Halotools: A New Release Adding Intrinsic Alignments to Halo-Based Methods

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Summary

Halotools, originally published in 2017, is a Python package for cosmology and astrophysics designed to generate mock universes using existing catalogs of dark matter halos (Hearin et al., 2017). A theoretical basis of the library is the so-called halo model, which describes the matter distribution of dark matter as gravitationally self-bound clouds of dark matter particles that we call halos. Halotools is designed to take an underlying catalog of dark matter halos and populate them with galaxies using subhalo abundance, or halo occupation distribution (HOD) models, creating catalogs of simulated galaxies for use in research. This release (v0.9) adds functionality to align galaxies, injecting what are known as intrinsic alignments (IA) into these catalogs. As a result, these simulated galaxy catalogs can now be created with realistically complex correlations between galaxies, mimicking some effects seen in more expensive hydrodynamic simulations.

Statement of Need

According to the halo model, galaxies form within dark matter halos, and the intrinsic shapes and orientations of these galaxies can be related with those of the host halo and with the large-scale structure of the universe (e.g. the local gravitational tidal field). This effect is known as intrinsic alignment (IA, see, e.g., Blazek et al., 2019; Hirata & Seljak, 2004). The observed shapes and orientations also have a contribution from weak gravitational lensing, the measurement of which is a pillar of modern observational cosmology (e.g. Abbott et al., 2022; Heymans et al., 2021; Li et al., 2023). IA can thus become an important systematic effect on weak lensing measurements, and it must be properly understood and mitigated to ensure accurate cosmological results (e.g. Krause et al., 2015; Samuroff, 2017; Secco et al., 2022).

Measurements of weak lensing shear help researchers study the distribution of matter and dark energy. The large-scale structure of the Universe can influence the intrinsic shapes and orientations of galaxies through gravitational interactions. Therefore, accurately modeling this effect is important for precision cosmology with weak lensing. With upcoming surveys such as the Rubin Observatory Legacy Survey of Space and Time (LSST, Ivezić et al., 2019), analyses of the data will need to consider contributions from IA. A fast and flexible simulation method that includes IA is required to to provide realistic mock galaxy catalogs and to test other IA models.

Understanding and measuring IA also provides a window into the accurate modeling of galaxy formation and a is probe of cosmic structure and potentially new physics (e.g. Chisari & Dvorkin, 2013). Halotools already provides tools for modeling the relationship between galaxies and the halos in which they reside (the galaxy–halo connection), and it is widely used in the

field. The expanded functionality added in this release allows Halotools to be used to produce mock galaxy catalogs with realistically complex galaxy orientations. These catalogs can then be used to test and validate IA models, to study IA in observational data and in hydrodynamic simulations (Marinacci et al., 2018; Naiman et al., 2018; e.g. Nelson et al., 2017; Pillepich et al., 2017; Springel et al., 2017), and to provide a fully nonlinear, simulation-based model for observed galaxy clustering and lensing statistics.

Significance

Halotools provides a way for users to create halo occupation models such as abundance matching and the halo occupation distribution (HOD), and enables a modular approach to mock universe creation. The user can provide a series of component models to the HOD model describing features that will govern how Halotools populates these dark matter halos with galaxies. This release provides methods to describe galaxy alignment, including IA similarity, analogous to how other features in HOD models are defined.

The new release of Halotools creates the capability to construct realistically complex IA correlations, comparable to those of a hydrodynamic simulation, at a tiny fraction of the computational cost of a hydrodynamic simulation, as explained in Van Alfen et al. (2024). This flexibility extends Halotools to be of considerable benefit to simulation-based studies of IA. In Van Alfen et al. (2024), the authors demonstrated the flexibility of the Halotools package to create galaxy catalogs with IA comparable to various aspects of high-resolution cosmological simulations. Specifically, Figure 1 (taken from Figure 12 in Van Alfen et al., 2024) shows various IA correlation functions from both IllustrisTNG300-1 (Marinacci et al., 2018; Naiman et al., 2018; Nelson et al., 2017; Pillepich et al., 2017; Springel et al., 2017) and a galaxy catalog generated using Halotools with its available Bolshoi–Planck (Bolplanck) halo catalog (Klypin et al., 2011).
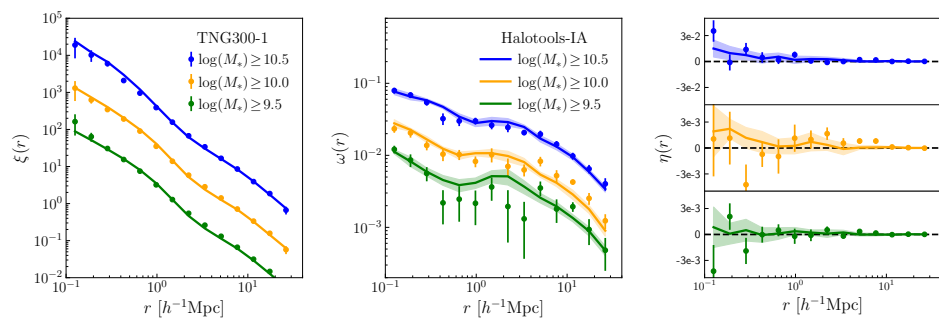

Figure 1: Correlation functions from IllustrisTNG300 (points with error bars) and correlation functions measured on an HOD made with Halotools (solid lines with shaded error regions) showcasing the flexibility of the model. Reproduced from Figure 12 in Van Alfen et al. (2024).

This release is part of a suite of modeling tools and analysis pipelines being developed to aid upcoming cosmological surveys, including LSST, Euclid, and Roman. The specific advantage of the type of models generated by Halotools is that they are faster and lighter-weight than more expensive simulations, allowing users to quickly generate and populate catalogs of galaxies following a set of parameters. The efficiency of Halotools also allows for direct simulation-based modeling.

Structure

Currently, the user needs to provide the following in order to build a mock galaxy catalog with IA using Halotools (optional components are in parentheses):

- Occupation Model: Determines the number density of galaxies within a given halo.

- Phase Space Model: Determines the location and velocity of a galaxy within its halo.

- Alignment Model: The focus of this release. Determines the orientation of the galaxy by aligning it with respect to some reference vector (halo major axis, radial vector to center of halo, etc.) according to the alignment strength, a parameter that can either be set globally or vary between objects.

- Alignment Strength Model: Optional component added in this release. Allows each galaxy to have its own alignment strength based on individual properties (e.g. distance from center of its host halo) rather than assigning a single alignment strength to all galaxies.

Future Work

In the current iteration of IA tools available through Halotools, we only consider orientation, rather than full shape information. Plans for future work include extending the functionality of the package to incorporate distributions of three-dimensional shapes. We also plan to extend the available alignment models and to allow for more complex determinations of alignment strength, such as assigning each galaxy an alignment strength based on redshift, color, luminosity, mass, etc.

Acknowledgements

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