Precision Cosmology from Redshift-space galaxy Clustering

~ Progress of high-precision template for BAOs ~

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In collaboration with
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• Classic method to measure the clustering anisotropies of galaxies is renewed with a great interest to clarify the nature of dark energy and to test theory of gravity.

• Accurate theoretical models for power spectrum have made a rapid progress, and are now available, taking fully account of the effect of clustering anisotropies.

• Large N-body simulations reveal a new feature of clustering anisotropies in halo catalogs, which sensitively depends on clustering bias. Only the improved model can account for this.
Introduction

Lambda CDM model

- Standard cosmological model characterized by 6 parameters

- Flat universe filled with the unknowns energy contents

SN Ia obs.

Late-time cosmic acceleration

(Perlmutter et al. ’99; Riess et al. ’98)

Possible solution?

- Dark energy: dynamical scalar field or cosmological const.

- Modified gravity: IR modification to general relativity
“beyond Lambda CDM model”

- Dark energy or Modified gravity?
  - Yes, Nature of cosmic acceleration
  - Yes, Test of gravity on cosmological scales

Key: Precision measurements of Cosmic expansion and Growth of structure

Need independent and complementary probes other than CMB and SN Ia
Large-scale structure (LSS)

Fundamental observable: Galaxy clustering patterns

Note: weak lensing can also probe LSS
Cosmological information in LSS

All information is encoded in statistical quantities:

Power spectrum $P(k)$ or correlation function $\xi(r)$

Historical record of the primordial Universe
(Initial condition & late-time evolution)

Additional information coming from observational effect:

- Alcock-Paczynski effect
- Redshift distortion effect

With BAOs as standard ruler;
measurements of these are now top priority in future surveys
Alcock-Paczynski (A-P) effect

Anisotropies caused by apparent mismatch of underlying cosmological models

\[ \Delta r_{\perp} = D_A(z) \Delta \theta \]

\[ \Delta r_{\parallel} = c \Delta z / H(z) \]

Using BAO as standard ruler, \( H(z) \) & \( D_A(z) \) can be measured simultaneously

e.g., Seo & Eisenstein ('03); Hu & Haiman ('03); Blake & Glazebrook ('03); Shoji et al.'09

Alcock & Paczynski ('79)
Redshift distortion (RD) effect

Anisotropies caused by peculiar velocity of galaxies through redshift measurements

Measurement of $f(z)$ offers a test of gravity on cosmological scales

e.g., Linder ('08); Guzzo et al. ('08); Yamamoto et al. ('08); Song & Dore ('09); Percival & White ('09); White, Song & Percival ('09); Song & Percival ('09); Blake et al. ('11)
Revival of classic method

Measuring clustering anisotropies is not a new method

**A-P effect**
- Matsubara & Suto ('96)
- Ballinger, Peacock & Heavens ('96)

Use global shape of power spectrum/correlation function to determine $\Omega_\Lambda$

**RD effect**
- Hamilton ('92)

Adopt GR valid over cosmological scales to determine $\Omega_m$

温故知新 (learning from the past)
### Complementarity

<table>
<thead>
<tr>
<th>Method</th>
<th>Observable</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN Ia</td>
<td>Light curves of distant SNe</td>
<td>$D_L(z)$</td>
</tr>
<tr>
<td>Weak lensing</td>
<td>Shear field from galaxy images</td>
<td>$D_A(z), g(z)$</td>
</tr>
<tr>
<td>Clusters</td>
<td>Number density of clusters</td>
<td>$D_A(z), H(z), g(z)$</td>
</tr>
<tr>
<td>Galaxy clustering</td>
<td>Spatial clustering of galaxies</td>
<td>$D_A(z), H(z), f(z)$</td>
</tr>
</tbody>
</table>

$g(z)$: growth factor

Advantage:
galaxy clustering provides a way to separately measure $D_A$, $H$, & $f$
New ideas & innovation

Through RD effect, galaxy clustering further provides statistical information of velocity field

- Reconstruction of velocity power spectrum
  - Song & Kayo ('10), Tang, Kayo & Takada ('11)
  - Coherent combination to constrain dark energy (Song '11)
- Alternative probe of bulk flow
  - Song et al. ('11a,b)

Improved technique to reduce ‘noises’ has been developed

- Reducing cosmic variance
  - McDonald & Seljak ('09)
- Reducing shot noise/stochasticity
  - Seljak et al. ('09), Hamaus et al. ('10)
- Reducing Finger-of-God damping
  - Hikage, Takada & Spergel ('11)
Latest results

\[ D_V(z) \equiv \left[ (1+z)^2 D_A(z)^2 \frac{cz}{H(z)} \right]^{1/3} \]

Blake et al. arXiv:1105.2862
arXiv:1104.2908

WiggleZ++
(WiggleZ: ~150,000 galaxies)

SDSS DR7 LRG
(z=0.2 & 0.35)

WiggleZ (z=0.6)

BAO+CMB
On-going/up-coming surveys

Spectroscopic surveys aiming at precision measurements of $f(z)$ and/or $H(z)$ & $D_A(z)$

**Ground**
- WiggleZ
- BOSS
- HETDEX
- SuMIRe-PFS
- Big-BOSS

**Space**
- WFIRST
- EUCLID

VIPERS
- FastSound
- Subaru
- GAMA
Theoretical challenges

For fruitful science from high-precision measurements,

Accurate theoretical template
for power spectrum/correlation function

is crucial and highly demanding

Reducing the systematics is a big issue:

• **Non-linear gravitational evolution**
• **Non-linear redshift distortions**
• **Galaxy biasing**

Small, but non-negligible
at ~1% precision
Forward modeling approach

‘First-principle’ calculations of $P(k)$ & $\xi(r)$ based on perturbation theory (PT) of LSS

Development of improved treatment of PT

- Renormalized PT: Crocce & Scoccimarro (‘06ab, ’08)
- Closure theory: AT & Hiramatsu (’08), AT, Nishimichi, Saito & Hiramatsu (’09)
- Lagrangian resummation theory: Matsubara (’08), Okamura, AT & Matsubara (’11)
- Regularized PT: Bernardeau, Crocce & Scoccimarro (’08), Bernardeau, AT, Crocce & Scoccimarro (in prep.)

For BAO scales of our interest ($k<0.2\sim0.3$ h/Mpc @ $0.5<z<1.5$), non-linear gravitational evolution is now under control
Improved PT in real space

AT, Nishimichi, Saito & Hiramatsu ('09)
Improved PT in real space

For power spectrum, reliable range of improved PT becomes twice wider than that of standard PT

AT, Nishimichi, Saito & Hiramatsu ('09)
Modeling redshift distortions

\[ \mathbf{s} = \mathbf{r} + \frac{(\mathbf{v} \cdot \mathbf{z})}{a H(z)} \mathbf{z} \]

- peculiar velocity
- observer’s line-of-sight direction

Observed clustering pattern is apparently distorted.

- Anisotropy (2D power spectrum)
  \[ P(k) \rightarrow P^{(S)}(k, \mu); \quad \mu \equiv (\mathbf{k} \cdot \mathbf{z})/|\mathbf{k}| \]

- Power spectrum amplitude
  - Enhancement: Kaiser effect (small-k)
  - Suppression: Finger-of-God effect (large-k)
Redshift-space power spectrum

**Exact expression**

\[
P^{(S)}(k) = \int d^3 x \, e^{i k \cdot x} \left\langle e^{-i k \mu \Delta u_z} \{\delta(x) - \nabla_z u_z(x)\} \{\delta(x') - \nabla_z u_z(x')\} \right\rangle
\]

\[
u_z = (\vec{v} \cdot \hat{z})/(aH)
\]

\[
\Delta u_z = u_z(x) - u_z(x')
\]

**Exact expression**

\[
P^{(S)}(k, \mu) = e^{-(k\mu \sigma_v)^2} \left[ P_{\delta\delta}(k) - 2 \mu^2 P_{\delta\theta}(k) + \mu^4 P_{\theta\theta}(k) \right]
\]

**Finger of God**

**(non-linear) Kaiser**

**Fitting parameter**

*(1D velocity dispersion)*

... still phenomenological

(Popular) streaming model

(e.g., Scoccimarro (2004))
An improved model

Low-k expansion from exact formula

\[ P^{(S)}(k, \mu) = D_{\text{FoG}}[k \mu f \sigma_v] P_{\delta \delta}(k) - 2 f \mu^2 P_{\delta \theta}(k) + f^2 \mu^4 P_{\theta \theta}(k) \]

Damping func.

Non-linear mode-coupling btw velocity & density

Non-Gaussian correction

\[ A(k, \mu) = -2 k \mu \int \frac{d^3 p}{(2\pi)^3} \frac{p_z}{p^2} B_\sigma(p, k - p, -k) \]

anti-phase oscillation

Gaussian correction

\[ B(k, \mu) = (k \mu)^2 \int \frac{d^3 p}{(2\pi)^3} F(p) F(k - p) \]

small in amplitude (<1-2%)

These also depend on ‘f’

AT, Nishimichi & Saito ('10)
Role of corrections in dark matter

Improved model

\[ P^{(S)}(k, \mu) = \sum_{\ell=\text{even}} P_{\ell}^{(S)}(k) P_{\ell}(\mu) \]
Role of corrections in dark matter

Streaming model

\[ P^{(S)}(k, \mu) = \sum_{\ell=\text{even}} P^{(S)}_{\ell}(k) P_{\ell}(\mu) \]

Even in 1% convergence limit, discrepancy manifest (few % in P0, >5% in P2)
Blind test: recovery of $D_A$, $H$ & $f$

AT, Nishimichi & Saito (’10)

Fitting to $P_0$ & $P_2$ of N-body data to estimate $(D_A, H, f)$ using MCMC

Improved model of redshift distortions correctly recovers the input values
Testing PT models against redshift-space halo clustering

From dark matter to halos

The improved PT model has successfully passed several tests in the case of dark matter clustering.

As a natural step,

"Test against redshift-space halo clustering"

Why halo?

- Physically well-defined objects easy to handle by N-body simulations
- Reconstruction technique for halo density field from LRG samples
- Annoying Finger-of-God damping is expected to be small

Reid, Spergel & Bode ('09)
Reid et al. ('10)
Halo clustering from N-body simulations

Nishimichi & AT ('11)

Large N-body simulations ($L_{\text{box}}=1.14\text{Gpc}/h$, $N=1,028^3$) with 15 realizations

- 9 halo catalogs sampled over wide-mass range @ $z=0.35$
  
  \( \bar{M}_{h,i} \subset [3 \times 10^{12}, 7 \times 10^{13}] \text{ } h^{-1} M_\odot \)

- Volume & number density roughly match those of SDSS DR7 LRG

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**TABLE II**: Summary of the halo catalogs. The minimum, maximum and mean mass ($M_{\text{min}}$, $M_{\text{max}}$ and $\bar{M}_h$) are in units of $h^{-1} M_\odot$, while the halo number density ($n_h$) is in $h^3 \text{Mpc}^{-3}$. The bias parameter, $b_0$, is defined in Eq. (15). See Sec. IV A for more detail.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$M_{\text{min}}$</th>
<th>$M_{\text{max}}$</th>
<th>$\bar{M}_h$</th>
<th>$n_h$</th>
<th>$b_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$1.77 \times 10^{12}$</td>
<td>$2.49 \times 10^{12}$</td>
<td>$3.54 \times 10^{12}$</td>
<td>$4.98 \times 10^{12}$</td>
<td>$7.09 \times 10^{12}$</td>
</tr>
<tr>
<td></td>
<td>$5.54 \times 10^{12}$</td>
<td>$1.02 \times 10^{13}$</td>
<td>$1.74 \times 10^{13}$</td>
<td>$2.66 \times 10^{13}$</td>
<td>$4.04 \times 10^{13}$</td>
</tr>
<tr>
<td></td>
<td>$2.96 \times 10^{12}$</td>
<td>$4.65 \times 10^{12}$</td>
<td>$7.08 \times 10^{12}$</td>
<td>$9.37 \times 10^{12}$</td>
<td>$1.47 \times 10^{13}$</td>
</tr>
<tr>
<td>$n_h$</td>
<td>$1.57 \times 10^{-3}$</td>
<td>$1.26 \times 10^{-3}$</td>
<td>$9.46 \times 10^{-4}$</td>
<td>$6.87 \times 10^{-4}$</td>
<td>$4.87 \times 10^{-4}$</td>
</tr>
<tr>
<td>$b_0$</td>
<td>1.08</td>
<td>1.16</td>
<td>1.25</td>
<td>1.35</td>
<td>1.47</td>
</tr>
</tbody>
</table>
Real-space clustering

PT model prediction works very well at $k < 0.2 \, h/\text{Mpc}$

Halo bias possesses (very) weak scale-dependence

$$b(k) = \frac{P_{hm}(k)}{P_m(k)}$$

Adopting a scale-dependent linear bias,

$$\delta_h(\vec{k}) = b(k)\delta_m(\vec{k})$$

PT models are compared with simulations (--> Next slides)
Power spectrum in 2D

\[ P_{\text{halo}}(k_{||}, k_{\perp}) \]
\[ \frac{(b^2 + f \mu^2)^2 P_{\text{lin,no-wiggle}}(k)}{k_{||}^2} \]

- Dark matter
- Light halos (bin 1)
- Heavy halos (bin 9)

Line-of-sight observer

N-body result

‘shot-noise’ corrected
Power spectrum in 2D

\[ \mu \equiv \frac{k_{||}}{|k|} \]

\[ \mu = \begin{array}{c} 0 \\ 1 \end{array} \]

- Dark matter
- Streaming (L)
- Improved (L)

\[ k_{\perp} \]

\[ k_{||} \]

\[ \sigma_v = 5.2 \text{ Mpc/h} \]

\[ \sigma_v = 7.0 \text{ Mpc/h} \]

\[ \chi^2_{\text{red}} = 2.22 \]

\[ \chi^2_{\text{red}} = 1.52 \]
Power spectrum in 2D

\[ \mu \equiv \frac{k_{\parallel}}{|k|} \]

- Dark matter
- Light (bin 1)

\[ k_{\parallel} \]

\[ k \]

\[ \mu = 1 \]
Power spectrum in 2D

Dark matter

$\mu \equiv \frac{k_{||}}{|\vec{k}|}$

$\mu = 1$

$\mu = 0$

$k_{\perp}$

$k_{||}$

$\mu = 1$

$\mu = 0$

$k_{\perp}$

$\chi^2_{\text{red}} = 2.22$

$\sigma_v = 5.2 \text{ Mpc/h}$

$\chi^2_{\text{red}} = 1.52$

$\chi^2_{\text{red}} = 3.42$

$\sigma_v = 4.2 \text{ Mpc/h}$

$\chi^2_{\text{red}} = 1.17$

$\chi^2_{\text{red}} = 2.22$

$\sigma_v = 7.0 \text{ Mpc/h}$

$\chi^2_{\text{red}} = 1.52$
Multipole power spectra

\[ P^{(S)}(k, \mu) = \sum_{\ell=\text{even}} P^{(S)}_{\ell}(k) \mathcal{P}_\ell(\mu) \]

- **Light (bin1)**
  - Monopole
  - Quadrupole

- **Dark matter**
  - Monopole \((\ell = 0)\)
  - Quadrupole \((\ell = 2)\)

- **Heavy (bin9)**
  - Monopole
  - Quadrupole

\[ P^{(S)}_{\ell}(k) / [b(k)^2 P^{(S)}(k)] \]

\[ k \text{ [h Mpc}^{-1}] \]
Halo mass dependence

Choice of damping func.

\( L \): Lorentzian, \( G \): Gaussian

Fitted results of velocity dispersion

Goodness of fit
SDSS DR7 LRG samples

Assuming linear scale-(in)dependent bias, monopole & quadrupole spectra fit to PT model

Monopole

\[ b(k) = b_0 + b_1 k^c \]

Quadrupole-to-Monopole ratio

\[ \frac{P_0^{(S)}(k)}{P_0^{(S)}}(k) \]

Saito, Nishimichi, AT & Yamamoto (’10) in prep.
Constraints on $D_A, H & f$

Simultaneously constrain $D_A, H & f$
from SDSS DR7 LRGs

Resultant constraint on $D_A$ is rather sensitive to the galaxy bias
Summary

Clustering anisotropies by AP & RD effects offer unique probe to precisely measure cosmic expansion & growth of structure

• Key science of galaxy surveys in the coming decade
• New ideas & innovations
• Precision power spectrum template from perturbation theory

\[\begin{align*}
\text{New effect of non-linear RD amplified by galaxy/halo bias} \\
\rightarrow \text{Failure of popular “streaming model”} \\
\text{Impacts of precision model of RD on future measurements}
\end{align*}\]

The understanding of galaxy bias is still crucial issue