Cosmography with Galaxy Clusters

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In the present work we focus on future experiments using cluster abundance observations to constraint the Dark Energy equation of state parameter, \(w\). To obtain tight constraints from this kind of experiment, a reliable sample of galaxy clusters must be obtained from deep and wide-field images. We therefore present the computational environment (2DPHOT) that allow us to build the galaxy catalog from the images and the Voronoi Tessellation cluster finding algorithm that we use to identify the galaxy clusters on those catalogs. To test our pipeline with data similar in quality to what will be gathered by future wide field surveys, we process images from the Deep fields obtained as part of the LEGACY Survey (four fields of one square degree each, in five bands, with depth up to \(r'=25\)). We test our cluster finder by determining the completeness and purity of the finder when applied to mock galaxy catalogs made for the Dark Energy Survey cluster finder comparison project by Risa Wechsler and Michael Busha. This procedure aims to understand the selection function of the underlying dark matter halos.

1. INTRODUCTION

Observational evidences such as the luminosity-redshift relation of type Ia supernovae, the power spectrum of the cosmic microwave background radiation and the distribution of large scale structures in the Universe indicate that the total energy density of the Universe is dominated by the so-called dark energy, a slowly varying fluid with negative pressure. The nature of dark energy is an important open question connected to the fundamental theories of gravity and therefore the scientific community is investing great efforts in developing tools to address this problem. The best fit to current observations places Einstein’s cosmological constant in the role of Dark Energy (the Λ-CDM model), but the constraints on the equation of state parameter \(w \equiv p/\rho\), where \(w = -1\) is the signature of the cosmological constant, are not definitive. The combination of all currently available datasets allowed to constraint \(w\) up to \(10 - 20\%\) uncertainty and the next generation of experiments aim to improve it to \(\lesssim 1\%\).  

One of the techniques used to study Dark Energy observationally is based on galaxy cluster surveys. The cluster redshift distribution \((d^2N/dzd\Omega)\) is the number of clusters per unit redshift per unit solid angle, which is obtained as the product of the volume element of the survey \((d^2V/dzd\Omega)\) and the number density of clusters \(n(z)\). Both quantities are sensitive to the cosmological model: the former through the angular diameter distance \(d_A(z)\) and the Hubble parameter \(H(z)\); while the later, being the integral of the halo mass function \(f(M, z)\), depends on the linear growth of density perturbations. The evolution of \(f(M, z)\) in the context of the linear growth theory, is studied using N-body simulations and it is shown that the number of clusters at redshifts larger than 0.5 decreases strongly with \(w\) and that this effect is more evident at the high mass tail of the distribution. Therefore, to improve
the constraints on $w$ using galaxy clusters, it is necessary to obtain a well-understood selection of a large sample of massive high redshift clusters. However, the abundance of such objects is as low as a few ones per square degree and this implies that the survey must have a large area coverage. A survey covering a few thousands square degrees up to $z \simeq 1.4$ would lead to less than 5% uncertainty on $w$, if the cluster masses are determined with uncertainty $< 10\%$. This means that galaxy clusters surveys alone can provide a significant improvement in the current status of the Dark Energy investigations and the combination with data obtained from other techniques will allow to achieve the subpercent uncertainty level.

The accomplishment of a dark energy study using galaxy clusters as described above requires the development of improved image processing tools and cluster finding algorithms. The image processing must perform accurate star-galaxy separation at faint flux levels (up to magnitude $r' \sim 25$, two magnitudes fainter than the current wide field surveys) and produce a galaxy catalog with high completeness and low contamination. The cluster finder will take this galaxy catalog and produce a cluster catalog. The leading algorithms currently in use are very efficient up to $z \sim 0.5$, but a significant improvement is needed to achieve the same efficiency at the redshift range of interest for dark energy studies. Here we present results for both the 2DPHOT image processing package and the Voronoi Tessellation (VT) cluster finder algorithm. To test our pipeline with data similar in quality to what will be gathered by the next generation of wide field surveys, we process images from the Deep fields obtained as part of the LEGACY Survey. To understanding the selection function of the dark matter halos we compute the completeness and purity of the cluster catalog using mock galaxy catalogs made by Risa Weschler and Michael Busha for the Dark Energy Survey cluster finders comparison project. The present setup of our cluster finder produces a catalog with high completeness, but purity needs to be improved.

2. 2DPHOT

2DPHOT was developed to perform detection, global photometric measurements and surface photometry of objects in a given image. In order to estimate the completeness of the galaxy catalog, 2DPHOT adds simulated galaxies and stars to the image, using the point spread function and the distribution of galaxy structural parameters obtained from the processed image. Coordinates and magnitudes are randomly assigned within the range of observed objects. The image is reprocessed and the fractions of recovered and misclassified artificial objects correspond to the completeness and contamination of the processed catalog, respectively. We process the Deep fields of the LEGACY survey, which is not wide enough to set constraints on $w$, but has the same depth and image quality (seeing $\sim 0.7''$) of future wide surveys, being the ideal dataset to calibrate our pipeline. The results of this processing (Fig. 1) shows that the galaxy catalog has negligible contamination and completeness $> 90\%$ up to $r' = 24.5$. After processing the images in the remaining bands, we have, for each of the Deep fields, a galaxy catalog to be used as input for our cluster finder.

3. VORONOI TESSELLATION CLUSTER FINDER

The VT algorithm analyzes the spatial distribution of galaxies in 2 dimensions. To account for the depth of the catalog, we work in shells of either photometric redshift or magnitude. The magnitude binning is particularly...
useful when there is no photometric redshift available for a given dataset. In each shell, a unique partitioning of the plan into convex cells, each containing a single galaxy, is obtained. The local density is then measured as the inverse of the area of each cell and the clusters of galaxies are detected as local density enhancements with respect to the density distribution of background galaxies. VT is a non-parametric method that requires no smoothing of the input data and allows overdensities such as groups and clusters of galaxies to be identified independently of their geometry. To detect the clusters, we compare the distribution of cell areas with the distribution expected from a Poissonian process. The deviation between these distributions is negligible in the regions far from the cluster and gets larger as we approach an overdensity. We then set a density threshold below which we will consider the cells as being part of a cluster candidate. This threshold is the point where the cumulative distribution of cells becomes stiffer than the Poissonian distribution and corresponds to \( \sim 80\% \) of the distribution. We then estimate the probability that each cluster candidate has to have been generated by a background (Poissonian) fluctuation and we reject the ones for which this probability is larger than 5%. We finally use a percolation scheme to combine the cluster candidates in each bin into a unique list of clusters. We apply the VT on mock galaxy catalogs to estimate the completeness and purity of the resulting catalogs. Mock catalogs are produced using \( \Lambda \)CDM N-body simulations to generate the dark matter halos which are then populated with galaxies following the luminosity function observed in the local Universe. The mock catalogs are as deep as \( z \sim 1.4 \) and contain magnitudes, redshift and photometric redshift for each galaxy. In order to quantify the completeness and purity, we used a cylindrical matching scheme in which each VT cluster is matched to a mock halo within a cylinder with height \( \Delta z = 0.05 \) and 1.5Mpc radius. Completeness is defined as the fraction of matched halos while purity is the fraction of matched VT clusters. Using magnitude binning we obtained completeness \( \sim 95\% \), but purity was limited to 60\%. The analysis using photometric redshift is still in progress, but we expect to improve purity to \( \sim 90\% \) using an optimized binning and percolation setup.

4. CONCLUSIONS

In this work we show preliminary results about the development of tools to perform galaxy clusters detection from deep and wide field images, aiming at future dark energy studies using galaxy cluster survey data. We take the Deep LEGACY survey data, which covers a small area (4 sq deg) but is similar in quality to what will be gathered by these future experiments, as a benchmark data set to test our pipeline. We use the 2DPHOT package to process the Deep images and obtain the galaxy catalogs with 90\% completeness up to \( r' = 24.5 \). The VT cluster finder is being calibrated using mock galaxy catalogs. The current results show high completeness up to redshift 1.4, but purity has to be improved. After this calibration process, we intend to apply the VT cluster finder to the Deep catalogs produced using 2DPHOT to test our full pipeline on real high redshift data for the first time.

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