Cluster Stacking: Increasing Precision and Accuracy in Galaxy Cluster Mass Estimation

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Cluster Stacking

Galaxy clusters are high-mass structures visible throughout the near and distant universe and play a crucial role in the study of its evolution. However, measuring the total mass of galaxy clusters accurately and precisely is one of the major barriers in observational cosmology. For a given cluster, the caustic technique (see below) uses the kinematics of the surrounding galaxies to estimate the escape velocity profile and thus the Newtonian mass of the underlying dark matter. The precision and accuracy of the caustic technique performs well when sampling a large N number of galaxies from the cluster, but suffers greatly when working with only a handful of galaxies. We show that by overlaying, or *stacking*, the kinematic data of poorly sampled (low N) *individual clusters* into one larger *ensemble cluster*, we can significantly increase the caustic technique's precision and accuracy for a poorly sampled system. In Figures 1 and 2 (below) we quantify the precision and accuracy of our mass estimate's ability to recover the true, simulation defined mass.

We use the Millennium Simulation, one of the largest simulated universes containing thousands of clusters, to test the theoretical limitations of our method. To create an ensemble cluster, we choose an individual cluster and go to a random position away from the cluster center. We then make a mock observation along our line-of-sight view straight to the cluster and select a random N galaxies from the cluster as our sample. We iterate this process from a few to a hundred times, each time stacking the phase spaces of each mock observation. The number of times we iterate directly controls the final sample size of our ensemble, and consequently the precision of our mass estimation. We repeat this for up to 10^3 different clusters, quickly creating the need for high performance computing both for analysis and visualization.

By taking advantage of the FLUX high performance computer, we show that cluster stacking can increase both the precision and accuracy of a poorly sampled cluster mass estimate by upwards of 60%. With the aid of HPC, we will use this method on the largest available spectroscopic catalogs of galaxies, such as BOSS (Dawson et al. 2013) and GAMA (Driver et al. 2011), to try and constrain cosmological models of the early and recent universe.

The Caustic Technique: Critical Limitations at Low Sampling

As a dynamical method, the caustic technique needs only the cluster-centric distances and velocities of the surrounding galaxies to trace the escape velocity and therefore the gravitational potential of a cluster. In the figures to the upper right, we show how we infer the escape velocity as the iso-density edge of the phase space diagram, called a caustic surface. We use a model to relate escape velocity to gravitational potential. Using the caustic technique and the resultant potential profile of the cluster, we can infer a total dark matter mass with zero bias and low scatter (~30%) so long as we have a large sample of galaxies, N > 100 (Gifford et al. 2013). However, the accuracy and precision of the caustic technique quickly grow worse with decreased sampling, reaching a bias and scatter of >50% and 100% respectively at N=10, which is a typical sample size for realistic galaxy catalogs (e.g. BOSS, GAMA). In order to infer accurate and precise dynamical masses from poorly sampled clusters using the caustic technique, we can employ cluster stacking and recover the same low bias and scatter statistics of highly sampled clusters.

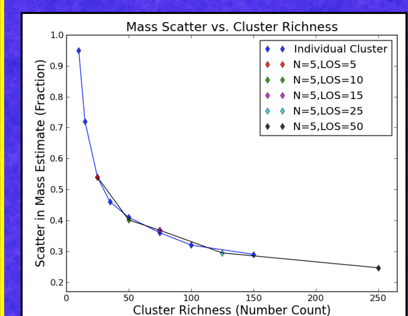


Figure 1: Mass Scatter of Individual and Ensemble Clusters
This figure shows that an ensemble cluster, stacked an LOS number of times from an N=5 individual cluster, can recover the same mass estimate precision as a highly sampled individual cluster.

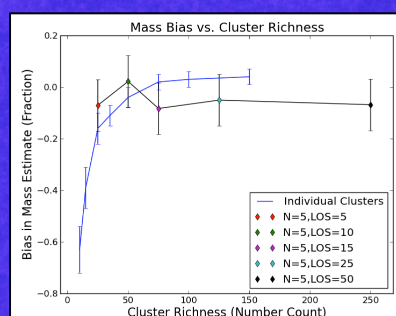


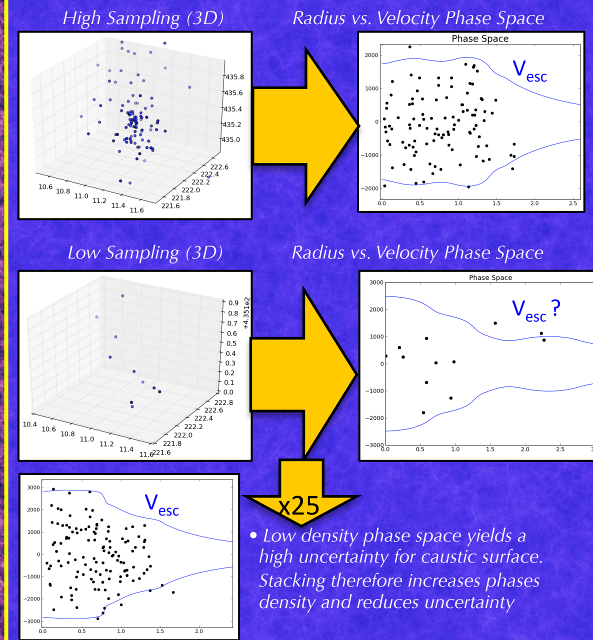
Figure 2: Mass Bias of Individual and Ensemble Clusters
Mass estimates of individual systems, when poorly sampled (N~5), show a significant mass bias (blue), whereas poorly sampled clusters after stacking recover small biases ~10% (black).

References
Dawson K. S. et al. 2013 The Astronomical Journal, 145 10

Driver S. P. et al. MNRAS (2011) 413 (2), 971-995

Gifford D., Miller C. J., & Kern N. S. 2013, ApJ, 773, 116

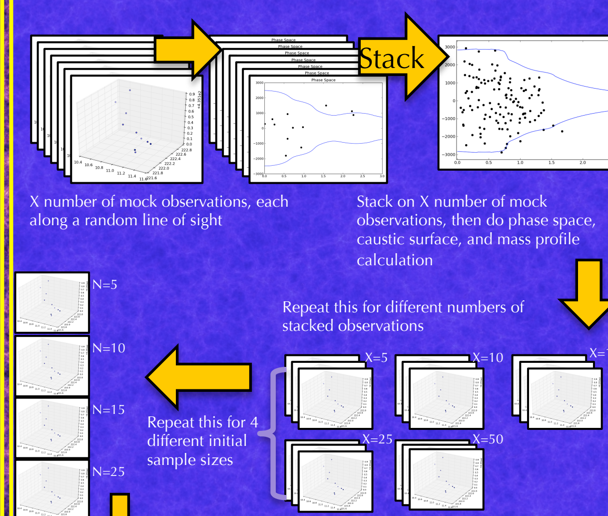
Visualization of a Mock Observation



- *Low density phase space yields a high uncertainty for caustic surface. Stacking therefore increases phases density and reduces uncertainty*

Low Sampling Phase Space after Stacking ~25 times

Need for High Performance Computing



Repeat this whole process for 10^3 different clusters with varying mass

This one week computation takes ~5 hours using HPC