Caustic Masses From Stacking Galaxy Clusters:
Toward an Unbiased Mass-Observable Relationship

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Abstract

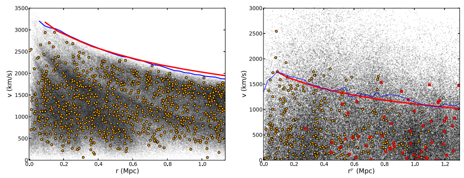
Knowing the masses of galaxy clusters in the local and far universe is a powerful tool for analyzing the growth of structure, and can also constrain models that characterize the evolution of the universe. However, measuring the masses of galaxy clusters accurately and precisely remains a major barrier. Ongoing and future spectroscopic surveys will measure the position and redshift of galaxies within clusters for tens of thousands of galaxy clusters. Many of these clusters will have only tens of spectra, which is too low to achieve precise and accurate mass estimates from dynamical estimators. We show that by joining multiple clusters' phase spaces together, also known as "stacking", we can achieve an average dynamical mass estimate for an ensemble cluster that is accurate and precise. We explore how different methods of stacking affect the bias and scatter of the resulting mass estimate, and how these methods can be applied to universal mass-observable relationships in real data.

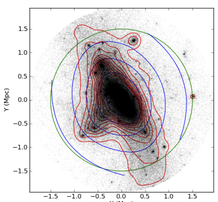
Galaxy Cluster Masses Through their Phase Space

- Challenge 1: Projection Effects
- Challenge 2: Low Galaxy Sampling

Projection:

Projection of a galaxy cluster along a line of sight (LOS) "blurs" the edge of the phase space, and also leaves us vulnerable to non-spherical shape effects; most clusters are triaxial in shape, not spherical.



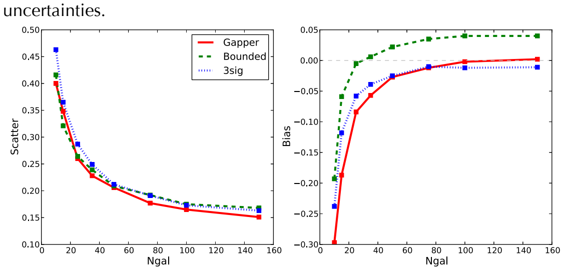


Above: A galaxy cluster's phase space in 3D coordinates (left), and after being projected along a line of sight (right).

Left: 2D view of a galaxy cluster's dark matter particles, red is the particle density contours and blue is the gravitational potential.

Low Galaxy Sampling

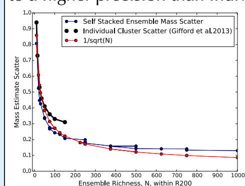
When the phase space isn't populated with enough data points, dynamical mass estimates suffer greatly from low-number statistic uncertainties.



Above: Fractional scatter and bias of caustic masses (red) as a function of the number of galaxies in the phase space, N.

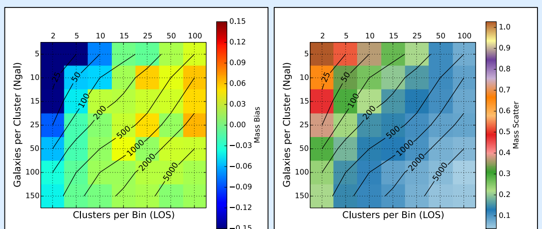
How Stacking Addresses These Issues

By stacking the phase spaces of galaxy clusters we average out spherical asymmetries. This allows for our mass estimates to plateau to a higher precision than individual cluster mass estimates.



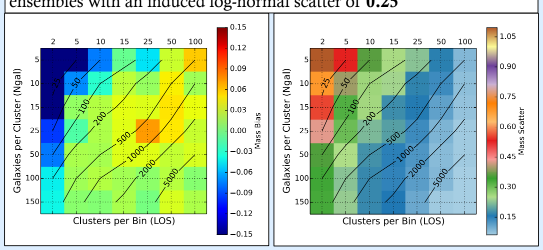
Left: Mass scatter as a function of phase space sampling. Black is the scatter of individual cluster masses, and the blue is the stacked mass estimates.

Stacking also increases the sampling of the phase space. For example, an ensemble cluster created by stacking 10 clusters each with 10 galaxies means that the resultant ensemble has 100 galaxies, rather than 10 for any one individual cluster. This allows us to recover the low bias and scatter that a highly sampled phase space achieves.



Above: Mass bias and scatter as a function of stacking method for ensembles with an induced log-normal scatter of **0.05**

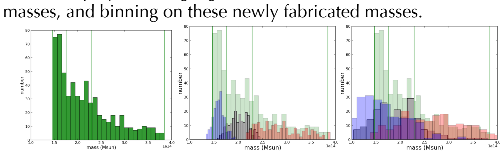
Below: Mass bias and scatter as a function of stacking method for ensembles with an induced log-normal scatter of **0.25**



Stacking Introduces Mass Mixing

The trade-off for stacking is that we are averaging systems that are not identical. We are blending together, or mixing, clusters of different masses into one ensemble. This is called "mass mixing".

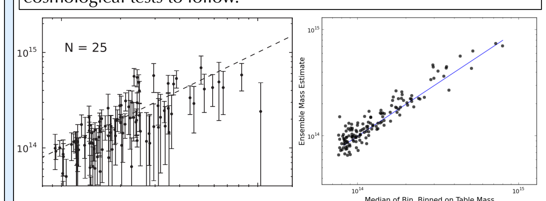
For real data, to stack, we determine an approximate cluster mass through some mass-observable relationship, like luminosity, and bin our data on the observable. However, the observable itself carries with it an uncertainty in its approximation of the true cluster mass, which propagates into our binning and enhances the mass mixing effect. We model the uncertainty in a given mass-observable relationship by inducing a generic fractional scatter into our known masses, and binning on these newly fabricated masses.



Above: Histogram of mass function: the number of clusters at a given mass. Left, mass function with no induced scatter in known mass. Vertical lines represent edges of bin. Center, mass function of clusters with **0.05** scatter. Right, mass function of clusters with **0.25** scatter. Colors trace members of bins.

We find that stacking with a mass mixing scatter of 5% and 25% produces low bias and low scatter results for highly sampled ensembles, (**left**). This can also be represented in a 1-1 scatter plot, which shows the increased precision and accuracy over individual systems, even with a mass mixing induced scatter of 25%.

We show that stacking galaxy clusters' phase spaces gives us precise and accurate ensemble cluster masses, even with an assumed mass-observable scatter of 25%. Ongoing work is aimed to apply this technique to low and high redshift spectroscopic surveys, and calibrate a mass-observable relationship for dynamical estimators with zero bias, which allows for a suite of cosmological tests to follow.



Left: Individual Clusters, **Right:** LOS=15, Ngal=15 Ensembles