Redshift space distortion of BOSS galaxies and its cosmological constraints

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The Hubble diagram of Supernova Ia: accelerated expansion

Luminosity Distance

\[ d_L = (1 + z) \int_0^z \frac{c \, dz'}{H(z', \Omega_m, \Omega_\Lambda)} \]

\[ H \equiv \frac{\dot{a}}{a} \]

\[ 5 \log(d_L) \]
Concordance Cosmology: Cosmological constant

Supernova

Accelerated Expansion

- \( \Omega_\Lambda \sim 1 \) (p=\( \rho \cdot c^2 \)), e.g. w=-1
  - vacuum energy

LSS and Clusters

- \( \Omega_m \sim 0.3 \)

CMB

- flat (\( \Omega_{TOT}=1 \))
- \( \Omega_m \sim 0.3 \rightarrow \Omega_\Lambda \sim 0.7 \)
- They together (with many others)
- \( \Omega_m \sim 0.3 \quad \Omega_\Lambda \sim 0.7 \)
Either side of the GR equation could be a solution

\[
R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^2} T_{\mu\nu}
\]

**R.H.S:** Dark Energy \( T_{\mu\nu} \rightarrow T_{\mu\nu} + T_{\mu\nu}(DE) \)

**L.H.S :** Modified Gravity \( R \rightarrow F(R) \)
**Redshift-space galaxy-galaxy correlation function** $\xi(r_p, \pi)$

- **Pair separation perpendicular to line-of-sight** $r_p$ (\(h^{-1}\) Mpc)
- **Pair separation along line-of-sight** $\pi$ (\(h^{-1}\) Mpc)

No redshift distortions

Full distortions, including small-scale “spindle” due to clusters of galaxies, $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$

Linear distortions only, flattening proportional to growth rate: depends on amount and kind of dark matter and dark energy

**Linear Growth rate** $f = b_L \beta$

**Compression parameter** $\beta$ (Kaiser 1987)

**Line of sight to observer**

**Compression parameter** $\beta$ (Kaiser 1987)
The sample contains about 600000 massive galaxies at redshift 0.6, perhaps most suitable for measuring RS P(K)
Challenge in measuring RS power spectrum

- It is generally preferred to measure the power spectrum in redshift space (RS), as the RS P(k) is coupled weakly at different scales, and the nonlinearities (such as mapping, galaxy bias, structure evolution) can be handled on quailinear scales (hopefully).

- But it is not easy to directly measure the RS P(K) because of two problems: 1) lines of the sights to galaxies not parallel; 2) convolved with a complex observational window function plus a shot noise.

- Use the moving-LOS method by Yamamoto et al. (2006, PASJ) to solve problem 1.

- It seems there is no good way to solve problem 2 especially on the scale comparable to that of the survey.
The method of Jing & Boerner (2001): simple and accurate

- Both the window function and the shot noise can be corrected in the correlation function (CF) measurement

$$P_g^s(k, \mu) = \int \xi_g^s(s_\perp, s_\parallel) e^{i \mathbf{k} \cdot \mathbf{s}} d^3s$$

$$= \int \xi_g^s(s_\perp, s_\parallel) e^{i (k_\parallel s_\parallel + k_\perp s_\perp \cos(\phi))} s_\perp ds_\perp d\phi ds_\parallel$$

$$= \int \xi_g^s(s_\perp, s_\parallel) K(k_\perp, k_\parallel; s_\perp, s_\parallel) s_\perp ds_\perp ds_\parallel , \; (3)$$

where $k_\parallel = k \cdot \mu$ and $k_\perp = \sqrt{k^2 - k_\parallel^2}$. Notice that $\mu$ here is not related to $\mu_s$ in the correlation function. The kernel $K$ is defined as $K(k_\perp, k_\parallel; s_\perp, s_\parallel) = \cos(k_\parallel s_\parallel) J_0(k_\perp s_\perp)$ with $J_0(x) = \int e^{i x \cos(\phi)} d\phi$ the zeroth order Bessel function. In practice, we need to cut

- One worry is that the errors of $P(k)$ could be correlated on different scales, but **we will see** the correlations are weak
Subhalo catalog, from an LCDM simulation with \( N_p=3072^3 \) and \( L=1200 \) Mpc/h

Using the Galaxy-Subhalo Matching method of Wang & Jing (2010), we have constructed a CMASS mock catalog (Cubic volume)

Result: \( P(K) \) from the FFT of CF and that directly from FFT are in good agreement, indicating one can get \( P(K) \) if the input CF is correct.
JB2001 method (red lines) vs direct FFT (black points with error bars)

Applied to CMASS sample DR11

Correlation function in redshift space

Power spectrum in redshift space
1. Estimate the error matrix of \( P(k) \) with MultiDark Patchy mock catalogs

2. Found different modes correlate weakly, the method not introduces mode-mode coupling
Comparing with previous works

Previous works: window function or shot noise may not be properly corrected
Reproduced RS CFs in previous studies

- $s^2 \xi_0$
- $s^2 \xi_2$

This work

- From measured $P_{0,2}(k)$
- Anderson14
- Sanchez14
- Samushia14
Incomplete list of approximations/simplifications in RSD modeling

\[ X^S = X + \frac{V \cdot \hat{x}}{H} \hat{X} \]

Neglecting AP/relativistic effects/lensing distortion

\[ P^S(k) = \int \langle (1 + \delta_1)(1 + \delta_2) e^{i k z (v_{1z} - v_{2z})/H} \rangle e^{i k \cdot r} d^3 x \]

Cumulant expansion theorem

\[ P^S_g(k, u) = \left[ P_g(k) (1 + \beta \tilde{W}(k) u^2)^2 + u^4 P_{\theta S \theta S}(k) + \cdots \right] D^\text{FOG}(k u) \]

Linear density-velocity relation, no velocity bias

Deterministic density-velocity

Negligible high order corrections

Further approximations often used in observations

- Scale independent galaxy density bias
- \( D^\text{FOG} \): Gaussian, Lorentz, more complicated? Meaning of \( \sigma_v \)?
Disentangle RSD:
A generic velocity decomposition

- Velocity decomposition into three eigen-modes:
  - Gradient part $v_E$
    - $v_\delta$: correlated with density: mostly linear, dominant at large scale
    - $v_S$: uncorrelated: significant at intermediate scale
  - Curl part $v_B$
    - Highly nonlinear, small scale

- Different origins
- Different scale/z dependence
- Different RSD

Zhang, Pan, Zheng, 2013
Zheng et al. 2013
A formula of Zhang et al. (2013)

\[ P_{\delta \delta}(k, u) = \left\{ P_{\delta \delta}(k)(1 + f \tilde{W}(k)u^2)^2 + u^4 P_{\theta \theta \theta \theta}(k) \right\} \]
\[ \quad + C_N(k, u) + C_G(k, u) + C_S(k, u) \]
\[ \times D_{\delta}^{FOG}(ku) D_{S}^{FOG}(ku) D_{B}^{FOG}(ku) . \] (26)

\[ \theta(x) \equiv - \nabla \cdot v(x) / \dot{H} \equiv - \nabla \cdot v_E(x) / H . \]

\[ W(k) = \frac{P_{\delta \theta}(k)}{P_{\delta \delta}(k)} \]

\[ \tilde{W}(k) \equiv \frac{W(k)}{W(k \rightarrow 0)} = \frac{W(k)}{f} = \frac{1}{f} \frac{P_{\delta \theta}(k)}{P_{\delta \delta}(k)} \]
Disentangle RSD: nonlinear velocity-density

\[ P^s(k, u) = \left[ P(k)(1 + f\tilde{W}(k)u^2)^2 + P_{\theta_s\theta_s}(k)u^4 + C_G(k, u) + C_{NG,3}(k, u) \right] D^{FOG}(ku) \]

- Velocity growth is suppressed w.r.t density.
- Leading order correction to the Kaiser formula
- 10% at k=0.1h/Mpc and z=0

Zheng et al. 2013
1. Mainly depend on power spectrum, only weakly on cosmology
2. With third-order PT + simulations, we can predict $W(k)$ at the accuracy better than 1%
Anisotropy Measure (AM)

- One of the main aims to measure RS $P(k)$ is to measure the motion of galaxies, thus the growth rate of structures;
- To minimize uncertainties of galaxy bias and non-linear evolution, we define the anisotropy measure:

$$AM(k, \mu) \equiv \frac{P_g^s(k, \mu)}{P_g^s(k, \mu = 0)}.$$  

- To the major order, it is related to the galaxy motion on:

$$AM^{md}(k, \mu) = (1 + \beta W(k)\mu^2)^2 \exp\{-k\mu\tilde{\sigma}_v\}.$$
Anisotropy Measure of CMASS galaxies

$k\mu < 0.1 \, h/\text{Mpc}$ for our model fitting, in order to minimize high order effects (which will be considered in a future work)
Fig. 6.— Two dimensional likelihood function of $\beta$ and $\sigma_v$ for BOSS-DR11 CMASS galaxies. The orange contours show 68% confidence level, while the green contours show 95% confidence level.
Our main result of the growth rate at $z=0.57$

$$f(z_{\text{eff}})\sigma_8(z_{\text{eff}}) = 0.440 \pm 0.037$$

Fig. 7.— Normalized likelihood function of $f(z_{\text{eff}})\sigma_8(z_{\text{eff}})$ BOSS-DR11 CMASS galaxies. The black solid curve shows results assuming $\Omega_m = 0.3$ in measuring $b_5\sigma_8(z_{\text{eff}})$ and the magenta dashed curve corresponds to $\Omega_m = 0.274$. The figure shows negligible difference for these two cases.

Fig. 8.— Constraints on $f(z_{\text{eff}})\sigma_8(z_{\text{eff}})$ from BOSS CMASS DR10, DR11 and DR12 release. Our result are shown in red diamond. Black diamonds show the results from various literatures. Magenta diamonds show those analysis that do not include the AP effect or use fiducial parameters for the AP effect. The green band show the 1σ confidence level allowed by Planck15 assuming $\Lambda$CDM+GR model and grey band for WMAP9 assuming $\Lambda$CDM+GR model.
Simulation test for $w(k)$

It is necessary to include nonlinearity($W(k)$), which can bias the f measure to a lower value (for our cut $k$ and $\mu$, it is 5-10%)
Summary

- RSD is potentially a powerful tool to study dark energy and modified gravity.
- Our method of measuring RS power spectrum from RS correlation function is simple and accurate.
- It is necessary to include the quasi-nonlinear effect $W(k)$ in the velocity field even at scale $k<0.24$ and $k \mu < 0.1$.
- Applied to SDSS DR11, we get
  $$f(z_{\text{eff}}) \sigma_8(z_{\text{eff}}) = 0.440 \pm 0.037$$

Outlook

- Modeling: high order effects; full simulations
- Observations: SDSS DR12, and future surveys

Thank you!

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