Postdoc Research

Modelling small-scale galaxy clustering in redshift-space

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Background

Galaxy clustering: Galaxy clustering is one of the primary methods that will be used to test cosmological models with current and future astronomical surveys, including Euclid and Roman. The clustering of galaxies refers to the fact that galaxies reside near other galaxies considerably more often than would be expected if they were randomly distributed throughout the Universe. This is described mathematically by the two-point correlation function, $\xi(r)$, which expresses the excess number of galaxy pairs separated by a distance r, compared with the number expected for a random distribution.

Redshift space distortions: The locations of galaxies in a galaxy redshift survey are determined by their positions on the sky, as well as their redshifts. Redshifts are a reasonable proxy for the distances to galaxies, but receive contributions from galaxy velocities. These distort maps of the inferred galaxy distribution, a process known as redshift space distortions (RSD). While RSD complicates the analysis of clustering data, it also provides an opportunity. The distortions depend on galaxy velocities, which in turn depend on how mass is distributed and on the nature of gravity. Analysis of RSD can therefore constrain cosmological models, including those in which gravity is something different from Einstein's General Theory of Relativity.

Joint analysis: JPL's Dark Sector (an informal group within 3268) are currently working on implementing a state-of-the-art pipeline to jointly analyze data from the next generation of large scale structure surveys. Most of the constraining power from future RSD measurements will come from scales below 30 Mpc (Zhai et al. 2019), but these are the same scales on which analytical techniques such as perturbation theory break down (White et al. 2015). I am building machinery to model RSD on small scales (1-30 Mpc), including its dependence on cosmological parameters, as well as the theory of gravity.

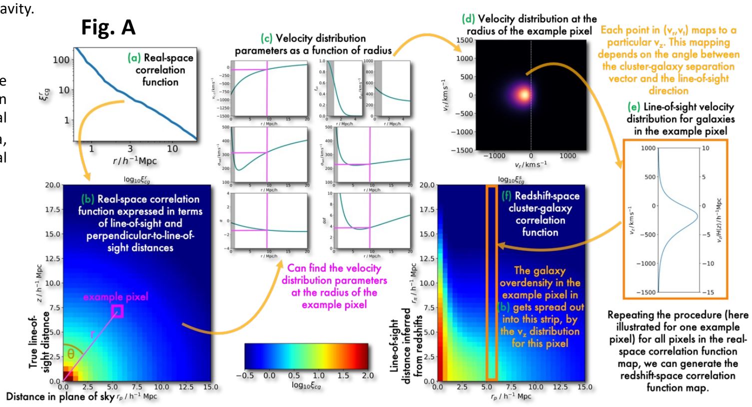
Objectives

The primary objective of my research is to build a model for the effects of the cosmological parameters and the theory of gravity on RSD on small scales (down to a Mpc or so). This will be an integral part of JPL's joint analysis pipeline for large scale structure data, enabling robust and precise measurements of cosmological parameters, and tests of different theories of gravity.

Approach and Results

My approach to modelling redshift-space clustering splits up the calculation into two distinct parts, the clustering in "real space" (what we would see without RSD) and the pairwise velocity distribution (how galaxies move relative to one another as a function of their separation). The approach is shown schematically in Figure A. The real space clustering is isotropic (b), meaning that the density of galaxies 10 Mpc "behind" another galaxy is the same as the density of galaxies 10 Mpc "to the left" or "to the right". RSD breaks this isotropy because separations along the line-of-sight are shifted by galaxies' pairwise velocities.

Fig. A


(a) Real-space correlation function

(b) Real-space correlation function expressed in terms of line-of-sight and perpendicular-to-line-of-sight distances

(c) Velocity distribution parameters as a function of radius

Can find the velocity distribution parameters at the radius of the example pixel

(d) Velocity distribution at the radius of the example pixel

Each point in (v_r, v_t) maps to a particular v_z. This mapping depends on the angle between the cluster-galaxy separation vector and the line-of-sight direction

(e) Line-of-sight velocity distribution for galaxies in the example pixel

(f) Redshift-space cluster-galaxy correlation function

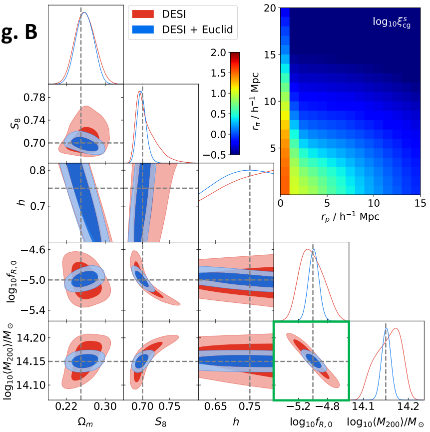
The galaxy overdensity in the example pixel in (b) gets spread out into this strip, by the v_z distribution for this pixel

Repeating the procedure (here illustrated for one example pixel) for all pixels in the real-space correlation function map, we can generate the redshift-space correlation function map.

The curves in (c) show how parameters describing the pairwise velocities of galaxies vary with radius. For example, the top-left panel of (c) shows the mean radial velocity, with negative values corresponding to galaxies falling towards one another. The curves in (c) were fit to velocity data from cosmological simulations run with different cosmologies and theories of gravity, from which a Gaussian Process emulator for the cosmology-dependence of pairwise velocities was built. At each real-space position in (b), the curves in (c) encode the distribution of radial and tangential pairwise velocities (d), from which the line-of-sight pairwise velocity distribution can be calculated (e). These line-of-sight velocities alter the line-of-sight separations of galaxy pairs, mapping the real-space galaxy clustering (b) to redshift space (f).

As an example application of my method, I forecast the constraints on cosmological parameters and modifications to gravity that one expects from applying my model to the cluster-galaxy cross-correlation from a DESI-like survey. The resulting posterior distribution is shown in red in Figure B. The panel outlined in green demonstrates that cluster-galaxy RSD from DESI will constrain a degenerate combination of the mean mass of the galaxy clusters and f_{R0} (which describes the strength of modification to gravity). Intuitively this can be understood from the fact that galaxies fall faster into more massive clusters, or if gravity is enhanced. An independent measurement of the mass of the cluster samples (as could be provided by Euclid weak lensing) breaks this degeneracy (blue posterior in Figure B), leading to a precise measurement of potential deviations from General Relativity.

Fig. B



Significance of Results/Benefits to NASA/JPL

I now have a working model for RSD on small scales, which can be used in the analysis of data from future NASA missions such as Roman. In the near term, jointly analyzing data from Euclid (which has considerable NASA involvement) and DESI, will provide a good stepping stone towards jointly analyzing Euclid, Roman and Rubin data in the future. This joint analysis will be key to maximizing the return on investment from the cosmology portions of NASA's missions, as illustrated in a recent report to NASA, the NSF and the DOE (Chary et al. 2020). Having the capability to do joint analysis in-house at JPL is of immense benefit when planning future missions, as the full impact of various design choices on cosmological constraints can be understood.

Future Work

Having implemented an emulator for RSD on small scales, the next major goal is to apply it to real data to constrain cosmological models. Before this can be done, there are a few key developments that are required:
- the model needs to be extended to allow for variations in the "galaxy-halo connection" (the way in which galaxies populate dark matter structures)
- the RSD model needs to be combined with a flexible model for the real-space correlation function (a in the figure above), which is the other key ingredient for predicting galaxy clustering in redshift-space

Sharing results: I have been presenting this work at several institutes involved with these future missions, and am about to submit a paper detailing the emulator-based RSD model that I have devised.

Publication: Modelling the cluster-galaxy correlation function on Mpc scales in redshift space; Robertson, Huff and Markovič (in prep)

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