Measuring Dynamics of Dark Energy

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One of the greatest mysteries of modern science is the fact that the universe is expanding faster than ever, whereas standard gravitational theory predicts an eventual slowing down of the expansion. One possible explanation of this phenomenon is a repulsive force exerted by a component called dark energy. Although little is known about the physical nature of dark energy, the current effort is focused on a phenomenological model for it, and measuring the dark energy parameters using various cosmological probes. Current observations suggest that the "standard model" of the universe is consistent with Einstein's cosmological constant. However, the data cannot rule out an evolving dark energy (as for, example, the so-called "quintessence" models).

A natural question to ask is, if the dark energy equation of state is evolving, what was its initial value? When did it make a transition to the value we see today–that is, close to the cosmological constant? And how fast did this transition happen? All quintessence models of dark energy evolve from an initial seed perturbation of dark matter and dark energy. The evolution of the two dark components are coupled via the Friedmann equation. The main probes of the standard model of cosmology are the cosmic microwave background (CMB) and large-scale structure (LSS). Although CMB by itself cannot provide information about the entire dynamical history of dark energy, the low redshift observations of large-scale structure when combined with CMB can be useful for studying the evolution of dark energy starting from the CMB era to the current epoch.

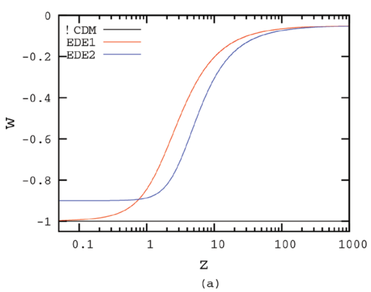

Fig. 1. The two different models of dark energy considered in this study and how each model evolves with redshift, z. The reference LCDM model, which does not evolve, is represented by the black line.

If a non-negligible amount of early dark energy is present, the main effect is seen in low-multipole CMB temperature anisotropy observations. The first peak shifts its position in the presence of early dark energy and the overall normalization of the CMB power spectrum changes [1]. However, CMB data from the Wilkinson Microwave Anisotropy Probe (WMAP) satellite have already measured the position of the first peak and the normalization of the CMB very accurately. Once the normalization and the first peak position are fixed, the normalization at smaller scales is decreased. This particular effect can be seen in LSS observations. The net result is of early dark energy to arrest the formation of galaxies and clusters seen at low redshift. Thus cluster counts, in combination with CMB observations, can be used to measure and constrain the early component, late component, redshift of transition from early to late component, and the width of transition of dark energy over the entire history of universe.

We demonstrate in [2] that galaxy cluster observables, namely galaxy cluster counts, and the CMB secondary anisotropies can prove to be excellent probes for constraining dark energy dynamics. The CMB photons, while passing through galaxy clusters, get Compton scattered, resulting in a distortion of the CMB power spectrum. This distortion is called the Sunyaev-Zeld'ovich (SZ) effect and can be observed at arc-minute scales—it is sensitive to the number of clusters formed in the universe. We forecast how different dark energy parameters can be constrained from current and future cluster and high resolution CMB surveys. We consider two models where a non-negligible amount of early dark energy is present, namely EDE1 and EDE2 as shown in Fig. 1. While both the models are valid under current observations, they have different evolution histories. We show that future experiments should be able to distinguish between the two models. We specifically consider a full-sky X-ray survey for cluster counts (eROSITA), a full-sky medium resolution CMB experiment (Planck) for the SZ power spectrum, and a one-tenth-sky, high-resolution CMB experiment (ACT/SPT) for measuring both cluster counts and the SZ power spectrum.

Our forecasts for the SZ power spectrum and cluster counts are shown in Figs. 2, 3, and 4. Figures 2 and 3 show the predictions for cluster counts for Lambda-Cold Dark Matter (LCDM) (the currently favored cosmological model) and the two dark energy models. Figure 4 shows the prediction for the SZ power spectrum. The error bars for cluster counts shown in Figs. 2 and 3 are representative statistical error bars

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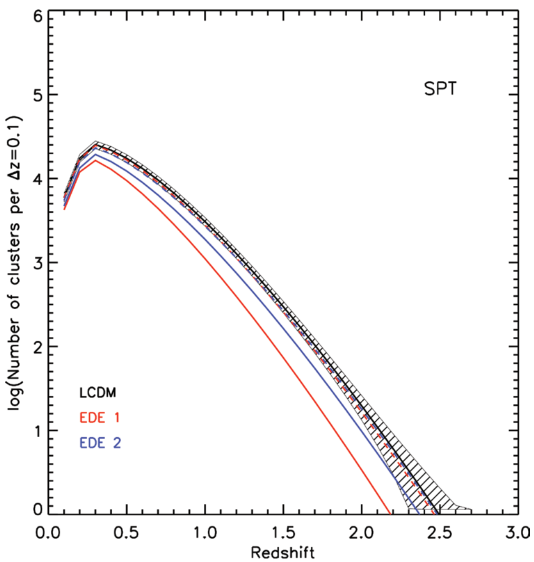

Fig. 2. Prediction for cluster number counts expected from SPT-like surveys. The error bars represent the expected statistical error bars. The lines denote cluster counts expected for LCDM and different dark energy models.

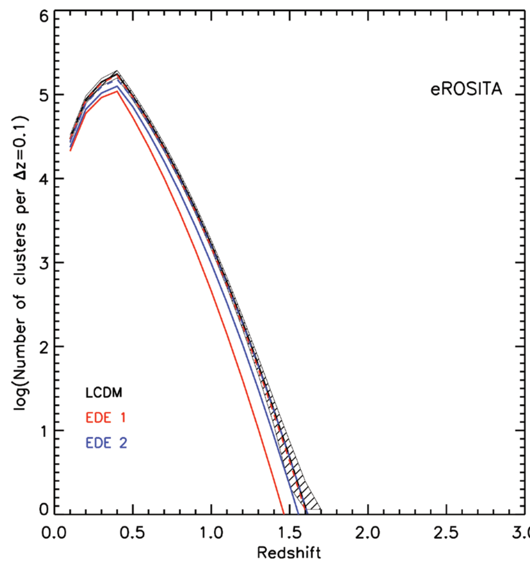

Fig. 3. Same as in Fig. 2. except for eROSITA-like surveys.

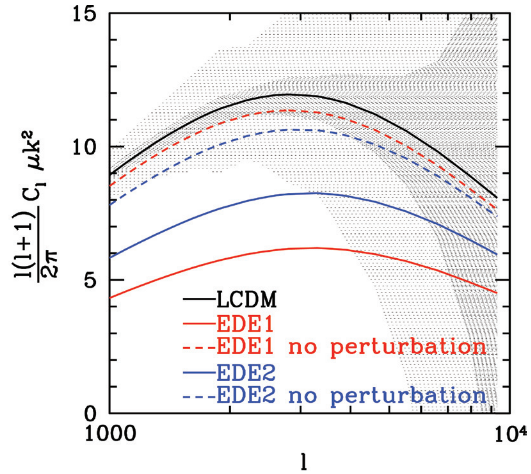

Fig. 4. Predictions for the SZ power spectrum. The error bar represents instrumental error and cosmic variance. The light shaded area is the error bar for a Planck-like full-sky survey. The dark shaded area represents SPT-like surveys. Note the significance of including self-consistent dark energy fluctuations.

expected from the SPT and eROSITA surveys. The error bar for CMB experiments shown in Fig. 4 represents the instrument noise and cosmic variance. Both the dark energy models considered here can be distinguished from the LCDM model of the universe by these experiments. Figure 4 also shows that early dark energy fluctuations have a significant effect–if they are neglected, one is led to the incorrect conclusion that the three models cannot be distinguished by observations.

Galaxy cluster observables, namely cluster counts and the SZ power spectrum, will be able to constrain the amount of early dark energy and its dynamics. We show that, compared to CMB alone, cluster observables can improve the dark energy constraints significantly and will be able to detect any dark energy evolution up to redshifts of Z~2–4, or equivalently, as early as when the universe was only 30–20% of its current size.

[1] Alam, U., *Astrophys J* **714,** 1460 (2010).
[2] Alam, U., et al., arXiv:1004.0437 (2010).

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