Dark Energy Constraints from Optical Galaxy Clusters: The Impact of Observational and Theoretical Uncertainties

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Galaxy clusters are powerful probes for cosmology, especially the accelerated expansion of the universe and the properties of dark energy. Given the statistical power of upcoming optical galaxy cluster surveys like the Dark Energy Survey (DES), the constraints on dark energy will depend on how various systematic errors are controlled. We present analyses on the impact of (1) observational uncertainties in relating the optical richness to halo mass, focusing on using follow-up observations to constrain the observable-mass distribution, and (2) theoretical uncertainties in predicting the halo statistics, proposing the required precision in predicting the halo mass function and halo bias.

Introduction

- Galaxy cluster surveys: In the ΛCDM cosmology, dark energy accounts for the late-time expansion of the universe and halts the growth of structure. In galaxy cluster surveys, we probe the expansion history and the growth of structure. The properties of dark energy can thus be inferred from these surveys.
- Observable-mass distribution: To link observed cluster counts to the theoretical dark matter halo mass function, we need to calibrate the observable-mass distribution. This distribution is one of the most significant systematics in cluster surveys and critically determines their capability to constrain dark energy.
- Self-calibration: The observable-mass distribution can be better constrained if we include information from halo bias, which quantifies the clustering of dark matter halos. In a cluster counts analysis, the halo bias can be measured from the sample variance in the counts-in-cells. By observing the cluster mean density and sample variance, we can “self-calibrate” the observable-mass relation and improve dark energy constraints (Lima & Hu, 2004, 2006).
- Dark energy figure of merit (FoM): As a convenient quantity to compare different dark energy experiments, it can be defined as FoM = 1/(σ_mσ_z), where the equation of state is parameterized as w(z) = w_0 + w_a(z - z_0), and w_0 is the pivot redshift at which the uncertainty in w(z) is minimized (Abbott, 2006).

Observational aspect: How to design a follow-up program for optical surveys that maximizes the dark energy information

[Based on Wu, Rozo, & Wechsler 2010]

We apply a simulated annealing algorithm to maximize the dark energy FoM at fixed observational cost, and find that optimal follow-up strategies can reduce the observational cost required to achieve a specified FoM by up to an order of magnitude.

Follow-up Strategies

We consider the optical clusters in the Dark Energy Survey followed up by X-ray (left panels) and SZ (right panels) methods. Top: We estimate the “observational cost proxy” based on the telescope time required for each method to observe a cluster. Each pixel indicates a bin in mass and redshift in the optical survey. Middle and bottom: optimal follow-up strategies for small and large follow-up programs. We maximize the FoM at a given total cost and show both the number and the percentage of follow-up targets in each bin. As can be seen, the configurations depend on the allowed cost. In general, X-ray follow-up programs favor low-redshift clusters first and extend to high-redshift as the allowed cost increases. On the other hand, SZ follow-ups include high-mass clusters in a wide redshift range and extend toward low mass as the allowed cost increases.

Theoretical uncertainties: How well do we need to predict the dark matter halo mass function and halo bias?

[Based on Wu & Zentner; Wechsler 2010]

We study the impact of theoretical uncertainties in predictions of the halo mass function and halo bias on dark energy constraints from upcoming cluster surveys. We find that for an optical cluster survey like the DES, the accuracy required on the predicted halo mass function to make an insignificant source of error on dark energy parameters is ±1% (consistent with the results in Cunha & Evrard 2010).

Degradation of FoM due to theoretical uncertainties

We disentangle the halo mass function into different mass and redshift bins and assign each bin a pair of nuisance parameters for mass function, M and halo bias, B. The figure shows the degradation in the FoM due to the uncertainties in f and g. Given the statistical power of a DES-like survey, the mass function needs to be predicted with a few percent precision to avoid 10% degradation in the FoM.

Conclusions

- Optimizing the follow-up strategies for optical galaxy cluster surveys can significantly improve the dark energy constraints and also reduce the observational cost. X-ray and SZ follow-ups have different follow-up strategies and are complementary to each other.
- Theoretical uncertainties in predicting dark matter halo mass function and bias will significantly degrade the power of upcoming optical surveys and need to be controlled at percent level. The low mass regime is the most important when calibrating the theoretical uncertainties.

Primary References