Caustic Masses From Stacked Galaxy Clusters:

Toward an Unbiased Mass-Richness Relationship for Galaxy Clusters

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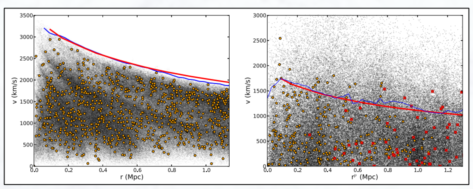
Abstract

Knowing the masses of galaxy clusters in the local and far universe is a powerful tool for analyzing the growth of structure over cosmic time and allows us to constrain cosmological models and parameters. The dominant matter component of galaxy clusters lies in their dark matter halos, however, measuring these masses accurately and precisely remains a major observational barrier. Ongoing and future spectroscopic surveys (BOSS, DESI, Pan-STARRS) will measure the positions and redshifts of galaxies for tens of thousands of galaxy clusters. Because these surveys are magnitude limited, many of the most interesting clusters at high redshift will contain spectra for only tens of galaxies, which is too low to derive accurate cluster masses. To circumvent this, we developed an algorithm that joins the kinematic galaxy data of multiple galaxy clusters, known as stacking, specifically designed for parallelization and use on high performance computing clusters. We systematically test our stacking technique on 6,000 dark matter halos in the Millennium Simulation and show that our technique can recover accurate and precise galaxy cluster masses. We then apply our technique to low-redshift spectroscopic data and derive a Mass-Richness relationship for 900 galaxy clusters. This is the first work that has been able to implement a stacking algorithm with galaxy cluster dynamical mass estimation techniques.

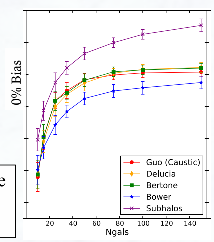
The Caustic Technique:

The Caustic technique projects each galaxy from a cluster into a cluster-centric radius and line-of-sight velocity phase space. The edge of this phase space traces the escape velocity profile of the cluster, which is directly to its gravitational potential and Newtonian Mass via Newtonian dynamics: $v_{esc}^2 = -2\Phi(r)$



A galaxy phase space in 3D (left), where the blue line is the caustic surface and the red line is the gravitational potential. The same cluster is then shown in projection (right), where the surface is blurred due to projection effects.

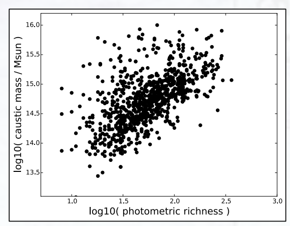
We tested the Caustic Technique against 100 dark matter halos in the Millennium Simulation (Gifford et al. 2013) and found that the Caustic Technique recovers the true mass of a cluster (0 +/- 5% bias) with low scatter (35%) if the phase space is sampled with over 50 galaxies. This level of galaxy sampling, however, is not the case for a large number of low-mass clusters and almost all clusters at high redshift. This creates the need for a stacking algorithm that can then use these poorly sampled galaxy clusters and produce meaningful information, such as their average mass.

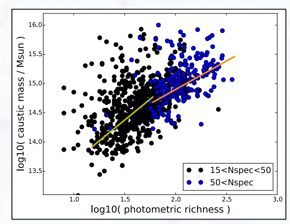


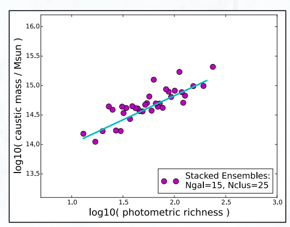
Right: Bias of the Caustic Technique as a function of phase space galaxy sampling. Above ~50 galaxies, the Caustic technique produces effectively unbiased mass estimates.

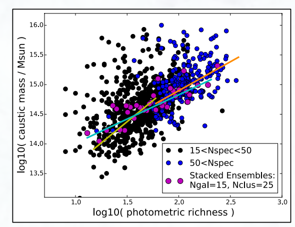
Mass-Richness Relationship for 900 Low-Z Clusters

We measure the Mass-Richness relationship for 900 galaxy clusters out to a redshift of 0.15 using SDSS DR12 spectroscopic data. We then stack on these clusters as a "proof-of-concept" that stacking works on real data. **Top-Left:** MR relationship using the Caustic technique for masses. **Top-Right**: MR relationship separated by galaxies that have at least 50 spectroscopic members and those that don't. **Bottom-Left:** Stacked ensemble masses plotted against the median of the constituent clusters' N200. **Bottom-Right**: All the plots put together, showing that the ensembles recover unbiased masses.



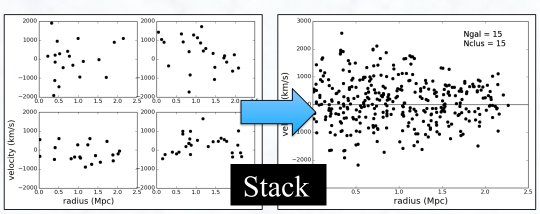




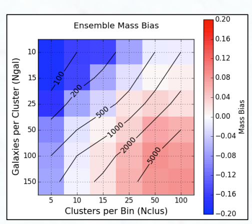


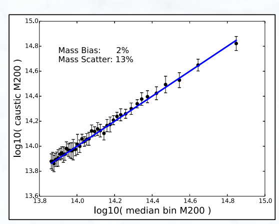
The Stacking Algorithm

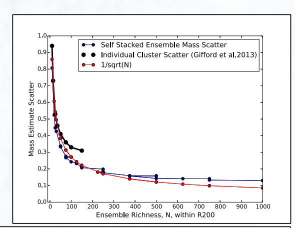
One thing that we discovered was that our stacked ensembles do a more precise job than the Caustic Technique by itself. This is because the scatter in the Caustic Technique is dominated by the spherical asymmetry of galaxy clusters. When we stack, we average out the asymmetries making the ensemble more spherically symmetric. This has the effect of allowing the Stacking Technique to level out at higher precision. We systematically test our stacking algorithm against 6,000 simulated dark matter halos and find that it can produce accurate and precise masses.



Above: Sparsely sampled galaxy clusters can be stacked into an Ensemble cluster, where we can measure the average Caustic surface to higher precision.







Left: Parameter space where we vary Ngal and Nclus to probe the uncertainties of the algorithm. **Center:** One-to-one line of Ensemble masses showing they can achieve theoretical zero biased and low scatter. **Right:** The Stacking algorithm levels out at a much higher precision than the individual Caustic technique.