Measuring Peculiar Motion using Redshift Space Distortion

Large Scale Structure and Galaxy Flows, Quy Nhon
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Implication of cosmic acceleration

• Breaking down our knowledge of particle physics: we have limited knowledge of particle physics bounded by testable high energy, and our efforts to explain the cosmic acceleration turn out in vain:
  
  Alternative mechanism to generate fine tuned vacuum energy
  
  New unknown energy component
  
  Unification or coupling between dark sectors

• Breaking down our knowledge of gravitational physics: gravitational physics has been tested in solar system scales, and it is yet confirmed at horizon size:
  
  Presence of extra dimension
  
  Non-linear interaction to Einstein equation

• Failure of standard cosmology model: our understanding of the universe is still standing on assumption:
  
  Inhomogeneous models: LTB, back reaction
Implication of cosmic acceleration

- Breaking down our knowledge of particle physics: we have limited knowledge of particle physics bounded by testable high energy, and our efforts to explain the cosmic acceleration turn out in vain:
  - Alternative mechanism to generate fine tuned vacuum energy
  - New unknown energy component
  - Unification or coupling between dark sectors

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  - Presence of extra dimension
  - Non-linear interaction to Einstein equation

Dynamical Dark Energy: modifying matter
\[ G_{\mu\nu} = 4\pi G_N \ T_{\mu\nu} + \Delta T_{\mu\nu} \]

Geometrical Dark Energy: modifying gravity
\[ G_{\mu\nu} + \Delta G_{\mu\nu} = 4\pi G_N \ T_{\mu\nu} \]

- Failure of standard cosmology model: our understanding of the universe is still standing on assumption:
  - Inhomogeneous models: LTB, back reaction
Galaxy clustering seen in redshift space

- Spectroscopy wide surveys have provided the key observables of distance measures and growth functions, such as 2dF, SDSS, WiggleZ, BOSS.

- Most unknowns in the universe will be revealed through LSS.
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Future wide deep field survey

- Photometric wide-deep survey
- Spectroscopic wide-deep survey

WL measures $\phi - \psi$

Galaxy-Galaxy correlation

Modified by mass screening effect

Continuity eq.

Coherent motions

$G_{\mu\nu} = 4\pi \kappa G_N$

YSS 2006, YSS, Kazuya 2009
Cosmological probe of coherent motion

The first measured $f\sigma_8$

$\sigma_8$

$\text{Current}$

YSS, Percival 2009
Cosmological probe of coherent motion
Planned surveys in the future
History and plan for spectroscopy surveys

DESI ahead of the curve if completed by 2024

Size of redshift surveys

- DESI: 30 million
- SDSS-III, 2014: 2.8 million
- SDSS, 2009: 929,000
- 2dF, 2003: 221,414
- CfA-2, 1998: 18,000
- LCRS, 1996: 18,678
- CfA1, 1983: 1840

log N(galaxies)

140 billion

1980

1990

2000

2010

2020

2030

2040

2050

2061

Year
Galaxy clustering seen in redshift space

Four target classes spanning redshifts $z=0 \rightarrow 3.5$
Includes all the massive black holes in the Universe (LRGs + QSOs)

- 0.6 million Ly-A QSOs
- 1.4 million QSOs
- 23 million ELGs
- 4 million LRGs
Cosmological probe of coherent motion

CMASS (Chuan et.al. 2015)
CMASS (YSS et.al. 2015)

Precision is matter!

CMASS (YSS et.al. 2015)
Key cosmological observables of the universe

• Angular diameter distance $D_A$: Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

• Radial distance $H^{-1}$: Exploiting redshift distortions as intrinsic anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

• Coherent motion $G_\Theta$: The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.
Standard ruler

$$D_s = \Delta z / H(z)$$

$$D_s \sim 150 \text{ Mpc}$$

$$D_s = (1+z) D_A(z) \theta$$
Anisotropy galaxy clustering
Anisotropy galaxy clustering

BAO signature appear as 2D ring

$D_s \sim 150 \text{ Mpc}$

Sabiu, YSS 2016
Measured anisotropy galaxy clustering
Perpendicular and radial distance measures

\( (D_A, H^{-1}, G_\delta, G_\Theta, \text{FoG}) \)
Perpendicular and radial distance measures

\((D_A, H^{-1}, G_\delta, G_\Theta, \text{FoG})\)

\(\Omega_m = 0.2 - 0.35\)
\(\Omega_k = -0.1, 0, +0.1\)
Growth function measurements

\((D_A, H^{-1}, G_\delta, G_\Theta, \text{FoG})\)
Growth function measurements

\( D_A, H^{-1}, G_\delta, G_\Theta, \text{FoG} \)

\[ \Omega_m = 0.2 - 0.35 \]

\[ \Omega_k = -0.1 \]

\[ w = -1 \]

\[ -0.8 \]

**Coherent motion**

**Planck**

**Variation of \( H^{-1} \)**

**Variation of \( G_\delta \)**
Cosmological probe of coherent motion

YSS et al. 2015
Anisotropy correlation without corrections
Improved RSD model

Squeezing effect at large scales

(Kaiser 1987)

\[ P_s(k, \mu) = P_{gg}(k) + 2\mu^2 P_{g\theta}(k) + \mu^4 P_{\theta\theta}(k) \]

\[ P_s(k, \mu) = [P_{gg}(k) + \Delta P_{gg} + 2\mu^2 P_{g\theta}(k) + \Delta P_{g\theta} + \mu^4 P_{\theta\theta}(k) + \Delta P_{\theta\theta} \\
+ \mu^2 A(k) + \mu^4 B(k) + \mu^6 C(k) + ... ] \exp[-(k\mu\sigma_p)^2] \]

Taruya, Nishimichi, Saito 2010; Taruya, Hiramatsu 2008; Taruya, Bernardeau, Nishimichi 2012
Improved RSD model

\[ P_s(k, \mu) = [Q_0(k) + \mu^2Q_2(k) + \mu^4Q_4(k) + \mu^6Q_6(k)] \exp[-(k\mu\sigma_p)^2] \]

\[ \xi(\sigma, \pi) = \int d^3k \ P(k, \mu) e^{ikx} = \Sigma \xi_l(s) \ P_l(v) \]

\[ \xi_l(s) = i^l\int k^2dk \ P_l(k) j_l(ks) \]

\[ P_0(k) = p_0(k) \]
\[ P_2(k) = 5/2 [3p_1(k) - p_0(k)] \]
\[ P_4(k) = 9/8 [35p_2(k) - 30p_1(k) + 3p_0(k)] \]
\[ P_6(k) = 13/16 [231p_3(k) - 315p_2(k) - 105p_1(k) + 5p_0(k)] \]

\[ p_n(k) = 1/2 \ [ \gamma(n+1/2, \kappa)/\kappa^{n+1/2}Q_0(k) + \gamma(n+3/2, \kappa)/\kappa^{n+3/2}Q_2(k) \]
\[ + \gamma(n+5/2, \kappa)/\kappa^{n+5/2}Q_4(k) + \gamma(n+7/2, \kappa)/\kappa^{n+7/2}Q_6(k) \]

\[ \kappa = k^2\sigma_p^2 \]
Cosmological probe of coherent motion

\[ P_s(k, \mu) = P_{gg}(k) + 2\mu^2 P_{g\theta}(k) + \mu^4 P_{\theta\theta}(k) \]
Cosmological probe of coherent motion

\[ P_s(k, \mu) = [P_{gg}(k) + 2\mu^2 P_{g\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + \mu^2 A(k) + \mu^4 B(k)] \exp[-(k\mu \sigma_p)^2] \]
Cosmological probe of coherent motion

\[ P_s(k, \mu) = [P_{gg}(k) + 2\mu^2P_{g\Theta}(k) + \mu^4P_{\Theta\Theta}(k) + \mu^2A(k) + \mu^4B(k)] \exp\left[-(k\mu\sigma_p)^2\right] \]
Open new window to test cosmological models

$\left( D_A, H^{-1}, G_\delta, G_\theta, F_0 G \right)$

**Standard model**
- Cold dark matter
- Massless neutrino

**New physics**
- Quintessence dark energy
- Phantom dark energy
Open new window to test cosmological models

(\(D_A, H^{-1}, G_{\delta}, G_{\theta}, \text{FoG}, \text{New}, \text{New}, \ldots\))

**Standard model**
- Cold dark matter
- Massless neutrino
- Hot or warm dark matter
- Massive neutrino
- Interacting dark matter
- Unified dark matter

**New physics**
- Quintessence dark energy
- Phantom dark energy
- Decaying vacuum
- Chameleon type gravity
- Dilaton or Symmetron
- Vainstein type gravity
- Inhomogeneity of universe
- non-Friedman universe
Open new window to test cosmological models

\((D_A, H^{-1}, G_8, G_\Theta, F_0G, \ldots, \text{New}, \ldots)\)

New physics

Chameleon type gravity
Probing modified gravity

\[ \frac{d\delta_m}{dt} + \frac{\theta_m}{a} = 0 \]

\[ \frac{d\theta_m}{dt} + H\theta_m = k^2\psi/a \]

\[ k^2 \phi = \frac{3}{2} H_0^2\Omega_m \delta_m/a \, F(\epsilon) \]

\[ k^2 \psi = -\frac{3}{2} H_0^2\Omega_m \delta_m/a \, G(\epsilon) \]

\[ \phi_{fR} - \psi_{fR} = \varphi \]

\[ k^2 \psi = -\frac{3}{2} H_0^2\Omega_m \delta_m/a - \frac{1}{2} k^2 \varphi \]

\[ (1+w_{BD}) k^2/a^2 \varphi = 3H_0^2\Omega_m \delta_m/a - I(\varphi) \]

\[ I(\varphi) = M_1(k)\varphi(k) + \frac{1}{2} \int \cdots \int d^3k_1 \cdots d^3k_n \, M_1(k) \cdots M_n(k) \, \varphi(k_1) \cdots \varphi(k_n) \]

YSS et.al. 2015
Probing modified gravity

\[ d\delta_m/dt + \theta_m/a = 0 \]
\[ d\theta_m/dt + H\theta_m = k^2 \psi/a \]
\[ k^2 \phi = 3/2 H_0^2 \Omega_m \delta_m/a \quad F(\varepsilon) \]
\[ k^2 \psi = -3/2 H_0^2 \Omega_m \delta_m/a \quad G(\varepsilon) \]

\[ \phi_{fR} - \psi_{fR} = \varphi \]
\[ k^2 \psi = -3/2 H_0^2 \Omega_m \delta_m/a - 1/2 k^2 \varphi \]
\[ (1+w_{BD}) k^2/a^2 \varphi = 3H_0^2 \Omega_m \delta_m/a - I(\varphi) \]

\[ I(\varphi) = M_1(k)\varphi(k) + 1/2 \int \cdots \int d^3k_1 \cdots d^3k_n \: M_1(k) \cdots M_n(k) \: \varphi(k_1) \cdots \varphi(k_n) \]

YSS et.al. 2015
We find new constraints on f(R) gravity models using BOSS DR11

$|f_{R0}| < 8 \times 10^{-4}$ at 95% confidence limit

YSS et al. 2015

$D_A, H^{-1}, G_\delta, G_\Theta, F_{oG, |f_{R0}|}$
Open new window to test cosmological models

\((D_A, H^{-1}, G_\delta, G_\Theta, F_{\text{FoG}}, \text{New}, \ldots)\)

Standard model

Massive neutrino
Probing neutrino mass

We build the neutrino RSD templates at small mass limit $m_{\nu} < 1$eV
Probing neutrino mass

\( (D_A, H^{-1}, G_\delta, G_\Theta, \text{FoG}, m_\nu) \)

It is interesting to note that all distance measures and growth functions are weakly dependent on the present of neutrino mass.

Oh, YSS arXiv:1607.01074
Excavating neutrino mass buried under LSS

The measured neutrino mass is $m_\nu = 0.2^{+0.28}_{-0.17}$ eV.

The combined constraints on $m_\nu$ is distinguishable from massless $m_\nu$.

CMB distance measure

$H_0 = 65 \pm 1.3$ km/s/Mpc

Oh, YSS arXiv:1607.01074
Challenge to the future precision cosmology

Four target classes spanning redshifts $z=0 \rightarrow 3.5$
Includes all the massive black holes in the Universe (LRGs + QSOs)

0.6 million Ly-A QSOs
+1.4 million QSOs
23 million ELGs
4 million LRGs
Mapping of clustering from real to redshift spaces

\[ P_s(k, \mu) = \int d^3x \ e^{ikx} \langle \delta \delta \rangle \]

\[ P_s(k, \mu) = \int d^3x \ e^{ikx} \langle e^{iv(\delta + \mu^2 \Theta)(\delta + \mu^2 \Theta)} \rangle \]

\[ = \int d^3x \ e^{ikx} \exp\{\langle e^{iv} \rangle_c \} \left[ \langle e^{iv(\delta + \mu^2 \Theta)(\delta + \mu^2 \Theta)} \rangle_c + \langle e^{iv(\delta + \mu^2 \Theta)} \rangle_c \langle e^{iv(\delta + \mu^2 \Theta)} \rangle_c \right] \]

\[ P_s(k, \mu) = [P_{gg}(k) + 2\mu^2 P_{g\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k, \mu) + B(k, \mu) + T(k, \mu) + F(k, \mu)] \exp[-(k\mu\sigma_p)^2] \]

- Higher order polynomials are generated by density and velocity cross-correlation which generate the infinite tower of correlation pairs. We take the perturbative approach to cut off higher orders.

- The FoG effect consists of the one-point contribution and the correlated velocity pair contribution. The latter is perturbatively expanded as F term, and the former is parameterised using \( \sigma_p \).
Direct measurement of higher order polynomials

\[ A(k, \mu) = j_1 \int d^3x \, e^{i \mathbf{k} \cdot \mathbf{x}} \langle A_1 A_2 A_3 \rangle_c, \]

\[ B(k, \mu) = j_1^2 \int d^3x \, e^{i \mathbf{k} \cdot \mathbf{x}} \langle A_1 A_2 \rangle_c \langle A_1 A_3 \rangle_c, \]

\[ T(k, \mu) = \frac{1}{2} j_1^2 \int d^3x \, e^{i \mathbf{k} \cdot \mathbf{x}} \langle A_1^2 A_2 A_3 \rangle_c, \]

\[ F(k, \mu) = -j_1^2 \int d^3x \, e^{i \mathbf{k} \cdot \mathbf{x}} \langle u_z u'_z \rangle_c \langle A_2 A_3 \rangle_c, \]

Yi, YSS 2016
We subtract out the perturbative higher order polynomials, and the remaining’s can be considered to be FoG effect. If our formulation is correct, those all residuals should be consistent in terms of scale, and fitted to be Gaussian with constant $\sigma_p$. 

$$\exp[-(k\mu\sigma_p)^2]$$
Challenge to the precision cosmology

$V_{\text{survey}} = (1.89 \text{Gpc}/h)^3$

$P_s(k, \mu)$

$z = 0.5$

$z = 0.9$

$z = 1.5$

$z = 3.0$

Yi, YSS 2016
Bispectrum in redshift space

\[ B(k_1, k_2, k_3, \mu_1, \mu_2) = D^B_{FoG} B^{PT}(k_1, k_2, k_3, \mu_1, \mu_2) \]

\[ B^{PT}(k_1, k_2, k_3, \mu_1, \mu_2) = 2[Z_2(k_1, k_2)Z_1(k_1)Z_2(k_2)P(k_1)P(k_2) + \text{cyclic}] \]

\[ Z_1(k_1) = b + f \mu_1^2 \]
\[ Z_2(k_1, k_2) = \frac{b_2}{2} + bF_2 + f \mu_{12}G_2 \]
\[ + fk_{12}\mu_{12}/2[\mu_1/k_1Z_2(k_2)+\mu_1/k_1Z_2(k_2)] \]
BAO cloud in bispectrum

Sabiu, YSS 2016 prepared
The full RSD theory for bispectrum

First order (equivalent to Kaiser term)

\[
\left[ \langle \Delta\Delta'\Delta'' \rangle_c 
+ j_1 \left( \langle V\Delta\Delta'\Delta'' \rangle_c + \langle \Delta\Delta' \rangle_c \langle V\Delta'' \rangle_c + \langle \Delta'' \rangle_c \langle V\Delta' \rangle_c + \langle \Delta' \Delta'' \rangle_c \langle V \Delta \rangle_c \right) 
+ j_2 \left( \langle V'\Delta\Delta'\Delta'' \rangle_c + \langle \Delta\Delta' \rangle_c \langle V'\Delta'' \rangle_c + \langle \Delta'' \rangle_c \langle V'\Delta' \rangle_c + \langle \Delta' \Delta'' \rangle_c \langle V' \Delta \rangle_c \right) \right]
\]

Second order

\[
+ j_1 j_2 \left( \langle VV'\Delta\Delta'\Delta'' \rangle_c + \langle \Delta\Delta' \rangle_c \langle VV'\Delta'' \rangle_c + \langle \Delta'' \rangle_c \langle VV'\Delta' \rangle_c + \langle \Delta' \Delta'' \rangle_c \langle VV \Delta \rangle_c 
+ \langle V\Delta\Delta' \rangle_c \langle V'\Delta'' \rangle_c + \langle V'\Delta\Delta' \rangle_c \langle V\Delta'' \rangle_c + \langle V\Delta'' \rangle_c \langle V'\Delta' \rangle_c + \langle \Delta' \Delta'' \rangle_c \langle V' \Delta \rangle_c 
+ \langle V'\Delta\Delta' \rangle_c \langle V\Delta'' \rangle_c + \langle \Delta\Delta' \rangle_c \langle V'\Delta'' \rangle_c + \langle \Delta'' \rangle_c \langle V'\Delta' \rangle_c + \langle \Delta' \Delta'' \rangle_c \langle V \Delta \rangle_c \right)

+ j_2^2 \left( \frac{1}{2} \langle V^2\Delta\Delta'\Delta'' \rangle_c + \frac{1}{2} \langle \Delta\Delta' \rangle_c \langle V^2\Delta'' \rangle_c + \frac{1}{2} \langle \Delta'' \rangle_c \langle V^2\Delta' \rangle_c + \frac{1}{2} \langle \Delta' \Delta'' \rangle_c \langle V^2 \Delta \rangle_c 
+ \langle V\Delta\Delta' \rangle_c \langle V\Delta'' \rangle_c + \langle V\Delta'' \rangle_c \langle V\Delta' \rangle_c + \langle V\Delta' \rangle_c \langle V\Delta'' \rangle_c \langle V \Delta \rangle_c \right)

+ j_2^2 \left( \frac{1}{2} \langle V'^2\Delta\Delta'\Delta'' \rangle_c + \frac{1}{2} \langle \Delta\Delta' \rangle_c \langle V'^2\Delta'' \rangle_c + \frac{1}{2} \langle \Delta'' \rangle_c \langle V'^2\Delta' \rangle_c + \frac{1}{2} \langle \Delta' \Delta'' \rangle_c \langle V'^2 \Delta \rangle_c 
+ \langle V'\Delta\Delta' \rangle_c \langle V'\Delta'' \rangle_c + \langle V'\Delta'' \rangle_c \langle V'\Delta' \rangle_c + \langle V'\Delta' \rangle_c \langle V'\Delta'' \rangle_c \langle V' \Delta \rangle_c \right) \right]
\]

FoG term

\[
\exp \left\{ \frac{1}{2} (j_1^2 + j_2^2 + j_3^2) \sigma_z^2 - j_1^2 \langle u_z(\vec{r})u_z(\vec{r'}) \rangle_c - j_2^2 \langle u_z(\vec{r})u_z(\vec{r''}) \rangle_c 
+ j_1 j_2 \left[ \langle u_z(\vec{r'})u_z(\vec{r''}) \rangle_c - \langle u_z(\vec{r})u_z(\vec{r'}) \rangle_c - \langle u_z(\vec{r})u_z(\vec{r''}) \rangle_c \right] \right\}
\]

YSS et.al. 2016 prepared
Improved coherent motion in the future

YSS, Taruya, Akira 2015
Conclusion

• We measure coherent motion of the universe with BOSS catalogue using RSD perturbative theory, which provides us with trustable measurements.

• The full perturbative approaches allow us to prove the exotic cosmic acceleration model such as modified gravity of f(R) gravity.

• We probe the non-trivial neutrino mass about 0.2eV, and the measured Hubble constant gets to be even smaller about 65.

• The future experiment opens new precision cosmology era, and we are ready for the challenge. Our new RSD theoretical model is promising to probe coherent motion in a percentage precision.

• The combination of power and bi spectra is essential to probe the coherent motion tightly. We make lots of efforts for it.