

# cluster-lensing: A Python PACKAGE FOR GALAXY CLUSTERS AND MISCENTERING

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*Draft version April 7, 2016*

## ABSTRACT

We describe a new open source package for calculating properties of galaxy clusters, including NFW halo profiles with and without the effects of cluster miscentering. This pure-Python package, `cluster-lensing`, provides well-documented and easy-to-use classes and functions for calculating cluster scaling relations, including mass-richness and mass-concentration relations from the literature, as well as the surface mass density  $\Sigma(R)$  and differential surface mass density  $\Delta\Sigma(R)$  profiles, probed by weak lensing magnification and shear, respectively. Galaxy cluster miscentering is especially a concern for stacked weak lensing shear studies of galaxy clusters, where offsets between the assumed and the true underlying matter distribution. This software has been developed and released in a public GitHub repository, and is licensed under the permissive free MIT license. The `cluster-lensing` package can be downloaded through the Python Package Index, <https://pypi.python.org/pypi/cluster-lensing>, or directly from GitHub, at <https://github.com/jesford/cluster-lensing>. Full documentation is available at <http://jesford.github.io/cluster-lensing/>.

*Subject headings:* methods: data analysis – methods: numerical – galaxies: clusters: general – gravitational lensing: weak – dark matter

## 1. INTRODUCTION

Clusters of galaxies are the largest gravitationally collapsed structures to have formed in the history of the universe. As such, they are interesting both from a cosmological as well as an astrophysics perspective. In the former case, the galaxy cluster number density as a function of mass, known as the cluster mass function, is a probe of cosmological parameters including the fractional matter density  $\Omega_M$  and the normalization of the matter power spectrum  $\sigma_8$ . Astrophysically, the deep potential wells of galaxy clusters are environments useful for testing theories of general relativity, galaxy evolution, and gas and plasma physics, among other things (Voit 2005).

The common thread among these diverse investigations is the requisite knowledge of the mass of the galaxy cluster, which is largely composed of its invisible dark matter halo. Although many techniques exist for estimating the total mass of these systems, weak lensing has emerged as somewhat of a gold standard, since it is sensitive to the mass itself, and not to the dynamical state or other biased tracers of the underlying mass. Scaling relations between weak lensing derived masses, and other observables, including richness, X-ray luminosity and temperature, for examples, are typically calibrated from large surveys and extrapolated to clusters for which gravitational lensing measurements are impossible or unreliable. Since weak lensing masses are often considered the “true” masses, against which other estimates are compared (e.g. Leauthaud et al. 2010; von der Linden et al. 2014; Hoekstra et al. 2015), it is paramount that cluster masses from weak lensing modeling are as unbiased as possible.

For stacked weak lensing measurements of galaxy clusters, an important source of bias in fitting a mass model is the inclusion of the effect of miscentering offsets. Miscentering occurs when the center of the mass distribution, the dark matter halo, does not perfectly coincide with the

assumed center around which tangential shear (or magnification) profiles are being measured. Candidate centers for galaxy clusters are necessarily chosen from observational proxies, and often include a single galaxy, such as the brightest or most massive cluster galaxy, or the centroid of some extended quantity like the peak of X-ray emission or average of galaxy positions (George et al. 2012). The particular choice of center may be offset from the true center due to interesting physical processes such as recent mergers and cluster evolution, or simply due to misidentification of the proxy of interest (Johnston et al. 2007).

The miscentering effect on the stacked weak lensing profile can be included in a proper modeling of the measurement, as done in Johnston et al. (2007); George et al. (2012); Ford et al. (2014, 2015). The inclusion of this effect commonly assumes a form for the distribution of offsets, such as a Rayleigh distribution (or, equivalently, a 2D Gaussian in the plane of the sky), which is convolved with the centered profile. Software for performing the integrations for the miscentered weak lensing profiles was developed in order to produce results in Ford et al. (2014, 2015), and has recently been publicly released to the astronomical community.<sup>2</sup>

- Background about clusters and weak lensing.
- NFW halos (Navarro et al. 1997; Wright & Brainerd 2000)
- composite-NFW fits for weak lensing (Ford et al. 2012, 2014, 2015)
- What is new = miscentering (Johnston et al. 2007; George et al. 2012; Ford et al. 2014, 2015)

## 2. DESCRIPTION OF THE CODE

- Purpose and general use.
- Relation to existing code

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<sup>2</sup> <http://jesford.github.io/cluster-lensing/>

- `SurfaceMassDensity()` class, generic to all NFW halos
- `ClusterEnsemble()` class
- mass-richness functions
- mass-concentration functions
- We use units from the `astropy.units` package ([Astropy Collaboration et al. 2013](#)).

### 3. EXAMPLES

- No miscentering
- With miscentering
- others...

### 4. FUTURE DEVELOPMENT

Plans for the future.

### 5. SUMMARY

Summary goes here.

### ACKNOWLEDGEMENTS

The authors are grateful for funding from the Washington Research Foundation Fund for Innovation in Data-Intensive Discovery and the Moore/Sloan Data Science Environments Project at the University of Washington. This project makes use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration, 2013), <http://www.astropy.org>.

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