Thesis Proposal: Redshift-Space Distortions

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1 Proposed TAC Members

The following list is in rough order of preference, but I would be happy to have any of them on my TAC.

- Cora Dvorkin (Harvard Physics)
- Doug Finkbeiner
- Lars Hernquist
- Chris Stubbs (Harvard Physics)
- Avi Loeb

2 Redshift-Space Distortions

Galaxy surveys of large scale structure contain cosmological information not only in the positions of galaxies but also in the velocities. Galaxies in the cosmic web act as "test particles" in the flow of matter along filaments into halos, so their velocities probe the rate of growth of structure. These velocities appear as peculiar redshift deviations from the Hubble flow, an effect known as "redshift-space distortion" (RSD). The resulting clustering in redshift space is anisotropic relative to the observer's line of sight; this is the hallmark of RSD (Kaiser, 1987, see Fig. 1). Measuring this anisotropy probes the parameter combination $f(z)\sigma_8(z)$, the product of the matter growth rate and clustering amplitude (e.g. Hamilton, 1998; Percival & White, 2009).

Redshift-space distortions are a potentially powerful probe of cosmology but are limited in their usefulness by systematic uncertainties in small-scale clustering. Many analyses are thus restricted to quasi-linear regimes; for example, the SDSS-III BOSS RSD analysis (Chuang et al., 2016) takes a lower limit of 40 h^{-1} Mpc. Better modeling in the non-linear regime will be needed to take full advantage of the sub-percent constraints on $f(z)\sigma_8(z)$ that Stage-IV dark energy experiments (*Euclid*, LSST, eBOSS) will provide (Weinberg et al., 2013). This is the motivation for this thesis proposal.

Following the discussion in Weinberg et al. (2013), the purpose of improving constraints on RSD is twofold. First, RSD can improve our measurements of cosmological parameters, assuming General Relativity. Linear RSD probes $\Omega_M^{0.6}$ via $f = d\ln D/d\ln a \approx \Omega_M^{0.6}$, which is degenerate with σ_8, but still constraining for cosmological models. Note, however, that non-linear RSD can potentially break this degeneracy with information from smaller scales (see below). In the context of dark energy, RSD is expected to improve the errors in the DETF FoM[1] by 10–15%, if theoretical modeling can be improved to sub-percent accuracy in the mildly non-linear regime.

The second use of RSD is to test GR itself. RSD directly measures the growth rate of structure, which can be compared to the cosmic expansion history that other probes (e.g. BAO) measure in "snapshots" at various redshifts. The expansion and growth history are closely linked in GR via the Hubble drag, but this relation does not hold in various forms of modified gravity. Low-redshift

[1] Dark Energy Task Force Figure of Merit: the inverse of the area encompassed by the error ellipse in the w_0–w_a plane.

RSD measurements are particularly constraining for modified gravity, but this is precisely where the non-linearities of structure are the strongest, and thus require the most stringent theoretical modeling.

Cosmological N-body simulations are the premiere tool for testing models of RSD, since they are the only method capable of following the strong non-linearities that are so important for this probe. While there are many methods of leveraging simulations to measure RSD, one successful approach has been halo occupation distribution (HOD) modeling (c.f. Tinker et al., 2006; Tinker, 2007, for application to RSD). In HOD, dark matter halos are populated with galaxies in a Poisson process whose expectation value depends on various properties of the halo — most commonly the mass, but also the concentration, formation history, etc. This explicit modeling approach has the advantage of being self-consistent on all scales (unlike some piecewise analytic approaches), allowing access to information at intermediate and non-linear scales that can break the well-known $f(z)\sigma_8(z)$ degeneracy. Tinker et al. have had success with a single velocity bias parameter, but more sophisticated treatments may be needed for application to real survey data, especially of the precision that will be provided by upcoming surveys.

The goal of the proposed thesis work is to improve extraction of cosmological information from galaxy surveys with RSD. In particular, I will extend previous HOD models to account for galaxy formation physics that can bias galaxy velocities and occupation distributions, such as halo formation history. With these modeling improvements, I will aim to push the usable range of galaxy surveys to smaller scales. I will use high-quality N-body simulations to test these models, primarily through the anisotropic power spectrum and two-dimensional two-point correlation function.

3 Previous work and ongoing projects

I have one published paper (Garrison et al., 2016) on discreteness effects in cosmological N-body simulations. One product of that work was an initial conditions generator that will help with the detailed numerical studies for the proposed thesis work.

I have another paper (Sinha & Garrison, in prep.) announcing a new, AVX[2]-accelerated code for computing two-point correlation functions faster than any public code by a factor of two. This type of code is central to the kinds of clustering analyses that will be used in the proposed thesis work.

Much of my work has been in development of the highly accurate, GPU-accelerated N-body code Abacus (Ferrer et al., in prep.), which will enable the precision numerical tests necessary for the proposed thesis work. Furthermore, I am planning on parallelizing the code to enable massive, trillion-particle scale cosmological simulations with only a handful of machines.

I have also developed a pipeline for running and analyzing suites of N-body simulations with different cosmologies. The outputs of this pipeline (halo catalogs, power spectra, etc.) are being used by our collaborators for forecasting of future surveys. The grids of cosmologies that are already in-hand are only of modest resolution, but will be a useful testing ground for RSD effects under varying cosmology.

Another part of my work is building and maintaining high-performance computers for running large cosmological simulations with Abacus. Currently, I am running several large cosmological simulations on these machines, which are geared towards eBOSS and JWST science goals. These large simulations (or similar ones) will prove useful for model tests that require large volumes and will be complementary to the smaller boxes of varying cosmology.

References

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Hamilton, A. J. S. 1998, in Astrophysics and Space Science Library, Vol. 231, The Evolving Universe, ed. D. Hamilton, 185

Kaiser, N. 1987, MNRAS, 227, 1

[2]Advanced Vector Extensions, a set of CPU instructions for accelerating vector operations on data

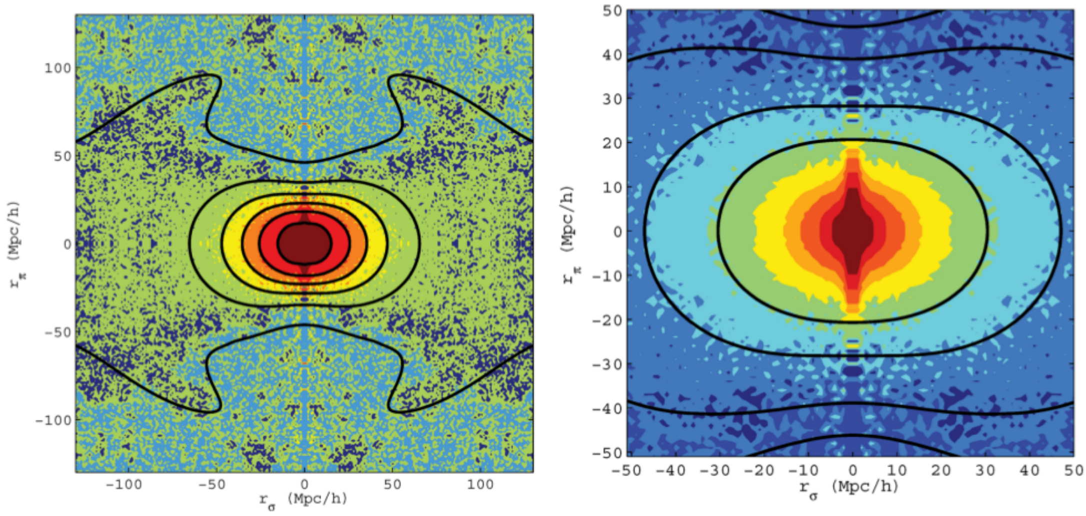

Figure 1: The two-dimensional two-point correlation function (2PCF) of CMASS galaxies from Reid et al. (2012). The right-hand panel is a zoom-in of the left-hand panel. The 2PCF without RSD would appear as perfect circles. The large scale "squashing" along r_π (line-of-sight separation) is the linear RSD effect of infalling galaxy pairs. The small-scale up-scattering of galaxy pairs is the finger-of-god effect of virialized galaxy motions inside halos.

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