Substructure and Shape of Galaxy Clusters

Abstract: The primary goal of this research is to measure the ellipticity and alignment of dark matter halos associated with the galaxy clusters, and to understand its relation with the shape of the gas distribution. I will be using multiwavelength data from optical, X-ray, Sunyaev Zeldovich (SZ) effect and lensing to measure the shapes of dark matter and gas in clusters. Initially I will be studying an X-ray selected sample of 10 clusters using lensing, X-ray and optical data. Subsequently, I will increase this sample by using the SZ cluster catalogs that are being developed by the South Pole Telescope (SPT) and the Atacama Cosmology Telescope (ACT). I will also propose for pointed observations with HST in the optical, Chandra in the X-rays, and CARMA for SZ. This study will aid in the mass (obtained from lensing) - observable (X-ray temperature, Compton Y-parameter from SZ) calibration of clusters, and the ellipticity measurements of clusters will help constrain the amplitude of mass fluctuations, $\sigma_8$.

Galaxy clusters, being the largest gravitationally bound systems of dark matter, are excellent probes of dark matter dynamics, cosmological structure formation, gas-physics and galaxy formation. My research focusses on understanding galaxy clusters as individual systems and as tracers of large scale structure. As a postdoc, I will undertake several studies to combine gravitational lensing, a powerful probe for mapping dark matter, with multifrequency observations of clusters, to better calibrate the mass-observable relationship and to measure the shape of the cluster halos. As a part of my thesis, I am involved in the development of high fidelity mass reconstruction algorithms, which are extremely relevant in the light of the large amount of existing and upcoming data. Existing surveys like SDSS and 2dF in the optical, and ROSAT in X-rays have detected thousands of galaxy groups and clusters, and future surveys like DES, LSST, JDEM and eROSITA promise to detect many more. CMB experiments like ACT and SPT are building their SZ cluster catalogs. Surveys like MACS perform pointed observations of individual clusters from HST and CHANDRA. These observations will help us get insight into triaxiality of galaxy clusters, whether the central region of the cluster profile is cuspy as predicted by $\Lambda$CDM simulations or shallower as suggested by observations, and the amount of substructure present in galaxy clusters. With the vast improvement in data and better mass modeling techniques we are shifting paradigms from studying one dimensional mass profiles to understanding two-dimensional mass and gas maps of the clusters.

I. CURRENT RESEARCH: CLUSTER MASS RECONSTRUCTION

My research aims at combining all possible lensing information optimally to map out the mass distribution of galaxy clusters. Clusters show a wide range of lensing phenomena: the spectacular multiple arcs near the core, flexion measurements at the semi-strong region, and very weak lensing distortions toward the periphery. These phenomena dominate at different scales and with varying signal-to-noise ratio. In order to combine them we need a technique that has a varying resolution. While pursuing such a method, I have led the development of “Particle Based Lensing” [1] or PBL[1] with my advisor Professor David Goldberg. This approach is similar to the adaptive mass reconstruction technique developed in [2]. Using this method, I can tune a reconstruction to produce a constant signal-to-noise ratio throughout and maximally exploit regions of high information density. I have studied three clusters, namely: the “Bullet Cluster” (1E0657-558) [3], the super cluster Abell901/902 [4] and A1689 [5]. I have made a mass map of the core of the ”Bullet Cluster” resolving the two peaks and measured their masses. Using the shear catalog provided by Dr. Catherine Heymans, I

have measured the ellipticity of each of the peaks of Abell901/902 both non-parametrically (using PBL) and parametrically. Two of the peaks (the southwest peak and A902) has non-zero ellipticity at 2-σ level. Figure 1 is an example of PBL reconstruction of A901a, as discussed in the caption I have also measured the alignment between peaks in the field of view. A1689 has 40 strong lensing systems and SUBARU weak lensing data out to a few Mpc analyzed by Dr. Hakon Dahle. I am comparing the S+W PBL reconstruction for this cluster with the parametric mass reconstruction provided by Dr. Marceau Limousin. I am also studying the shapes of the (S+W) map and the X-ray brightness map in collaboration with Dr. Signe Riemer-Sorensen, Dr. Andrea Morandi and Professor Kristian Pedersen.

![Figure 1](image1.png)

**FIG. 1:** Right Panel: A PBL reconstruction of one of the peaks Abell 901a. Left Panel: Error Map for the same field of view. The innermost contour for the central peak corresponds to $\kappa = 0.18$. A secondary peak is also detected, this peak has an infalling X-ray group associated with it. The error map confirms the significant detection of the peaks. The principal axis of this mass distribution makes an angle of $57 \pm 5.1^\circ$ with the x-axis. This peak has strong alignment with A901b and A902, two other peaks in the field of view and it is not aligned with the fourth peak the Southwest Group. From Deb et al. 2009.

### II. FUTURE PROJECTS

**Combining Lensing with X-ray and SZ Observations**

I will study the physical properties of galaxy clusters by comparing the distribution of dark matter (from lensing), gas (from X-ray and SZ) and light (from member galaxies). I will apply PBL to obtain reliable mass reconstructions of clusters using weak lensing and S+W lensing. Our technique has well understood uncertainties, the effectiveness of adaptive methods, and the simplicity of uniform gridding [1, 4]. This makes a PBL reconstruction ideal for comparison with X-ray brightness, the optical luminosity distribution and SZ decrement maps. I will measure the light distribution by smoothing the light profiles of member galaxies. In collaboration with Dr. Morandi and Dr. Sorensen, I will generate the X-ray and SZ maps. These studies will help me investigate the relation between dark matter and baryons in individual systems, which I will compare with predictions from hierarchical structure formation simulations [6] and hydrodynamical simulations [7].
Apart from studying individual systems, I will carry out a statistical study of morphology of the different components of clusters. I will choose a sample of significantly relaxed clusters and measure the quadrupole moments of their dark matter from lensing and gas using X-ray/SZ data. A systematic study of these moments for increasing aperture sizes and the calculation of the ellipticity (using isodensity contours) in each wavelength as a function of radius, will help us understand the asymmetry in each wavelength [8–10]. For a large sample, I will study the dependence of cluster ellipticity with mass, redshift and radius and test theoretical predictions from N-body ΛCDM simulations [11]. Since ellipticity of dark matter halos is a strong function of the amplitude of mass fluctuations σ_8 [12] reliable measurement of cluster ellipticity can be used to constrain cosmology. Clusters with dominant multiple peaks, such as the “Bullet Cluster”, can be used to test whether the major axes of both peaks are aligned as expected from simulations. Many cluster systems are reasonably clumpy and measuring their higher order moments [13] should describe them more accurately. A useful measure in this regard is the so-called power-ratio, which is the ratio of the higher order moment to the zeroth order moment within a given aperture [9]. Calculating the power ratios for increasing apertures will let me investigate the scales at which the substructure is dominant. These systems are also being studied parametrically using X-rays [14, 15] and with joint analysis of multiwavelength data [16].

I will also measure the masses of these clusters at varying redshifts through gravitational lens modeling which is independent of the physical state of the cluster. This will help in calibrating the scaling relationship between mass and temperature for X-rays and mass and Compton Y-parameter for SZ observations. An accurate calibration of this relationship will help us constrain the cluster mass function which will be used to constrain a wide range of cosmological parameters involving dark energy equation of state parameter and σ_8. A precise measurement of the cluster mass function can also be used to test theories of modified gravity since the mass function in clustered dark energy models are a function of fluctuations in dark energy and matter density [17].

List of Targets
There is publicly available Chandra and HST data on the following clusters (A1689 [18], A2218, A2390 [19], 1E0657-558 [3]) and XMM and HST data available for some clusters like CL0024+1654 [20]. The MAssive Cluster Survey (MACS) is an ideal dataset for such a study. Part of this survey (for example MACS J1149.5+2223, MACS J0417.5-1154, MACS J0025.4-1222) is done and there is public HST and Chandra data. I will be collaborating with Dr. Dahle for obtaining shear catalogs for a sample of 10 X-ray selected clusters. Furthermore SZ surveys like ACT and SPT will make their cluster catalogs public in the near future and the DES will cover the same patch of sky providing invaluable lensing data. This mass selected sample will have many high redshift clusters which can be probed by strong lens modeling. I would propose for HST observations for these clusters. I am also interested in spectroscopic confirmation of multiple images in galaxy clusters using the Keck Observatory.

Survey Clusters
There is a wealth of data in all sky surveys like the SDSS. However the lensing signal-to-noise is low per cluster in such datasets, and clusters have to be stacked for constraining their mean profile [21] and shape [22]. The stripe 82 data from SDSS is ideal for this analysis because of the SZ coverage by ACT and the possibility of X-ray followup with the Chandra Observatory. I will undertake a study of the ellipticity of stacked cluster profiles with lensing, SZ and X-ray data. This will give a comparison of the ellipticity of the gas and dark matter in the typical cluster. I will also use survey data to study the alignment among cluster halos (similar to Abell901/902) and compare them to simulations [11].
III. DISCUSSION

In this proposal, I have outlined techniques to measure the ellipticity and higher order shape parameters of halos, which I will use on a sample of clusters with pointed observations, and on stacked data from sky surveys. Another interesting result from this study will be the lensing mass measurements of a sub-sample of clusters from future SZ cluster catalogs which will help us understand the scaling relationship between SZ Y-parameter and mass of the clusters. The aim of this study is to make maximal use of available multi-wavelength data on galaxy clusters and compare the results with expectations from theory and simulations.