Cosmological Constraints from the Redshift Dependent of the Alcock-Paczynski Test

Xiao-Dong Li (李霄栋), KIAS

WITH Changbom Park & Cristiano G. Sabiu, Hyunbae Park, David H. Weinberg,
Donald P. Schneider, Juhan Kim, Sungwook Hong

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**What:** AP, the shape distortion of objects/structures, due to wrong cosmology (adopted to compute $r(z)$)

**How:** AP distortion is less significant than RSD, but more evolves with redshift. We focused on the redshift dependence, to probe AP and avoid RSD.

**Result:** We applied our idea to BOSS DR12 galaxies and obtained very tight cosmological constraint.


Combined: 

$$\Omega_m = 0.301 \pm 0.006$$

$$w = -1.054 \pm 0.025$$
The Alcock-Paczynski Test

Alcock & Paczynski, Nature 281, 358 (1979)

The Alcock-Paczynski (AP) effect refers to the geometric distortion when incorrect cosmological models are adopted for transforming redshift to comoving distance.

\[
\Delta r_{\text{LOS}} = \frac{c}{H(z)} \Delta z \\
\Delta r_{\perp} = (1 + z) D_A(z) \Delta \theta \\
H(z) = H_0 \sqrt{\Omega_m a^{-3} + (1 - \Omega_m) a^{-3(1+w)}} \\
D_A(z) = \frac{c}{1 + z} r(z) = \frac{c}{1 + z} \int_0^z \frac{dz'}{H(z')} 
\]

AP = Apparent shape distortion if \( H, D_A \) are wrong.
The Alcock-Paczynski Test

Incorrect cosmology → shape distortion
and, the distortion is redshift dependent

Viewpoint from $\Lambda$CDM observer
Q: How can we find isotropic objects in the Universe?

A: Large scale distribution of galaxies!

Credit: Sloan Digital Sky Survey.
Problem of RSD

Redshift Space Distortion (RSD) produces serious anisotropy

\[ r = \int_{0}^{z_{\text{cosmo}} + \Delta z} \frac{dz'}{H(z')} \], \ \Delta z = \frac{v_{\text{LOS}}}{c} (1 + z_{\text{cosmo}})

Difficult modeling (NL clustering)
Galaxy distribution in real space

SDSS DR7 after FoF contraction, 8.8h<RA<15.7h, 0<DEC<6deg
Galaxy distribution in redshift space
RSD effects on 2-point correlation function along ($\pi$) & across ($\sigma$) LOS

Horizon-Run 4 (Kim et al. 2015, JKAS, 48, 213)
Our Option: the redshift dependence

AP Distortion
Pattern evolves with distance

RSD
Kaiser effects on large scales and FoG
effects on small scales
(pattern ~ independent of redshift)
The Alcock-Paczynski Test

Incorrect cosmology $\rightarrow$ shape distortion
and, the distortion is redshift dependent

Viewpoint from $\Lambda$CDM observer
Redshift Evolution of AP

How much radial stretch at different z?

[Viewpoint from $\Omega_m=0.31$ ΛCDM observer]

\[
\frac{[\Delta r/\Delta r_{\perp}]_{\text{wrong}}}{[\Delta r/\Delta r_{\perp}]_{\text{true}}} = \frac{[D_A(z)H(z)]_{\text{true}}}{[D_A(z)H(z)]_{\text{wrong}}}
\]
We study the gradient field of the spatial distribution of galaxies.

The anisotropy (quantified by the mean direction of gradient vectors) has redshift dependence in case of adopting wrong cosmologies.
Proof-of-concept on HR3 N-body: 2pCF

X.-D. Li, Changbom Park, Cris G. Sabiu, Juhan Kim 2015 MNRAS

No RSD, No AP:

Isotropic

RSD, No AP:

anisotropic, but no significant redshift evolution

RSD & AP:

Redshift Evolution

\[ r(z) \]

\[ s \]

\[ \theta \]

\[ \Omega_m = 0.41, \ w = -1.3 \]

\[ \mu = \cos \theta \]

\[ \xi(s, \mu) \]
II. Application to BOSS DR12 Samples

~1/4 sky, \( z \sim 0.15-0.7 \),
~1.3 million galaxies
Application to BOSS DR12 galaxies

X.-D. Li, Changbom Park, C.G. Sabiu, et al., to appear

LOWZ 8,337 deg$^2$. CMASS 9,376 deg$^2$ (~1/4 sky)

~1.13 M gals at $0.15 \leq z \leq 0.7$
Systematics

1. RSD
   (still the most significant)
2. Galaxy bias
   (affect clustering)
3. Angular variation
4. Radial variation
   (incomplete LF coverage)
5. Fiber collision (high-density regions under-sampled)

We create mock surveys to model the observational artifacts
Horizon run $N$-body

**HR3** (Kim et al. 2012)
(10.815 $h^{-1}$ Gpc)$^3$
7120$^3$ particles
WMAP5 Cosmology

**HR4** (Kim et al. 2015)
(3.15$h^{-1}$ Gpc)$^3$
6300$^3$ particles
WMAP5 Cosmology

72 mocks $\rightarrow$ covariance estimation

4 mocks $\rightarrow$ modeling systematic
MultiDark-Patchy Mocks

2048 mocks → covariance
0.15 < z < 0.7; Six z-bins

1. Adopt a \( r(z) \) [in some cosmology], construct 3D LSS
2. Measure \( \xi(s, \mu) \) in each z-bin
3. Quantify the evolution [\( \xi \) from 5 high-z bins compared to the lowest redshift]
   Wrong Cos. \( \rightarrow \) Large redshift evolution \( \rightarrow \) Disfavored
4. Try different cosmologies and repeat 1-3 \( \rightarrow \) Cosmological Constraints
Likelihood

\[
\chi^2 \equiv \sum_{i=2}^{6} \sum_{j_1=1}^{n_{\mu}} \sum_{j_2=1}^{n_{\mu}} p(z_{i}, \mu_{j_1}) \text{Cov}_{i,j_1,j_2} p(z_{i}, \mu_{j_2}),
\]

where \( p(z_{i}, \mu_{j}) \) is the redshift evolution of clustering, \( \hat{\xi}_{\Delta s} \), with systematic effects subtracted

\[
p(z_{i}, \mu_{j}) \equiv \delta \hat{\xi}_{\Delta s}(z_{i}, z_{1}, \mu_{j}) - \delta \hat{\xi}_{\Delta s, \text{sys}}(z_{i}, z_{1}, \mu_{j})
\]

Redshift evolution of 2pCF

Sys. Correction from HR4

(Comparing all redshift bins w.r.t. the lowest redshift bin)
2-d 2pCF in six redshift bins

$\Omega_m = 0.31 \Lambda$CDM

FOG at $1 - \mu \rightarrow 0$ and Kaiser at $1 - \mu > 0.1$

Similar to each other: Small redshift evolution of RSD
1-d 2pCF as a function of angle

We follow the procedure of Li et al. (2015) and integrate the $\xi$ over the interval $6 \text{ Mpc/h} < s < 40 \text{ Mpc/h}$. We evaluate

$$\xi_{\Delta s}(\mu) \equiv \int_{s_{\min}}^{s_{\max}} \xi(s, \mu) \, ds.$$  

The redshift evolution of the bias of observed galaxies leads to redshift evolution of the strength of clustering, which is difficult to accurately model. To mitigate this systematic uncertainty we rely on the shape of $\xi_{\Delta s}(\mu)$, rather than its amplitude,

$$\hat{\xi}_{\Delta s}(\mu) \equiv \frac{\xi_{\Delta s}(\mu)}{\int_0^{\mu_{\max}} \xi_{\Delta s}(\mu) \, d\mu}.$$  

Focus on angular dependence

Normalizing the amplitude; focus on shape [avoid sys from gal bias]
HR4 mock reproduces observation very well
Estimating systematic

\[ \delta \hat{\xi}_{\Delta s}(z_i, z_1, \mu_j) \equiv \hat{\xi}_{\Delta s}(z_i, \mu_j) - \hat{\xi}_{\Delta s}(z_1, \mu_j) \]

Redshift evolution from RSD, and so on

Small in most redshift bins

Relative large in the 6th bin but still correctable
Considering the large variation of $M$, effect not significant

$z = 0$ snapshot data within the radius $r < 600\ Mpc$
The Redshift Evolution

Redshift evolution from AP detected at high CL
Cosmological constraint

\[ \Omega_m = 0.301 \pm 0.006 \]

\[ w = -1.054 \pm 0.025 \]
Cosmological constraint (HR3 N-body as Covmat)

\[ \Omega_m = 0.304 \pm 0.007, \ w = -1.04 \pm 0.03. \]
Robustness Tests
Robustness Tests

Covariance from 72 HR3 mock surveys
Covariance from 36 HR3 mock surveys
Merger timescale : LC93

Merger timescale : M12
Merger timescale : V13
Merger timescale : B08

$s_{\text{max}} = 30 \ h^{-1} \text{Mpc}$
$s_{\text{max}} = 50 \ h^{-1} \text{Mpc}$
$1 - \mu \geq 0.02$

$1 - \mu \geq 0.05$
$1 - \mu \geq 0.10$
Excluding the 6th redshift bin
Comparing the different probes of geometry

**BAO:** $D_A(z)/r_d, H(z)*r_d$

**AP:** $D_A*H(z)$

**SNIa:** $D_L(z)$

**Our:** $\sim d\ D_A*H(z)/dz$

* Simple idea, successfully overcoming RSD, powerful

* ~Independent from other techniques (combinable)

* No complicate modeling

* Enter small scales (6 - 40 Mpc/h) difficult for most techniques

A lot of information encoded in small-scale clustering!
Promising application to future spectroscopic surveys
Show is over.
Thank you.