Impacts of satellite galaxies on the redshift-space distortion analysis

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Ref. C.H., Kazuhiro Yamamoto, JCAP 08 (2013), 19
Galaxy redshift surveys

What can we learn?
- Dark energy
- Gravity test
- Neutrino mass
- Primordial Non-Gaussianity

Previous/on-going surveys
- CfA, LCRS, 2dF, SDSS, BOSS, WiggleZ, VVDS, VIPERS, FastSound, ...

Planned survey
- PFS, HETDEX, DESI, Euclid, WFIRST, ...
Redshift-space distortion (RSD)

Peculiar motion of galaxies distort the observed (redshift-space) galaxy distribution

\[ z_{\text{obs}} = z_{\text{true}} + \delta v / c \]

Linear regime
Coherent bulk motion squashes the galaxy distribution along the LOS direction
”Kaiser effect”

Nonlinear regime
Random motion of galaxies elongate the galaxy distribution along the LOS direction
“Fingers-of-God effect”

Hamilton 1992
Test of Gravity

Redshift-space galaxy power spectra in linear regime

\[ P_g(k, \mu) = (b + f \mu^2)^2 P_m(k) \quad (Kaiser1987) \]

- \( b \): linear galaxy bias  \( \mu = k_\parallel/k \)
- \( f \): growth rate

Growth rate is a key probe to test gravity

\[ f \equiv \frac{d \ln D}{d \ln a} \simeq \Omega_m(z)^\gamma \]

(Peebles 1976, Lahav et al. 1991)

- \( \gamma \simeq 0.55 \) for \( \Lambda \)CDM
- \( \gamma \simeq 0.68 \) for flat DGP (e.g., Linder & Cahn 2007)
- \( \gamma \simeq 0.43 \) for \( f(R) \) (e.g., Hu & Sawicki 2007)

2-point correlation functions for BOSS CMASS samples \( \xi(r_p, r_\parallel) \)

Reid et al. 2012
Constraints on Growth rate

\[ f(z) = \Omega_m(z)^\gamma \]

Samshia et al. 2014
Subaru/PFS cosmology survey

- Subaru 8.2m telescope
- Same sky coverage as HSC (1500deg$^2$)
- Target: 4M LRGs, ELGs (OII)
- $0.8 < z < 2.4$ (9.3 Gpc/h$^3$)
- Err. of $D_A(z)$, $H(z) \sim 3\%$ ($\Omega_k \sim 7\%$), $f_z \sim 5\%$ in 6 bins, $\Omega_k \sim 0.3\%$
- 2019-2023 (planned)

Growth rate

5% accuracy

Takada et al. 2013
Euclid

- 1.2m space telescope
- Imaging 15,000 deg$^2$ sky, 40gals/arcmin$^2$
- Spectrum of 50M Hα emitters at 0.5<z<2
- FoV 0.5deg$^2$, rizYJH(550nm~1800nm)
- 2021~

Growth rate ~1% accuracy

Euclid White Paper (arXiv:1206.1225)
Systematics

In order to achieve these goals, we have to control systematics at percent-level accuracy

1. Nonlinear Gravity

2. Relationship between galaxy and DM halo
   a) Galaxy biasing
   b) Non-linear redshift-space distortion (i.e., Fingers-of-God)
Fingers-of-God (FoG) effect

Nonlinear redshift-space distortion due to internal motion of galaxies in the host halos
Central and Satellite galaxies

Central galaxies, which locate around the halo mass center, has small internal motion.

Satellite galaxies have larger internal motion.

Main source of FoG

credit: NASA/JPL-Caltech/SDSS/NOAO
Reconstruction of halo catalogs

SDSS DR7 Luminous Red Galaxy sample (0.16<z<0.47)

Counts-in-Cylinder group finding method (Reid & Spergel 2010):

\[ \Delta z < 0.006(1+z) \]

\[ \Delta r_\perp < 0.8h^{-1}\text{Mpc/h} \]

LRG Multiplicity function

<table>
<thead>
<tr>
<th>( N_{\text{LRG}} )</th>
<th>Number of LRG FoF groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>87889 (95.5 per cent)</td>
</tr>
<tr>
<td>2</td>
<td>3713</td>
</tr>
<tr>
<td>3</td>
<td>358</td>
</tr>
<tr>
<td>4</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>92046 (100 per cent)</strong></td>
</tr>
</tbody>
</table>
We compare the power spectra of following 3 samples to see the impact of satellite galaxies

1) **ALL** : All LRGs

2) **BLRG** : Brightest LRG in each group
   (BLRGs are not always centrals, but many satellites are removed in this catalog)

3) **Single** : Single LRG systems only

Difference among the samples is just $\sim 5\%$ LRGs
Clustering anisotropy is described with the multipole power spectra

\[ P_\ell(k) = \frac{1}{2} \int_{-1}^{+1} P(k, \mu) L_\ell(\mu) d\mu, \]

\( L_\ell : \) Legendre polynomials

\( \mu = k_\parallel / k : \) cosine angle against the line-of-sight direction

**Clustering anisotropy**

**Kaiser effect** mainly generates quadrupole anisotropy (\( \ell = 2 \))

**Fingers-of-God** affects higher-\( \ell \) multipole anisotropy (\( \ell = 2, 4, \ldots \))
All LRG vs Brightest LRG

Sample difference is just ~5% satellites

Impact of satellites is significantly large even at k~0.2Mpc/h
Impact on Growth Rate measurement

Estimate growth rate by fitting monopole and quadrupole with Kaiser+FoG model

\[ P(k, \mu) = (b(k) + f \mu^2)^2 P_{\text{nl}}(k) D[k\mu \sigma_v], \]

FoG damping assuming Lorentzian form (velocity dispersion \( \sigma_v \) is free)

Systematic difference between ALL and BLRG/Single samples

Cosmology is fixed to WMAP9
Halo Model

\[ P_{\text{LRG}}(k, \mu) = P^{1h}(k, \mu) + P^{2h}(k, \mu). \]

1-halo term

\[
P^{1h}(k, \mu) = \frac{1}{n_{\text{tot}}^2} \int dM \frac{dn_h}{dM} \left[ 2 \langle N_{\text{cen}} \rangle \langle N_{\text{sat}} \rangle \tilde{p}_{\text{sat}}(k, \mu; M) \right. \\
+ \left. \langle N_{\text{sat}} (N_{\text{sat}} - 1) \rangle \tilde{p}_{\text{sat}}^2(k, \mu; M) \right]
\]

2-halo term

\[
P^{2h}(k, \mu) = \frac{1}{n_{\text{tot}}^2} \int dM \frac{dn_h}{dM} \int dM' \frac{dn_h}{dM'} \left[ \langle N_{\text{cen}} \rangle \left( 1 + \langle N_{\text{sat}} \rangle \tilde{p}_{\text{sat}}(k, \mu; M) \right) \right] \\
\times \left[ \langle N_{\text{cen}} \rangle \left( 1 + \langle N_{\text{sat}} \rangle \tilde{p}_{\text{sat}}(k, \mu; M') \right) \right] P_{\text{h}h}(k, \mu; M, M'),
\]

Satellite galaxy distribution inside their host halos

\[
\tilde{p}_{\text{sat}}(k, \mu, M) = \hat{u}_{\text{NFW}}^3(k; M) \exp \left[ -\frac{\sigma_{\text{sat}}^2(M) k^2 \mu^2}{2a^2 H^2(z)} \right]
\]

Assuming satellite velocity distribution is Gaussian with Virial velocity dispersion

\[
\sigma_{\text{sat}}^{-1}(M) = \left( \frac{GM}{2r_{\text{vir}}} \right)^{1/2}
\]
All LRG power spectrum

One halo term (blue line) is necessary to describe ALL LRG power spectra

One-halo term is dominated for $P_l$ ($l \geq 4$)
Brightest LRG power spectrum

BLRG power spectra can be described only with 2-halo term ($P_4$ & $P_6$ are consistent with 0)

$P_2$ is well described when 20% of Brightest LRG is satellite (blue lines)
High $l$ multipole power spectra ($l \geq 4$) are good probes of satellite fraction and velocity dispersions (or HOD).
Expected constraints on growth rate and satellite fractions/velocity: w/o $P_4$ vs w/ $P_4$

fitting parameters: HOD ($M_{\text{min}}$, $\sigma_{\log M}$, $M_{\text{cut}}$, $M_1$, $\alpha$) + growth rate (Cosmology is fixed)

High-l multipole components are useful for breaking the degeneracy between satellite FoG and growth rate.
Summary

- Galaxy redshift surveys have a huge potential to provide a key insight on the nature of gravity
- Major difficulty in this analysis comes from the systematic uncertainty due to Fingers-of-God effect
- Even just 5% fraction of satellite galaxies has large impact on the redshift-space galaxy clustering
- High-$l$ ($l\geq 4$) multipole power spectrum provides a good probe of satellite fraction and kinematics
- High-$l$ multipole information significantly improves the accuracy of both HOD and growth rate measurement