The Journal of Open Source Software

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

Nicholas Van Alfen [1*¶], **Duncan Campbell** [2*], **Andrew Hearin** [3*], and **Jonathan Blazek** [1]

1 Department of Physics, Northeastern University, Boston, MA 02115, USA **2** McWilliams Center for Cosmology, Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA **3** Argonne National Laboratory, Lemont, IL 60439, USA ¶ Corresponding author * These authors contributed equally.

DOI: 10.21105/joss.07421

Software

- Review
- Repository
- Archive

Editor: Ivelina Momcheva

Reviewers:

- @matroxel
- @cmlamman
- @fjcastander

Submitted: 12 September 2024
Published: 04 March 2025

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, that 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) (Blazek et al., 2019; see, e.g., 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 (Abbott et al., 2022; e.g. 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 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).

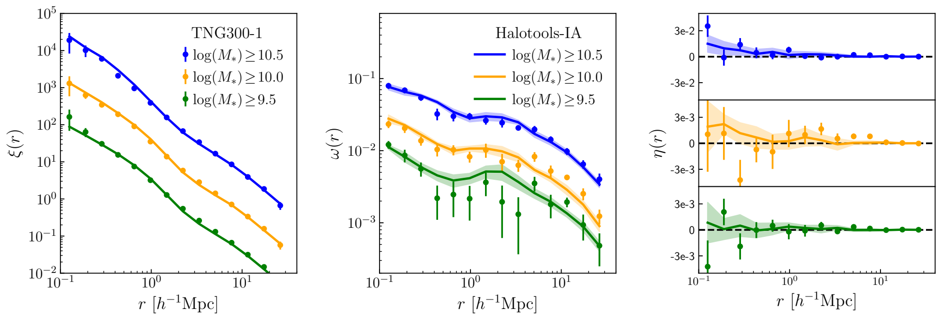

Figure 1: Correlation functions from IllustrisTNG300 (points with error bars) and correlation functions measured on an HOD made with `halotools` (solid lines with shaded error regions) showcasing the flexibility of the model. REproduced from Figure 12 in Van Alfen et al. (2024).

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

This work was supported in part by NASA under the OpenUniverse effort (JPL Contract Task 70-711320) and the Roman Research and Support Participation program (grant 80NSSC24K0088), by NSF Award AST-2206563, and by the DOE Office of Science under award DE-SC0024787 and the SCGSR program, administered by ORISE which is managed by ORAU under contract number DE-SC0014664. Work done at Argonne was supported under the DOE contract DE-AC02-06CH11357.

References

Abbott, T. M. C., Aguena, M., Alarcon, A., Allam, S., Alves, O., Amon, A., Andrade-Oliveira, F., Annis, J., Avila, S., Bacon, D., Baxter, E., Bechtol, K., Becker, M. R., Bernstein, G. M., Bhargava, S., Birrer, S., Blazek, J., Brandao-Souza, A., Bridle, S. L., … Zuntz, J. (2022). Dark energy survey year 3 results: Cosmological constraints from galaxy clustering and weak lensing. *Physical Review D*, *105*, 023520. https://doi.org/10.1103/PhysRevD.105.023520

Blazek, J. A., MacCrann, N., Troxel, M. A., & Fang, X. (2019). Beyond linear galaxy alignments. *Physical Review D*, *100*, 103506. https://doi.org/10.1103/PhysRevD.100.103506

Chisari, N. E., & Dvorkin, C. (2013). Cosmological information in the intrinsic alignments of luminous red galaxies. *Journal of Cosmology and Astrophysics*, *2013*(12), 029. https://doi.org/10.1088/1475-7516/2013/12/029

Hearin, A. P., Campbell, D., Tollerud, E., Behroozi, P., Diemer, B., Goldbaum, N. J., Jennings, E., Leauthaud, A., Mao, Y.-Y., More, S., Parejko, J., Sinha, M., Sipöcz, B., & Zentner, A. (2017). Forward modeling of large-scale structure: An open-source approach with halotools. *The Astronomical Journal*, *154*(5), 190. https://doi.org/10.3847/1538-3881/aa859f

Heymans, C., Tröster, Tilman, Asgari, Marika, Blake, Chris, Hildebrandt, Hendrik, Joachimi, Benjamin, Kuijken, Konrad, Lin, Chieh-An, Sánchez, Ariel G., van den Busch, Jan Luca, Wright, Angus H., Amon, Alexandra, Bilicki, Maciej, de Jong, Jelte, Crocce, Martin, Dvornik, Andrej, Erben, Thomas, Fortuna, Maria Cristina, Getman, Fedor, … Wolf, Christian. (2021). KiDS-1000 cosmology: Multi-probe weak gravitational lensing and spectroscopic galaxy clustering constraints. *Astronomy & Astrophysics*, *646*, A140. https://doi.org/10.1051/0004-6361/202039063

Hirata, C. M., & Seljak, U. (2004). Intrinsic alignment-lensing interference as a contaminant of cosmic shear. *Physical Review D*, *70*(6), 063526–+. https://doi.org/10.1103/PhysRevD.70.063526

Ivezić, Ž., Kahn, S. M., Tyson, J. A., Abel, B., Acosta, E., Allsman, R., Alonso, D., AlSayyad, Y., Anderson, S. F., Andrew, J., & al., et. (2019). LSST: From science drivers to reference design and anticipated data products. *The Astrophysical Journal*, *873*, 111. https://doi.org/10.3847/1538-4357/ab042c

Klypin, A. A., Trujillo-Gomez, S., & Primack, J. (2011). Dark Matter Halos in the Standard Cosmological Model: Results from the Bolshoi Simulation. *The Astrophysical Journal*, *740*(2), 102. https://doi.org/10.1088/0004-637X/740/2/102

Krause, E., Eifler, T., & Blazek, J. (2015). The impact of intrinsic alignment on current and future cosmic shear surveys. *Monthly Notices of the Royal Astronomical Society*, *456*(1), 207–222. https://doi.org/10.1093/mnras/stv2615

Li, X., Zhang, T., Sugiyama, S., Dalal, R., Terasawa, R., Rau, M. M., Mandelbaum, R., Takada, M., More, S., Strauss, M. A., Miyatake, H., Shirasaki, M., Hamana, T., Oguri, M., Luo, W., Nishizawa, A. J., Takahashi, R., Nicola, A., Osato, K., … Wang, S.-Y. (2023). Hyper suprime-cam year 3 results: Cosmology from cosmic shear two-point correlation functions. *Physical Review D*, *108*, 123518. https://doi.org/10.1103/PhysRevD.108.123518

Marinacci, F., Vogelsberger, M., Pakmor, R., Torrey, P., Springel, V., Hernquist, L., Nelson, D., Weinberger, R., Pillepich, A., Naiman, J., & Genel, S. (2018). First results from the IllustrisTNG simulations: radio haloes and magnetic fields. *Monthly Notices of the Royal Astronomical Society*, *480*(4), 5113–5139. https://doi.org/10.1093/mnras/sty2206

Naiman, J. P., Pillepich, A., Springel, V., Ramirez-Ruiz, E., Torrey, P., Vogelsberger, M., Pakmor, R., Nelson, D., Marinacci, F., Hernquist, L., Weinberger, R., & Genel, S. (2018). First results from the IllustrisTNG simulations: a tale of two elements – chemical evolution of magnesium and europium. *Monthly Notices of the Royal Astronomical Society*, *477*(1), 1206–1224. https://doi.org/10.1093/mnras/sty618

Nelson, D., Pillepich, A., Springel, V., Weinberger, R., Hernquist, L., Pakmor, R., Genel, S., Torrey, P., Vogelsberger, M., Kauffmann, G., Marinacci, F., & Naiman, J. (2017). First results from the IllustrisTNG simulations: the galaxy colour bimodality. *Monthly Notices of the Royal Astronomical Society*, *475*(1), 624–647. https://doi.org/10.1093/mnras/stx3040

Pillepich, A., Nelson, D., Hernquist, L., Springel, V., Pakmor, R., Torrey, P., Weinberger, R., Genel, S., Naiman, J. P., Marinacci, F., & Vogelsberger, M. (2017). First results from the IllustrisTNG simulations: the stellar mass content of groups and clusters of galaxies. *Monthly Notices of the Royal Astronomical Society*, *475*(1), 648–675. https://doi.org/10.1093/mnras/stx3112

Samuroff, S. (2017). *Systematic biases in weak lensing cosmology with the Dark Energy Survey* [PhD thesis, University of Manchester, UK]. https://doi.org/10.2172/1420403

Secco, L. F., Samuroff, S., Krause, E., Jain, B., Blazek, J., Raveri, M., Campos, A., Amon, A., Chen, A., Doux, C., Choi, A., Gruen, D., Bernstein, G. M., Chang, C., DeRose, J., Myles, J., Ferté, A., Lemos, P., Huterer, D., … DES Collaboration. (2022). Dark Energy Survey Year 3 results: Cosmology from cosmic shear and robustness to modeling uncertainty.

Physical Review D, *105*(2), 023515. https://doi.org/10.1103/PhysRevD.105.023515

Springel, V., Pakmor, R., Pillepich, A., Weinberger, R., Nelson, D., Hernquist, L., Vogelsberger, M., Genel, S., Torrey, P., Marinacci, F., & Naiman, J. (2017). First results from the IllustrisTNG simulations: matter and galaxy clustering. *Monthly Notices of the Royal Astronomical Society*, *475*(1), 676–698. https://doi.org/10.1093/mnras/stx3304

Van Alfen, N., Campbell, D., Blazek, J., Leonard, C. D., Lanusse, F., Hearin, A., Mandelbaum, R., & The LSST Dark Energy Science Collaboration. (2024). An empirical model for intrinsic alignments: Insights from cosmological simulations. *The Open Journal of Astrophysics*, *7*. https://doi.org/10.33232/001c.118783