also be used to select targets for spectroscopic experiments. As described above, the combination of likelihood information from multiple probes can yield stronger constraints than any single method on its own; cross-correlations will increase the constraining power of these experiments further. In this section, we will first quickly summarize the information provided by these experiments, and then focus on two examples of how analyses that incorporate cross-probe information and methods can be used to constrain dark energy: by measuring