Cluster Cosmology

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1 Introduction

Galaxy clusters contain a wealth of information about the matter density of our universe. Measuring the density of clusters as a function of redshift and mass can tightly constrain the mass density parameter of the universe, Ω_m. This constraint depends on a calibration of the mass-observable relations (MOR) and weak lensing. The standard model of cosmology ΛCDM is defined by six independent parameters. Cosmological analyses involve constraining some or all of these parameters.

The Dark Energy Survey (DES) utilizes optical images of the sky to catalog the galaxies and then to constrain cosmological parameters and explore the nature of dark matter and dark energy of the universe. The DES relies on the 4-meter Blanco telescope in Chile and the DECam camera to collect its data. The images are analyzed to produce galaxy catalogs. The catalogs are then processed through a cluster of galaxies finding algorithm, of which the most prominent is redMaPPer [1]. The space density of the clusters as a function of their mass are then utilized to constrain the cosmology by comparison to simulated and theoretical models.

Since the mass of clusters is not an observable, it is necessary to find an observable that correlates with mass. One of the most common is the or the count of red galaxies in a galaxy cluster, λ. The count of galaxies, richness, has been used in cluster catalogs since the first one [1] due to the simplicity of acquiring an accurate count. In modern surveys, weak lensing is used to calibrate the richness to a mass. Light curves when it passes through curved space due to the presence of massive objects, creating a lensing signal. This signal is highly sensitive to the mass of the cluster members which makes it ideal for the calibration of mass observable relation.

In 2020, the DES cluster cosmology group unblinded their cosmological analysis. The results found differed from the prior value of Ω_m. The DES collaboration believes systematics to be the cause of the discrepancy. In this project, we implemented a model of one of the systematics, the boost factor model. Details of the experiment are discussed in section 2. In section 3, the systematics necessary to the analysis are presented. Section 4 develops the Boost factor model implemented and the framework used to constrain the free parameters of the model. The goal of the project was to constrain the model parameters using MCMC which is explained in section 5. Lastly, section 6 shows the results and conclusions. The code used can be found on github using the details provided in section 7.

2 Experiment

RedMaPPer clusters are selected as overdensities of red-sequence galaxies in the DES year 1 photometric galaxy catalog. redMaPPer counts the excess number of red galaxies brighter than a specified luminosity threshold within a circle of a specified radius.This number of galaxies is called the richness, and is denoted as λ. All clusters of richness $\lambda \geq 20$ are used in the analysis. The galaxy clusters are placed in three redshift bins spanning the range $z \in [0.2, 0.65]$ and four richness bins spanning the range $\in [20, \inf]$. The following figure shows the the average change in the line-of-sight projected surface mass density $\Delta\Sigma$ as it varies with radius R.

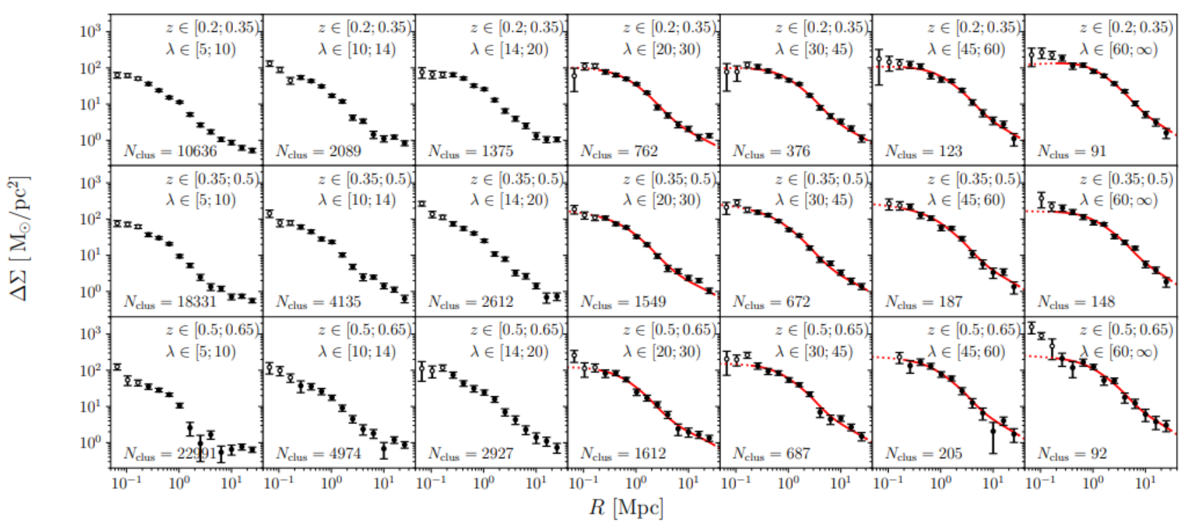

Figure 1: DES shear profiles for cluster in bins of rredshift (rows) and λ, columns. The data is represented by the points in black, the red line represent the model including its various systematics components. The panels without red lines were bins not used in the analysis. Likewise, the red-dashed lines show the portions of the model were no data was used in the fit. Figure is taken from [2].

Our goal is the experiment is to have a model of the average change in the line-of-sight projected surface mass density $\Delta\Sigma$ as a function of radius R. Therefore, our model requires an accurate representation of possible systematics due to various parts of the experiment. One of the systematics we study in this work is the Boost Factor Model systematic (or membership dilution). The following graph shows the boost factor component of the data and compares it to the boost factor model we use.

As you can see from Fig 2, the model captures the boost factor effect well for bins with $\lambda > 20$ and high radius.

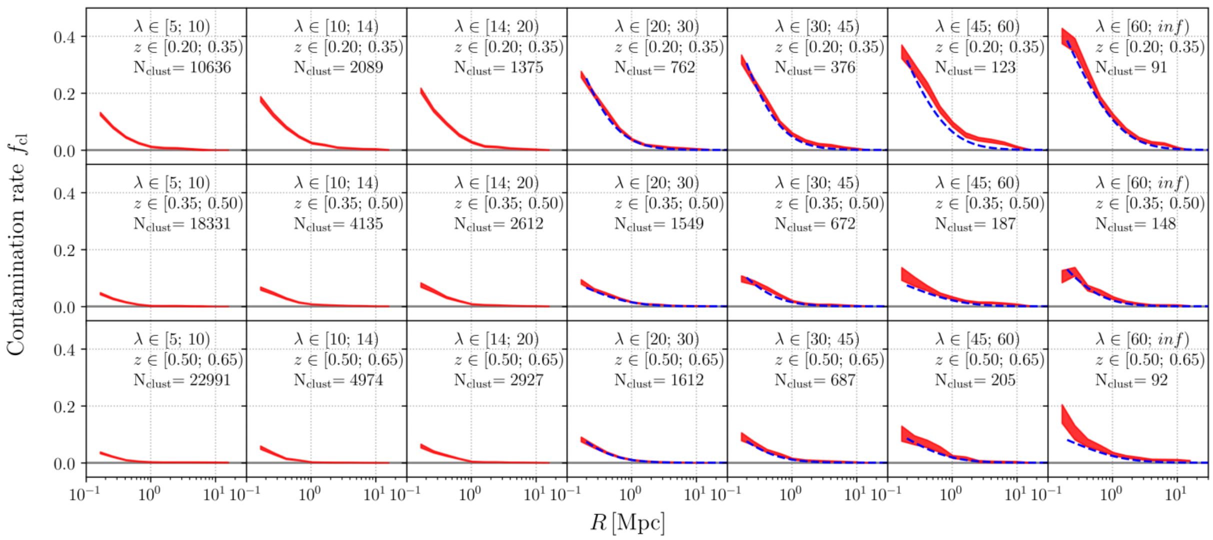

Figure 2: Cluster member contamination measured in the DES Year 1 data for the various bins of clusters in richness λ and redshift z. Red: calculated contamination profiles data. Blue: Boost factor model. Figure is taken from [3].

3 Methods

The analysis is done using CosmoSIS, which is a framework for structuring cosmological parameter estimation in a reusable and verifiable way using a variety of samplers. CosmoSIS was used on Perlmutter as part of NERSC, the fifth fastest supercomputer in the world. The sampler used for this analysis is emcee which is a form of Monte-Carlo Markov Chain (MCMC). This technique was used to find the probability distribution of the free parameters in the boost factor model discussed in the next section. (not sure what else to include here.)

4 Boost Factor Model

the following set of equations represent the projected NFW for the theoretical boost factor model[4]. The model is usually represented as the first equation for all possible values of x. Such representation fails to account for the undefined case when $x = 1$. To address the issue, we used the limit of the model equation as x approaches the value of one from both sides and found it to converge to the presented value for the case when $x = 1$.

$$\mathcal{B}_{\text{model}}(r) = \begin{cases} 1 + B_0 \left(\dfrac{1 - F(x)}{x^2 - 1} \right), & \text{if } x \neq 1 \\ \dfrac{B_0 + 3}{3}, & \text{if } x = 1 \end{cases} \tag{1}$$

where

$$F(x) = \begin{cases} \frac{\tan^{-1}\sqrt{x^2-1}}{\sqrt{x^2-1}}, & \text{if } x > 1 \\ 1, & \text{if } x = 1 \\ \frac{\tanh^{-1}\sqrt{1-x^2}}{\sqrt{1-x^2}}, & \text{if } x < 1 \end{cases} \tag{2}$$

Observe that there are 2 free parameters in this model: R_s and B_0. The following set of equations discusses the model we used to calculate these parameters for various redshift and richness bins.

$$R_s = r_s * \left(\frac{1+z}{1.25}\right)^{\alpha_{R_s}} * \left(\frac{\lambda}{50}\right)^{\beta_{R_s}} \tag{3}$$

$$B_0 = b_0 * \left(\frac{1+z}{1.25}\right)^{\alpha_{B_0}} * \left(\frac{\lambda}{50}\right)^{\beta_{B_0}} \tag{4}$$

These equations allow the free parameters in our model to vary across redshift and richness bins. Using MCMC, the posterior probabilities of the 6 parameters varying the two parameters in the model were calculated. This calculation allowed us to tightly constrain the values of the 6 parameters in the suggested model.

5 Systematics

There are several other systematics besides the one due to the boost factor effect. The following figure shows the other types of systematics and their percentage as calculated for the DES year 1 analysis.

Source of systematic	Y1 Amplitude Uncertainty
Shear measurement	1.7%
Photometric redshifts	2.6%
Modeling systematics	0.73%
Cluster triaxiality	2.0%
Line-of-sight projections	2.0%
Membership dilution + miscentering	0.78%
Total Systematics	4.3%
Total Statistical	2.4%
Total	5.0%

Figure 3: The error budget for each systematic is . Figure is taken from [5].

Shear measurements refers to the uncertainty in the ellipticity of the weak lensing signal. Photometric redshift bias and scatter are calculated by comparing the photometric redshift of the clusters to the spectroscopic redshift of the central galaxy of the cluster, when available. The photometric redshift performance is consistent with our expectations. Therefore, redshifts are very nearly unbiased, and have a remarkably tight scatter. [2] It is important to understand that this uncertainty is due to galaxies being included in the cluster due to being at the specified redshift of the cluster but not contributing to the weak lensing signal. The effect is not due to uncertainties we have at measuring the redshift of the clusters given the previous discussion.

Modeling systematics are the implicit uncertainty in the models we use for fitting the data. Cluster triaxiality is the systematics due to the shape of the clusters being an ellipsoid instead of a sphere. As a consequences, the signal of galaxies along a cluster axis that aligns with the line of sight gets boosted which increases their membership likelihood. Line-of-sight projections happen when background galaxies get projected on the line of sight. these galaxies contribute to the count of galaxies in the cluster even though they are not members of the cluster. Lastly, membership dilution is the boost factor effect where galaxies are included in the sheer catalog even though their mass does not influence the sheer signal. Miscentering refers to the algorithm choosing a galaxy as the center of the cluster that results in a non-spherical cluster.

6 Results and Conclusions

Mock data was used along with the model above to constrain the model parameters.Markov Chain Monte Carlo algorithm varied over the range of values for each model parameter. The values found are represented in the posterior plot given below. Posterior plots show the likelihood associated with a given value of the parameter. All of the analysis done for this research was performed using Cosmosis, a software used for cosmological analysis and constraining cosmological parameters. We implemented cosmosis on NERSC's Perlmutter to maximize the efficiency of the codes used.

The model implemented appears to work given the results. Therefore, the next steps are to test the model with the boost factor data collected by DES. We have attempted this, and so far we have been experiencing issues with constraining the parameters. More work needs to be done to constrain the model's parameters in the hopes of using the work done here for year three DES cluster cosmology analysis.

7 Appendix

We learned how to run CosmoSIS from the NERSC JupyterHub Jupyter notebooks. The key steps were putting into place the kernel.json file and the kernel helper file with the correct contents. The kernel.json file and other relevent fiels are in this git repository: `https://github.com/Ebtihal2/Boost_Factor.git`

References

[1] G.O. Abell, *The Distribution of Rich Clusters of Galaxies.*, ApJS **3** (1958) 211.

[2] T. McClintock, T.N. Varga, D. Gruen, E. Rozo, E.S. Rykoff, T. Shin et al., *Dark Energy Survey Year 1 results: weak lensing mass calibration of redMaPPer galaxy clusters*, MNRAS **482** (2019) 1352 [1805.00039].

[3] T.N. Varga, J. DeRose, D. Gruen, T. McClintock, S. Seitz, E. Rozo et al., *Dark Energy Survey Year 1 results: validation of weak lensing cluster member contamination estimates from P(z) decomposition*, MNRAS **489** (2019) 2511 [1812.05116].

[4] C.O. Wright and T.G. Brainerd, *Gravitational Lensing by NFW Halos*, ApJ **534** (2000) 34.

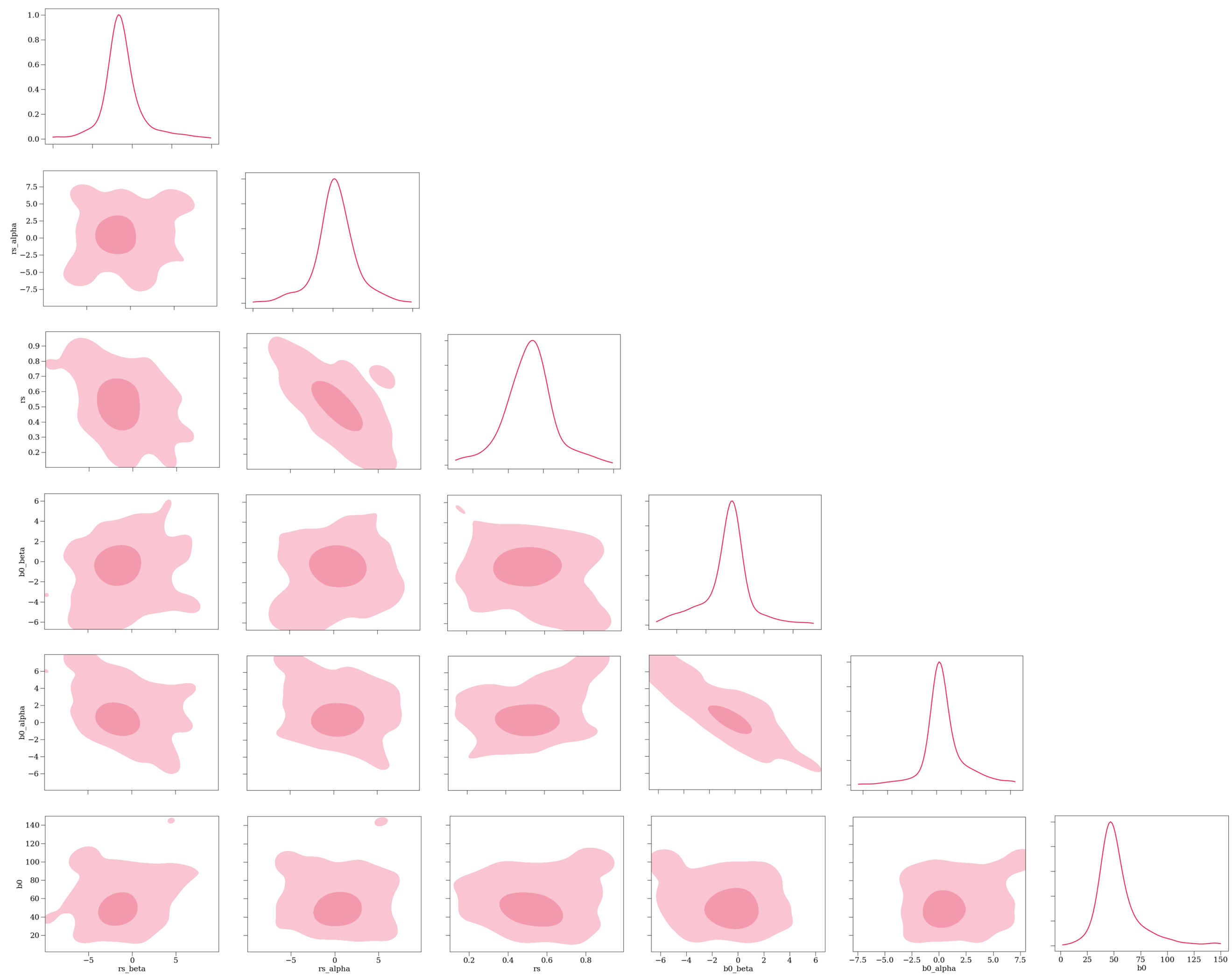

Figure 4: Boost factor model parameters posterior plot produced by cosmosis.

[5] T. McClintock, T.N. Varga, D. Gruen, E. Rozo, E.S. Rykoff, T. Shin et al., *Dark Energy Survey Year 1 results: weak lensing mass calibration of redMaPPer galaxy clusters*, MNRAS **482** (2019) 1352 [1805.00039].