Final Technical Report for DE-SC0012297

The work carried out in this award has been in support of the LSST Dark Energy Science Collaboration (DESC) and the preparations to measure the nature and evolution of dark energy with LSST. The DESC will employ the four principal techniques identified by the DOE-appointed Dark Energy Task Force (DETF) for measuring dark energy: weak gravitational lensing, galaxy clustering, galaxy clusters, and supernovae. Simultaneously measuring the properties of dark energy allows DESC to take advantage of the different sensitivity to systematic errors and degeneracies that each method provides. Taking advantage of these joint constraints, however, requires understanding and mitigating the biases inherent in each technique. As a result, the majority of the work of the DESC in the past few years has been aimed at understanding the sources of error in each of the measurements and developing algorithms to mitigate biases that can affect the measurement of dark energy. The work on this award has been aimed at determining biases to the gravitational lensing measurements of galaxy cluster masses with LSST.

Work on this proposal (and DESC preparatory work) focused on the high priority task "CL:H2" identified in the LSST DESC White paper: Calibrating shear measurements on LSST images. To further organize, and prioritize the work of developing the algorithms and software to measure dark energy with the LSST data, in 2015 the DESC developed a Science Road Map (SRM) detailing the tasks required for each of the major analysis groups (as well as for tasks that support multiple groups, such as theory, cosmological simulations, and photometric redshifts). The SRM, released in November, 2015, organized its task around three major DESC-wide "data challenge campaigns": DC1, which covers the period detailed in this award (actually through the end of 2017); DC2, (beginning mid-2017), and DC3 (beginning in Q2 of 2018). Within the DC1-era tasks of the SRM, our group has taken the lead role in Task CL2.3 (Calibrating reduced Shear Measures in the Cluster Environment), Task CL2.4 (Shear Profile Biases in Simplified Clusters), and Task CX1.2 (Galaxy Blending Biases in the Cluster Environment). The last of these is part of a cross-analysis group effort to understand how the overlapping of galaxies in LSST images affect shapes, photometric redshifts, and ultimately the cosmological analysis. In addition, we have used the expertise gained in these tasks to assist the work of collaborators on Task CL2.6 (Cluster Masses from existing cluster observations), providing additional simulated datasets to test the development of the clusters pipelines.

In addition to the projects directly covered by the award, the PI has taken on leadership tasks within the DESC organization, serving as Convener of the Galaxy Clusters DESC group from the inception of the DESC. As convener, he has been responsible for developing and prioritizing the development tasks required to be ready to measure dark energy with galaxy clusters with LSST data, and detailing them, first in the DESC White Paper and then in the SRM. Furthermore, as convener, he has been tasked organizing and tracking the work of DESC members on all the clusters analysis tasks, from cluster selection, shear measurement, mass calibration and modeling to theoretical constraints. In addition, the PI was elected to the DESC governing Council in October, 2016, and the elected as Council Chair, overseeing all aspects of collaboration governance, in January 2017.

ARCLETS—producing the simulations for the SRM DC1-era tasks

The first part of our work was to construct simulated LSST observations that would encode the essential elements of the image and color distortions that would be generated by galaxy clusters. This would allow us to calibrate the output of LSST analyses in the situation where the input lensing signal was known. Our approach necessarily differs from the approach taken in the weak lensing group because the massive galaxy clusters significantly distort the galaxies that are directly behind their central regions. The result is that, rather than just being made more elliptical, the galaxies have higher order distortions (e.g. flexion) and can even be distorted into rings and multiple images. Because one of the main goals of our study was to study the effect that ignoring these distortions (as the LSST L2 Data Management shape measurement pipeline does) makes on cluster mass estimates, we needed simulations that could accurately represent the distortions. Because the higher order distortions can result in significant magnification of faint galaxy and noise features, we required that the template galaxies we distort be free from noise (this is in contrast to the procedure used in GalSim as used by the weak lensing group in its simulations. At the same time, we required that the galaxies have sufficient structure that sub-image magnification could be handled correctly. The solution we arrived at involved extracting from the deep HST images (first the Hubble Deep Field and the CANDELS surveys) postage stamp images of real galaxies. These stamps are then used to construct (via flux rescaling, resizing and rotation) all of the simulated galaxies behind the cluster. Each galaxy image is then sub-pixel sampled and the subpixels are separately ray-traced through the cluster mass distribution (which generates the lensing deflection) and mapped onto the image plane. In reality, to allow for strong lensing, we have developed an efficient reverse-tracing method which connects output sub-pixels to the input image (thereby allowing multiple imaging). The individual distorted galaxies (still at the resolution of the space-based images) are then assembled into an image, and then the atmospheric and instrumental smoothing (or PSF) is applied to the image and it is resampled onto the LSST scale. An example of the postage stamps (taken from Liu et al., 2017, in preparation) is shown in Figure 1:

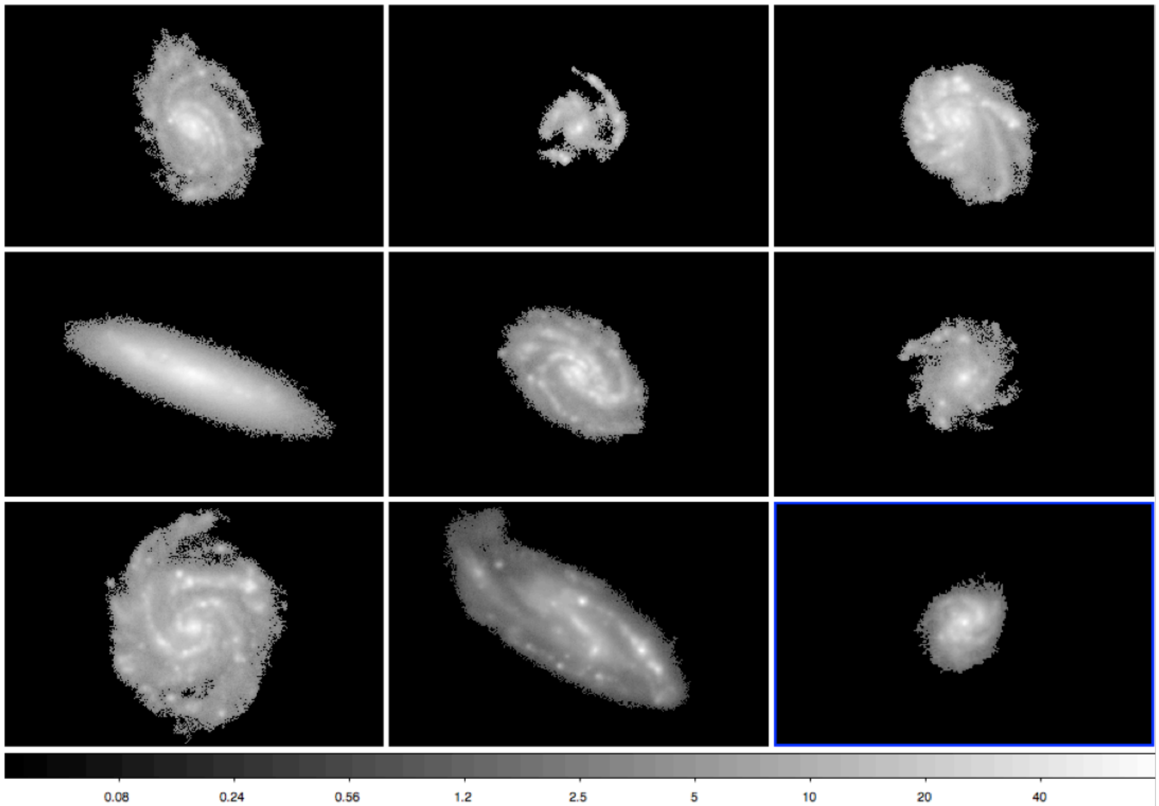

Figure 1: Examples of galaxy stamps from the HDF. From Liu et al. 2017

In collaboration with Doug Clowe (Ohio University), we produced more than 180 individual simulations of galaxy clusters (graduate student Binyang "Robert" Liu was funded from this award to produce the galaxy stamps and generate the simulations). These cluster images were released to the DESC (and indeed to the entire cosmology community) as an LSST DESC featured project in 2015. A second round of galaxy stamps including for the first time color information of the galaxies (from extracting matched stamps from the multi-band CANDELS data) were produced in the summer of 2016 (with work from Binyang Liu supported by Mingbin Leng, Shenming Fu, and Jacqueline McCleary). These will form the basis of the studies of color-dependent biases to be carried out among the DC-2 tasks.

In addition to the simulations of galaxy clusters, the ARCLETS project also embarked on a second set of simulations. In these simulations, the same postage stamp images are produced, but instead of simulating a galaxy cluster, a grid of galaxies is created in which each galaxy is subjected to the same distortion level (as measured by the reduced shear). These "grid simulations" are designed to test the LSST data management (DM) shear pipeline's output.

Shear Calibration into the Cluster regime

A key assumption in weak gravitational lensing is that the distortions of the galaxies caused by the mass distributions are small. In this limit (at least for shear lensing), the information about the lensing is entirely encoded in the ellipticity shape moments of the galaxies e_1 and e_2. As verified by the STEP and GREAT simulations, this approach works very well for measuring large-scale shear correlations, where the characteristic distortions have typical amplitudes smaller than 1-2%. However, clusters of galaxies distort images more, and this assumption becomes increasingly invalid as the dark matter surface density increases towards the center of the clusters. In studies of individual galaxy clusters, this is typically handled by extending the fit to include higher order shape moments (such as the octopole moments or "flexion"), or by separately fitting the strong lensing signal. However, for a survey such as LSST, this is impractical, because remeasuring higher order moments for billions of galaxies is computationally expensive. As an alternative, we (Liu et al. 2017) explored the calibration of the elliptical shear signal beyond the low-shear regime to derive a non-linear normalization of the shear signal. This is becoming more common (the DES is implementing a similar scheme for its cluster analysis), but, given LSST's greater depth and image quality, it is critical for LSST's measurement of the cluster masses.

In figure 2, we demonstrate the result of our investigation. Using the ARCLETS grid simulations, which have a fixed distortion (measured by the reduced shear), we employ the LSST DM software to measure the ellipticity shear moments of the galaxies at fixed reduced shear. For small shears ($g<0.1$), we recover a linear relationship between the input distortion and measured shear (albeit with a slightly higher normalization than that found in the STEP simulations). This is expected, because at small shears the non-linear effects are minimized. However, even at $g=0.1$ there is a noticeably deviation from linearity. Despite this, there is a monotonic relation between the distortion and the measured shear that is characterizable out to quite high shear values ($g=0.4$ for the current DM shape measurement algorithm, which is based on Hirata, Seljak and Mandelbaum 2006). By normalizing the shear measurements by the ratio between the measured values (points) and the dotted line, we can produce calibrated mass measurements almost into the central regions of galaxy clusters. These results (taken together with the results on cluster mass profiles discussed in the next session) demonstrate that the DM software can be used to probe the lensing signal in clusters in to $r<200$ kpc from the center, increasing the sample of clusters for which individual lensing signals can be measured dramatically. A paper (Liu et al. 2017) describing the results is awaiting the implementation by DM of its next generation shape measurement algorithm before submission.

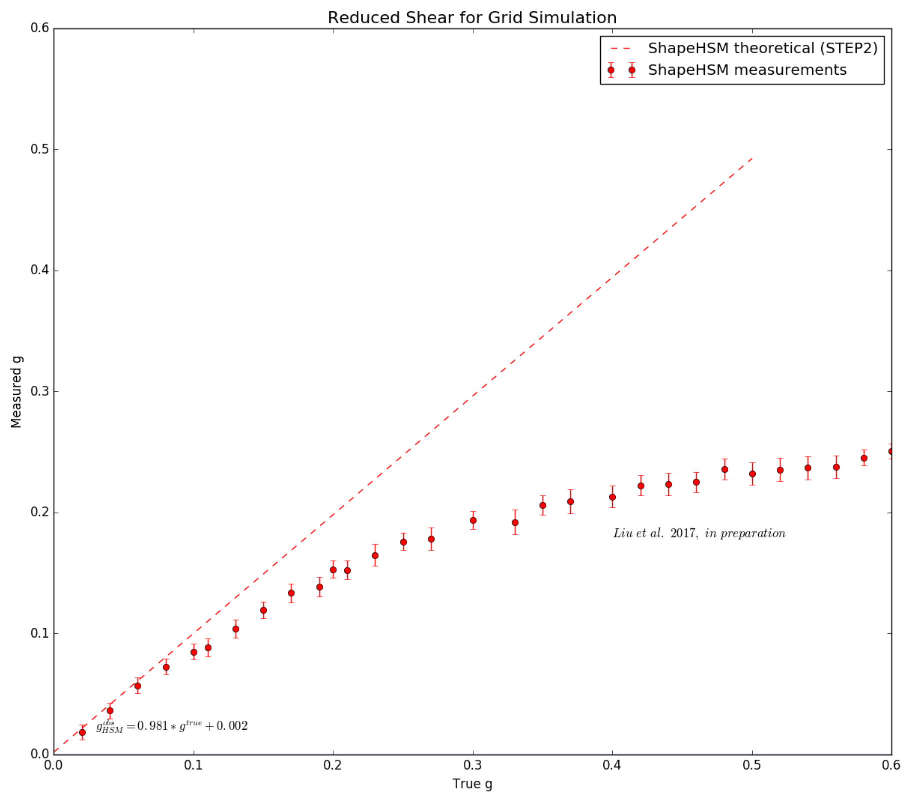

Figure 2: Mapping between input reduced shear in the ARCLETS grid simulations and the shear output by the LSST DM processing.

Cluster Shear Mass and Shear Profile Calibration

The strongest cosmological constraint on dark energy that will emerge from LSST's study of galaxy clusters comes from the evolution of the cluster mass function. Accurate reconstruction of the mass function depends critically on accurate mass determination. As part of this award, we have been using the ARCLETS simulations of clusters to measure the mass and mass profile of the simulated galaxy clusters to measure the mass-dependence of the mass bias in the reconstruction. Using the LSST DM software to analyze 240 clusters (60 each at four different masses), we first construct the maps of the mean tangential ellipticity as a function of cluster mass for a variety of radii. Figure 3 (from Liu et al. 2017) shows the results: as expected, the shear at radius increases with mass. However, the shear at the innermost radius for the massive clusters shows the characteristic saturation of the ellipticity demonstrated in Figure 2, whereas at larger radii the average shear scales linearly with mass. This suggests a strategy in which cluster masses are calibrated using the signal outside of 250 kpc (corresponding to reduced shear g=0.3, very similar to the conclusion of the grid simulations above).

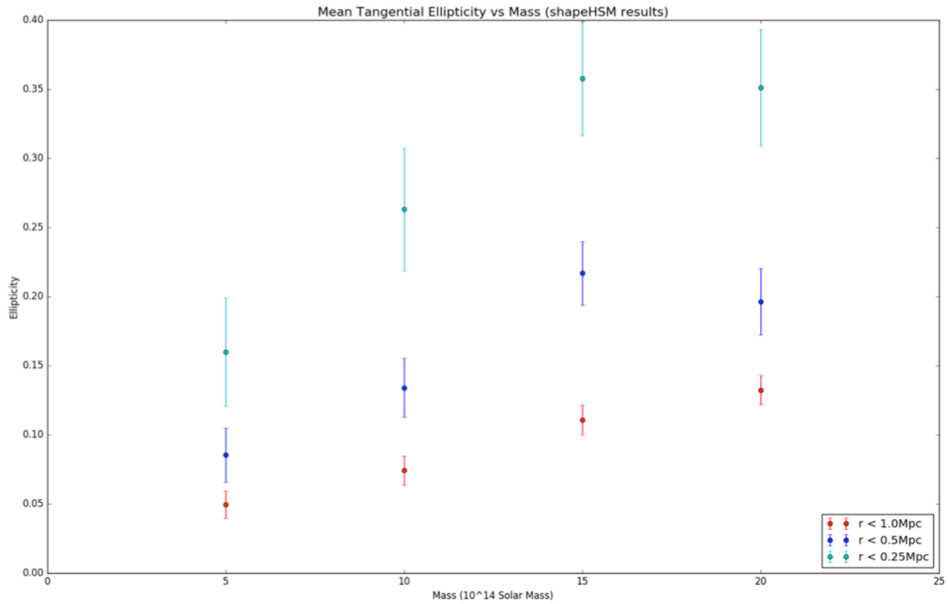

Figure 3: mean tangential ellipticity at a fixed radius for ARCLETS simulations of different mass

Figure 4 shows the mean tangential shear profile for four cluster masses.

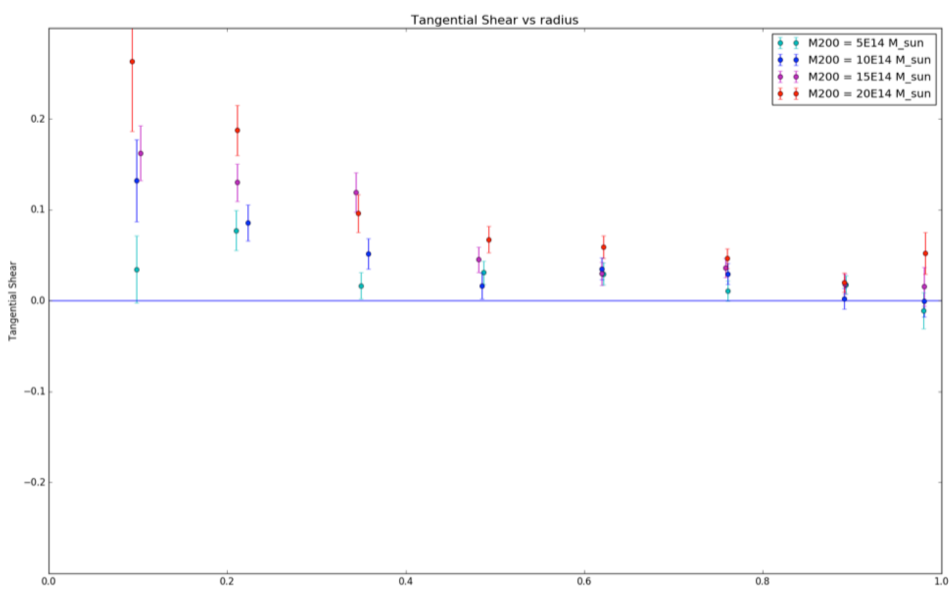

Figure 4: mean tangential ellipticity versus cluster radius for the four cluster masses in the ARCLETS simulations

Of course, the true measure of the bias is how well we can recover the mass of the clusters. To this end, we have collaborated with Nicolas Chotard, Celine Combet and Dominique Boutigny of IN2P3, who have been developing a cluster mass measurement pipeline for LSST (but testing it initially on data from CFHT's MegaCam). In addition to providing mass-mapping code for the pipeline, our group has been adapting the pipeline to accept the ARCLETS simulations (which do not have full photometric redshift data yet). In figures 5 and 6, we show the distribution of mass estimates from the MCMC realizations of the shear field for our simulated galaxy clusters (from Combet et al. 2017), demonstrating how LSST DM measurements that exclude the central regions of the cluster can reliably recover cluster masses. In the DC2 era, we will use these mass estimates to determine the mass-dependent bias that arises from the DM shear modeling.

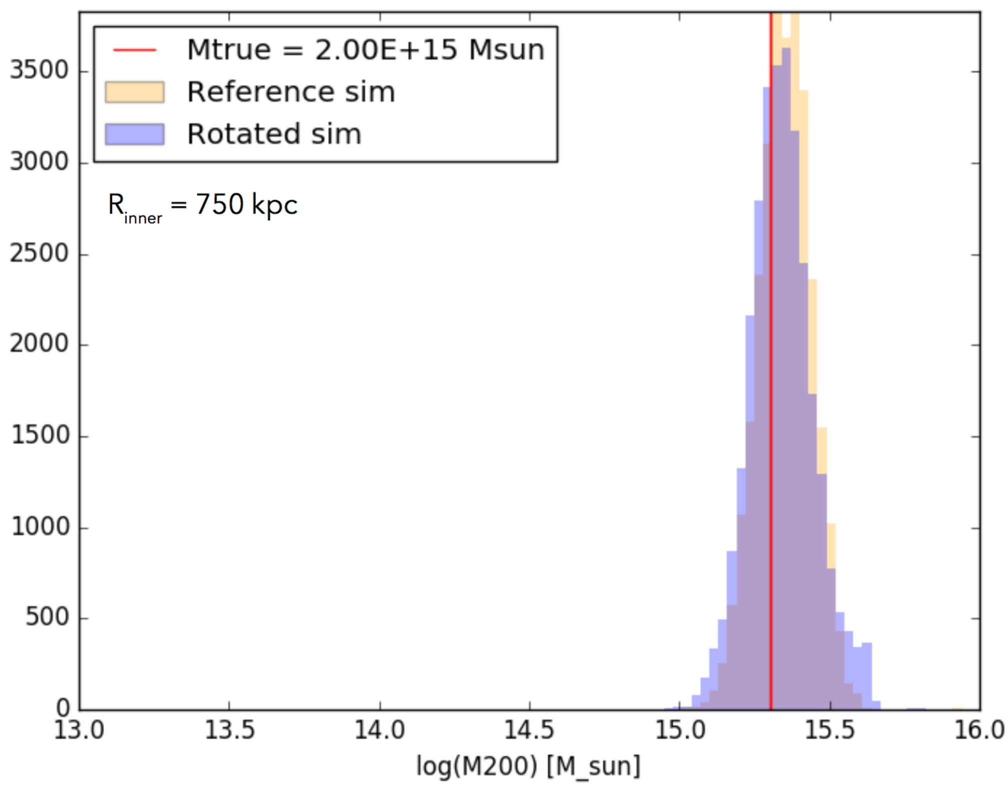

Figure 5: mass modeling through the DESC clusters pipeline of an ARCLETS cluster realization of a high mass cluster. From Combet et al. 2017

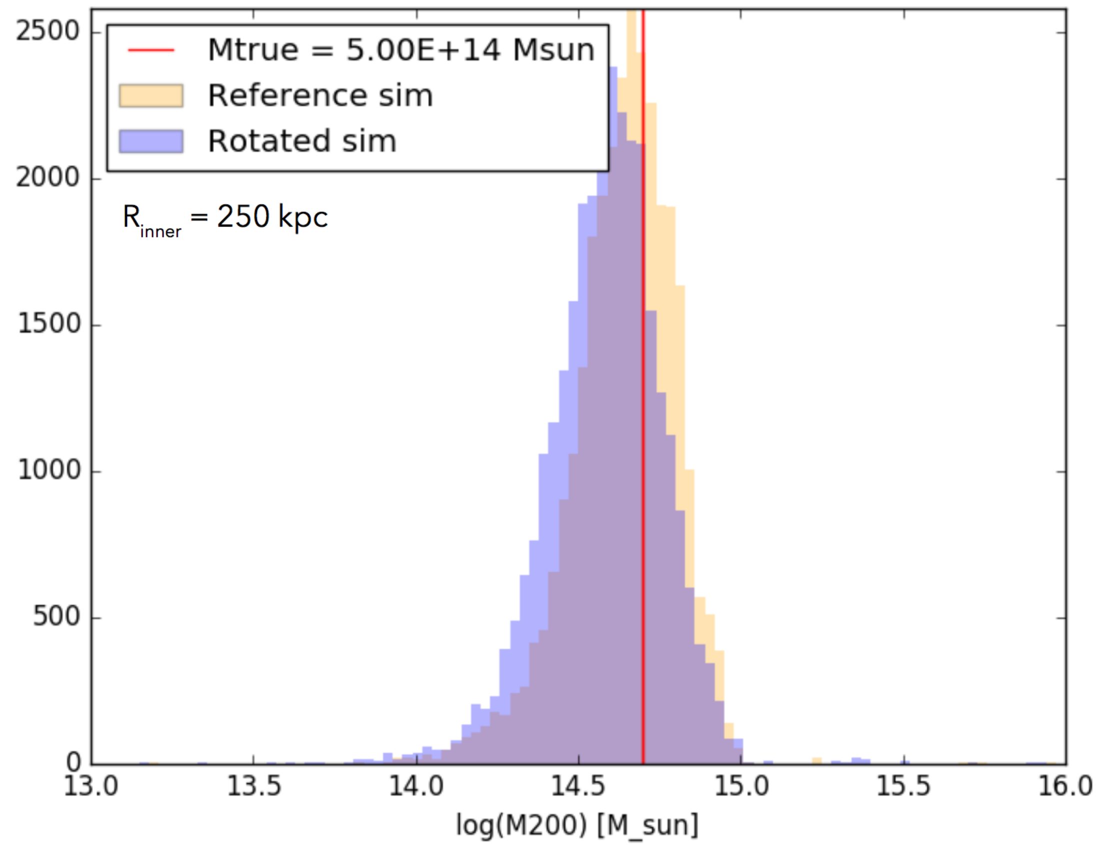

Figure 6: MCMC realization of cluster mass measurement of a low mass ARCLETS cluster. Note that for a lower mass cluster, the exclusion region can be considerably smaller. From Combet et al. 2017.

Shear Bias due to Blending in the Cluster Environment

The other main activity carried out under this award was the study of galaxy shear bias from deblending. Although galaxy blending is expected to be a major issue for all of the LSST science analyses, they present a particular difficulty for galaxy clusters, because the density of galaxies are larger in the cluster fields. Furthermore, the density of galaxies has a radial gradient. If blending with cluster galaxies biased the shapes, we would expect a radial shape bias that would directly affect mass measurements. Therefore, one of the essential requirements for cluster cosmology is that this bias be accounted for. However, when the project started, there was no estimate even of the size of the bias.

We measured the shear bias using the ARCLETS simulations for the background galaxies. Graduate student Shenming Fu (funded by Brown University through a TA) then used a similar procedure to generate postage stamps of cluster galaxies from the Hubble space telescope images from the CLASH survey of galaxy clusters.

Using the postage stamp as well as the measured distribution of galaxy sizes and surface densities from the Hubble imaging, he produced model foreground galaxy clusters. By measuring the shapes of the background galaxies (distorted by the cluster dark matter) with and without the cluster galaxies superimposed, we were able to measure the effect of the blending on the shear profile. Shenming presented these results at the LSST DESC collaboration meeting in February, 2017, and at the "One Percenter" meeting organized by the Simons Center for Cosmology that brought representatives from all the Stage III cosmology experiments, plus LSST and WFIRST to discuss aspects of cluster cosmology.

The results of our study are suprising, and different from the conclusions of the stage III experiments that have been conducting similar tests. In particular, all groups came into the study expecting the dominant bias to be due to the gradient in cluster galaxy density. In this scenario, we would see a bias even if the background galaxies were not distorted. Indeed, both the Dark Energy Survey (DES) and the HyperSuprimeCam imaging survey (HSC) took this approach, randomly placing galaxies of known shape onto the cluster fields and measuring the recovered shapes. They reported no bias (Melchior et al. 2017). However, in Figure 7, we show the results of our simulations, which show a bias in the inner regions of the cluster field. The reason for this is simple (in retrospect): the gravitational lensing distortions create a systematic alignment of the galaxies, which breaks the symmetry of the blending because blends are more likely to happen along the long axis of a galaxy. The net effect is to generate a shear-dependent bias in the galaxies. We test this hypothesis by generating simulations with zero-mass clusters (shown in Figure 8), showing that signal depends on mass. As Figure 7 sjpws, we demonstrate that results in a 3% mass bias with the default DM deblender. This is the first time that the blending bias to the cluster mass has been measured Unfortunately, this level of bias, if uncorrected, is larger than the mass calibration accuracy required for LSST. A revised deblending algorithm is under development by DM, and will be unveiled in Q1 2018, and we will repeat the measurement with the improved deblender. However, we have already demonstrated that the effect of the blending is to provide a multiplicative bias, allowing us to recalibrate the cluster shear measurements to cancel out this bias to better than 90% precision.

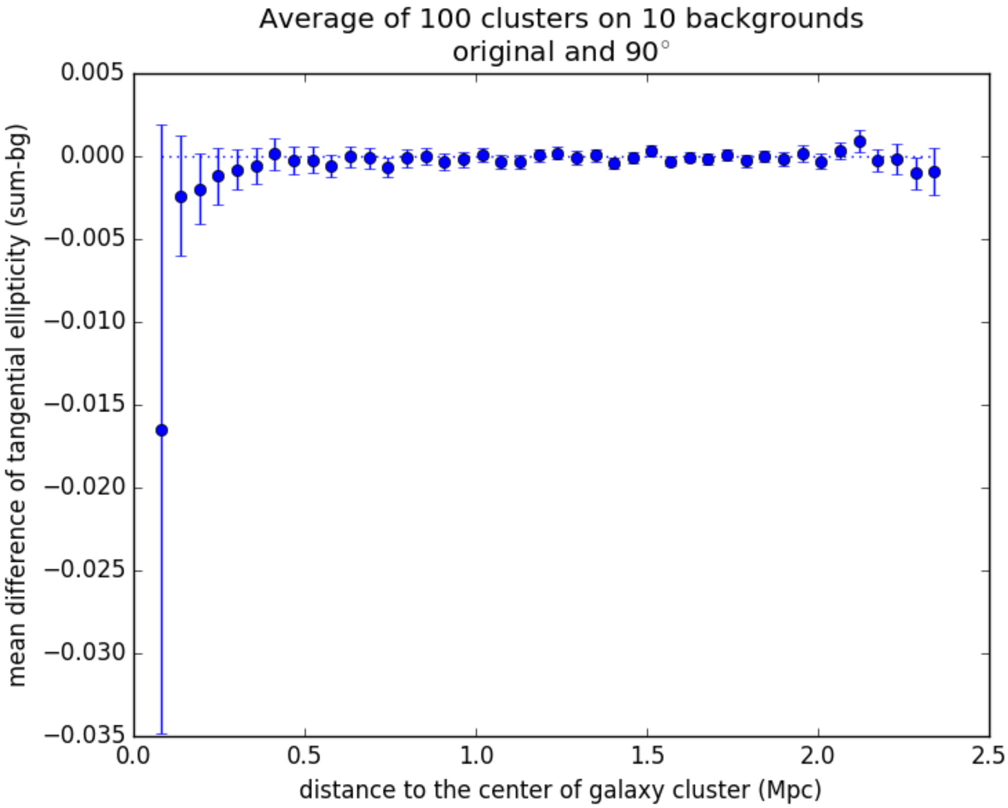

Figure 7: Tangential ellipticity bias resulting from blending as a function of cluster distance. From Fu et al. 2017

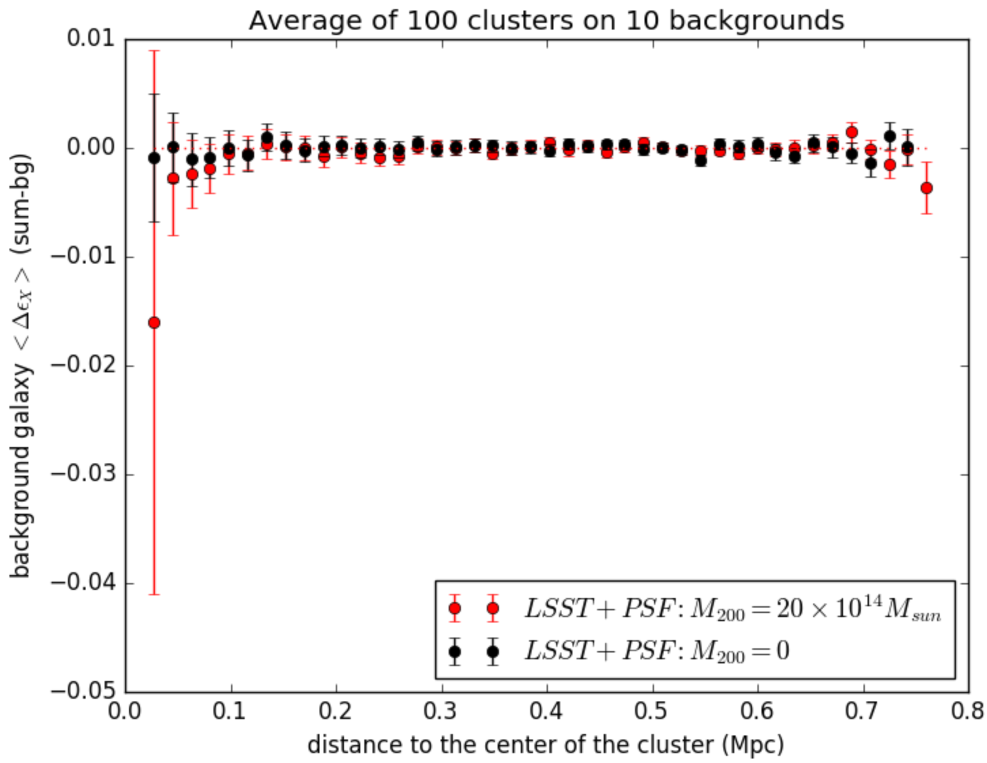

Figure 8: Comparison of tangential shear bias for massive and massless clusters. From Fu et al. 2017.