limHaloPT: A Numerical Package for Accurate Modeling of Line Intensity Power Spectrum

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Summary

`limHaloPT` is a modular numerical package, written in C, for computing the clustering and shot-noise contributions to the power spectrum of line intensity/temperature fluctuations using the halo-model framework. This package is the first publicly available code that combines the one-loop prediction of the halo power spectrum and the halo-model framework to model the power spectrum of emission lines originating from star-forming galaxies. Furthermore, the code includes routines to compute the stochastic contributions to the line power spectrum beyond the Poisson approximation. Several utility functions, e.g., for computing the theoretical halo mass functions, halo biases, and one-loop halo power spectrum, are provided in the package, which can be used in contexts other than Line Intensity Mapping (LIM). This code is released together with a scientific publication (Moradinezhad Dizgah et al., 2022) in which details of the implemented model and the comparison of model predictions against simulated intensity maps are presented. The current version of the code includes the first six rotational ladders of carbon monoxide, CO, and fine structure line of ionized carbon [CII], and the model of the power spectrum is limited to real space.

Scientific Context and Statement of Need

LIM is a novel technique to map the large-scale structure (LSS) of the Universe by measuring the aggregate intensity of the atomic and molecular emission lines from the unresolved sources (Kovetz, 2017). Measurements of spatial fluctuations and frequency of the line provide a 3-dimensional map of the LSS, whose statistical properties capture a significant amount of information about astrophysics and cosmology. To fully exploit this rich data, accurate theoretical models of the signal and efficient numerical codes for evaluating the models are crucial.

The modeling of the line signal is based on the halo-model framework and requires two main ingredients: modeling the relation between line luminosity and halo masses, and modeling the relation between halo properties and the underlying dark matter distribution. Until now, the models used in the literature have neglected the nonlinear effects in the latter relation and used the tree-level perturbation theory to relate the halo properties, and by extension line intensity properties, to the underlying dark matter distribution. Furthermore, the shot noise component of the line power spectrum has commonly been assumed to be Poissonian. As for numerical implementation, the only publicly available code to compute the line power spectrum, HaloGen (Schaan & White, 2021), is based on this simplified model.

The extended halo model of line intensity power spectrum implemented in `limHaloPT` combines the predictions of EFTofLSS in Eulerian space for halo power spectrum (Baumann et al., 2012;

Carrasco et al., 2012) with the standard halo model (Cooray & Sheth, 2002; Seljak, 2000) to account for the nonlinear evolution of matter fluctuations and the nonlinear biasing relation between line intensity fluctuations and the underlying dark matter distribution in the 2-halo term. Furthermore, the model includes the effect of large bulk velocities, i.e., the Infrared Resummation (Blas et al., 2016; Senatore & Zaldarriaga, 2015) in the 2-halo term. The deviations from Poisson shot noise on large scales are also computed within the halo model (Ginzburg et al., 2017).

Recently, there has been a shift in the cosmology community in publicly releasing the packages developed by various groups to promote reuse and reproducibility. Great examples of this approach are the CLASS Boltzman code (Blas et al., 2011), and the nbodykit toolkit for analysis of the LSS data from N-body simulations and from galaxy surveys (Hand et al., 2018). In LIM, limHaloPT is the first package that includes detailed modeling of the line power spectrum. The modular structure of the package facilitates future extensions of the code to other LIM statistics, such as the line bispectrum, as well as embedding this code in a full likelihood analysis pipeline such as CosmoSIS (Zuntz et al., 2015).

Dependencies

The `limHaloPT` package calls various functions from the CLASS Boltzmann solver, including the matter power spectrum, the transfer functions, the growth factor, and more. Therefore, prior to installation of `limHaloPT`, the CLASS code should be compiled and the static `libclass.a` library should be placed in the `Class/lib` folder. Furthermore, the loop calculations are performed with direct numerical integration, using routines of CUBA library. Lastly, the code heavily uses functions of the GSL scientific library. Therefore, the two libraries should be correctly linked to `limHaloPT` by making the necessary modifications to the makefile (placed in the main directory).

In order to compute the luminosities of spectral lines, a model for star formation rate as a function of halo mass and redshift, SFR(M_h,z), should be assumed. Currently, the implemented model uses SFR(M_h,z) from Behroozi et al. (2013). The necessary input file, `sfr_release.dat`, is included in `Input/release-sfh_z0_z8_052913/sfr/` subdirectory.

Usage

Currently, the main outputs of `limHaloPT` are the mean brightness temperature, the linear and the quadratic biases, the clustering and the shot noise contributions of seven emission spectral lines. The lines to compute are set using a switch in the initialization file; an example of the initialization file is provided in the package (see `LCDM.ini`). A more detailed description of the main outputs is given in the code documentation within the GitHub repository. In addition to saving the output for the mean brightness temperature, biases, shot and clustering components of power spectrum, when computing the clustering and shot powers, individual loop contributions (in the former) and individual beyond-Possion contribution to the shot (in the latter) are also saved to output files that are stored in `Output` directory, by default.

In addition to using `limHaloPT` through the `main.c` module that calls three specific functions, the package can also be exported as an external library to any other C code. Upon compilation of the package, a static library called `liblimHaloPT.a` is created and placed in the `lib` directory, which can then be linked to an external C code. Example of how to link an external code to the `liblimHaloPT.a` static library can be found in the `Test` directory.

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Future Extensions

Future releases will provide additional modules, for example, to include observational effects such as redshift-space distortions and the Alcock-Paczynski effect. Furthermore, we plan to extend this code to include modeling of other emission lines originating from star-forming galaxies, cross-correlations between different emission lines, and the bispectrum of line intensity fluctuations.

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