2D BAO constraints based on perturbation theory

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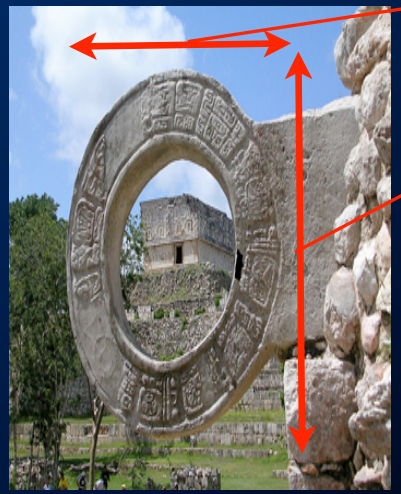
Introduction: BAOs as a Standard Ring

- Baryon Acoustic Oscillations (BAOs) in 3D galaxy distribution through spectroscopic surveys such as BOSS, SuMIRe, and WFIRST (Martin White's lecture)
- cosmological distortion Alcock & Paczynski (1979)

observer

real space

redshift space



$\propto 1/H(z)$

$\propto D_A(z)$

cf: This is famous (maybe) "Mexican Ring" that is the goal of the ancient Mayan ballgame, Pokatok at the Chichén Itzá (26hrs driving from Puerto Vallarta.)

Introduction: Redshift distortion (RSD) & Power Spectrum

- galaxy redshift survey: peculiar velocity along l.o.s. is contaminated

real space

$$\vec{s} = \vec{r} + \frac{\vec{v}\cdot\hat{z}}{aH(z)}\hat{z}$$

redshift space

line of sight direction

- RSD makes galaxy distribution statistically anisotropic

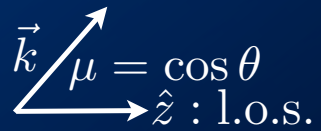
linear theory

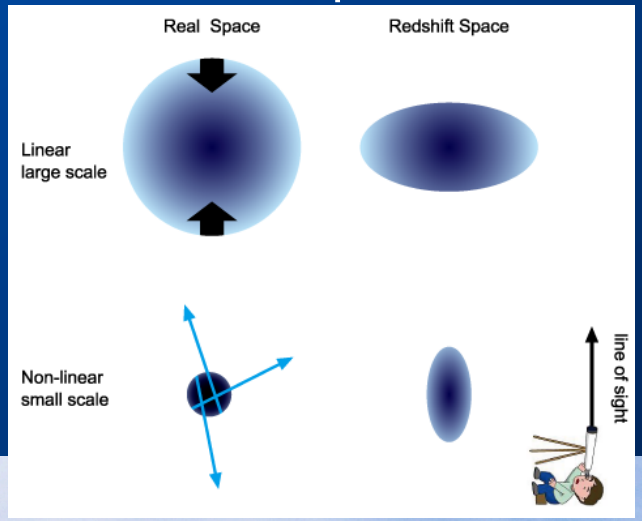
$$P(k) = \langle \delta_{\rm g}(\mathbf{k})^2 \rangle \rightarrow \quad P^S(k,\mu) = b^2\left(1+\frac{f}{b}\mu^2\right)^2 P^L_{\rm m}(k)$$

Gravity Test
(Ed.Bertschinger's lecture)

$$f \equiv \frac{d\ln D(a)}{d\ln a} \simeq \Omega_{\rm m}(z)^\gamma$$

- intuitive picture

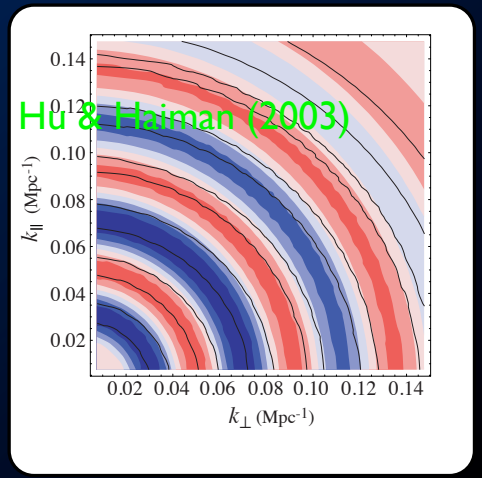




Large scale: Squashing effect
- amplitude become larger

Kaiser (1987)

Small scale: Finger-of-God
- amplitude becomes smaller



Hu & Haiman (2003)

Questions

- Can we model accurately nonlinear redshift-space power spectrum around BAO scales?

→ We propose a new model based on perturbation theory which works well up to $k<0.2h/\mathrm{Mpc}$

- How can we use full 2D BAO information?

→ Based on Fisher matrix analysis, we compare entire 2D information with use of multipole spectra.

- What is the actual constraint on the BAO ring?

→ We are applying our model to the SDSS DR7 data to constrain D_A & H separately.

Modeling of RSD based on perturbation theory

- What makes the problem complicated?

  - nonlinear mapping from real to redshift space $$J \simeq \left(1 + \frac{\partial}{\partial z}\left[\frac{\vec{v}\cdot\hat{z}}{aH(a)}\right]\right)^{-1}$$

- Exact expression & previous works

velocity field

$$P^S(k,\mu) = \int d^3\mathbf{x}\, e^{i\mathbf{k}\cdot\mathbf{x}} \langle e^{-ik\mu f \Delta u_z} \{\delta(\mathbf{r}) - f\nabla_z u_z(\mathbf{r})\}\{\delta(\mathbf{r}') - f\nabla_z u_z(\mathbf{r}')\}$$

standard PT Heavens, Verde, Mataresse (1998)

$$P^S(k,\mu) = \left(1 + f\mu^2\right)^2 P^{\rm L}_{\rm m}(k) + P^S_{1\,\rm loop}(k,\mu)$$

empirical formula Scoccimarro (2004)

$$P^S(k,\mu) = \underbrace{e^{-k^2 f^2 \sigma^2_{\rm V,L}\mu^2}}_{\text{FOG factor}} \underbrace{\left[P_{\delta\delta}(k) + 2f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\delta\theta}(k)\right]}_{\text{nonlinear Kaiser factor}}$$

New model

Taruya, Nishimichi, S.S. (2010)

$$P^S(k,\mu) = e^{-(kf\mu\sigma_v)^2}\left[P_{\delta\delta}(k) + 2f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) + \underline{A(k,\mu;f) + B(k,\mu;f)}\right]$$

"nonlinear" velocity dispersion treated as a "free parameter"

correction terms

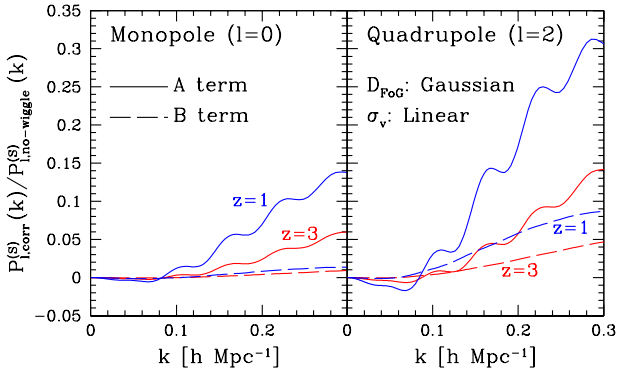
$$A(k,\mu) = (k\mu\, f)\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\,\frac{p_z}{p^2}$$

up to μ^6

$$\times\left\{B_\sigma(\boldsymbol{p},\boldsymbol{k}-\boldsymbol{p},-\boldsymbol{k}) - B_\sigma(\boldsymbol{p},\boldsymbol{k},-\boldsymbol{k}-\boldsymbol{p})\right\}$$

$$\left\langle \theta(\boldsymbol{k}_1)\left\{\delta(\boldsymbol{k}_2) + f\,\frac{k_{2z}^2}{k_2^2}\theta(\boldsymbol{k}_2)\right\}\left\{\delta(\boldsymbol{k}_3) + f\,\frac{k_{3z}^2}{k_3^2}\theta(\boldsymbol{k}_3)\right\}\right\rangle$$

$$= (2\pi)^3\delta_D(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)\,B_\sigma(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3). \quad (21)$$



$$B(k,\mu) = (k\mu\, f)^2\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}F(\boldsymbol{p})F(\boldsymbol{k}-\boldsymbol{p})\ ;$$

up to μ^8

$$F(\boldsymbol{p}) = \frac{p_z}{p^2}\left\{P_{\delta\theta}(p) + f\,\frac{p_z^2}{p^2}\,P_{\theta\theta}(p)\right\}$$

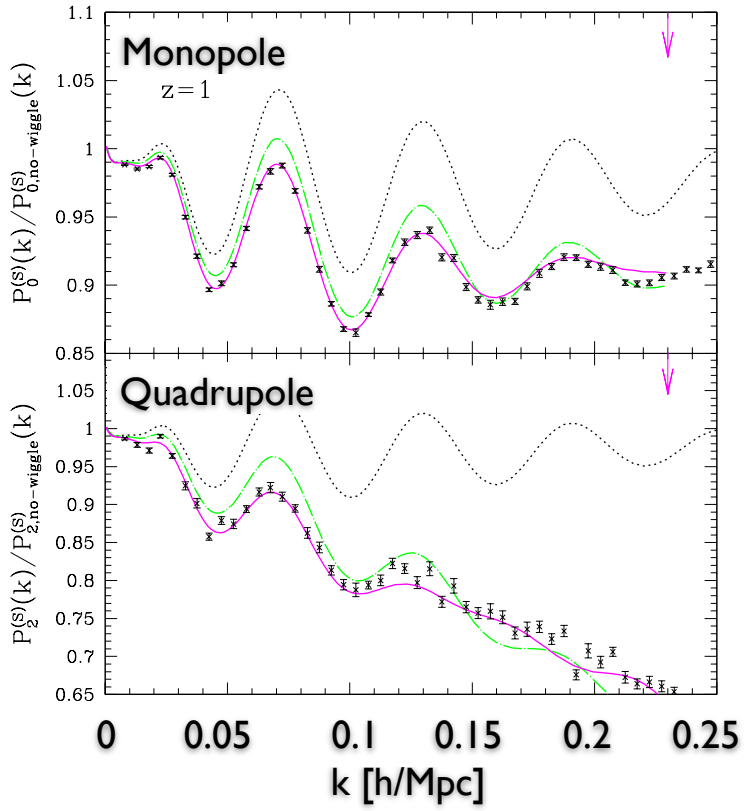
A: anti-phase correction

B: small amplitude (<1-2%)

Note: includes higher order of μ

Performance of New model

Taruya, Nishimichi, S.S. (2010)



Linear theory

New model

w/o A & B terms

Multipole expansion

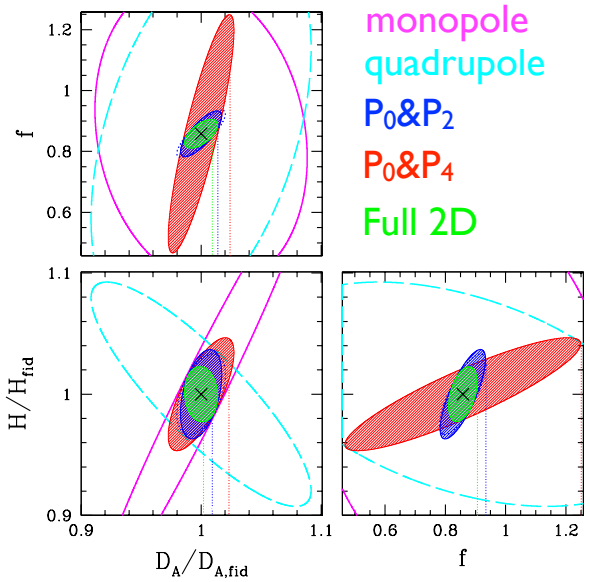
$$P(k,\mu) = \sum_{\ell=0}^{\text{even}} P_\ell(k)\,\mathcal{P}_\ell(\mu)$$

A & B terms are important to explain the BAO feature at very large scales, k < 0.1h/Mpc.

For monopole & quadrupole, the new model looks successful within the valid range of PT.

How many multipoles are important? Taruya, S.S., Nishimichi, to appear soon!

- The BAO forecast relies on using entire 2D information. Seo & Eisenstein (2003,2007) etc
- Nonlinearity induces higher order terms of μ than μ^4.
- Higher order multipole has lower S/N but helpful to break degeneracy.

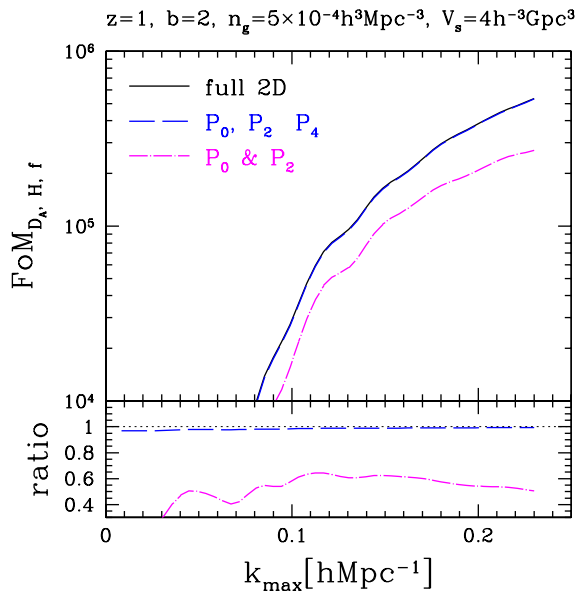


monopole
quadrupole
P_0&P_2
P_0&P_4
Full 2D

monopole
: sensitive to D_A^2/H

quadrupole
: sensitive to D_AH

See, eg., Padmanabhan & White (2008)



up to hexadecapole (l=4) is enough!

l=4 has small S/N but contribute to 40% information, because of breaking degeneracy

Application to the data

S.S++ in prep

- Modeling issue

- Monopole: Percival++(2009) eliminated smooth P(k) using cubic B-spline.

- Quadrupole: cosmological distortion can change the amplitude. Padmanabhan & White (2008)

- Our approach: simply apply our model to multipole spectra.

Galaxy Bias: simply assume linear scale-dependent bias $b(k)=b_0+b_1*k^c$

- Free parameters (D_A, H, f, σ_v, b_0, b_1, c) implemented in COSMOMC (L.Verde's lecture)

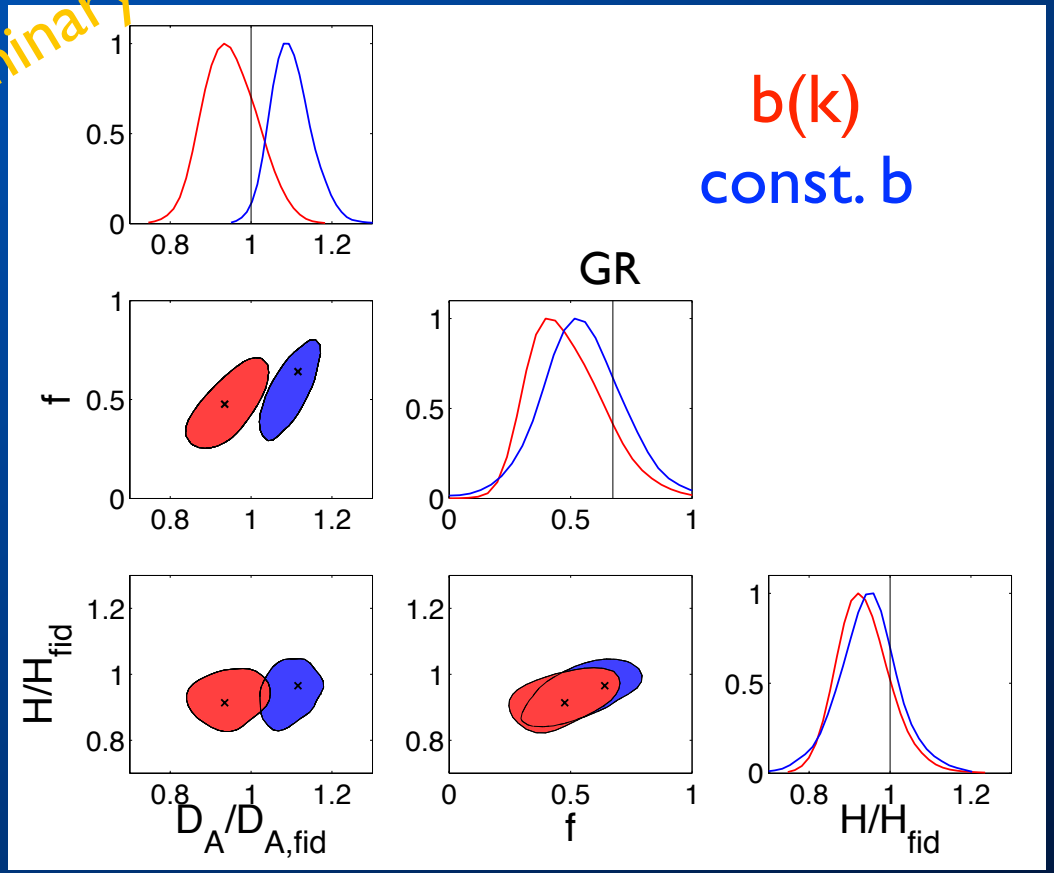
- Measurement issue

- definition of l.o.s: Yamamoto++(2006) developed a method to measure multipoles.

- SDSS DR7 100,157 LRGs (7150 deg^2)

Results

S.S++ in prep



- 2D BAO constraint
  - ΔD_A~5% & ΔH~5% (Note $\Delta D_A^2/H$~4%)
  - $r(D_A,H)$~0.28 expected from forecast
- gravity test
  - f = 0.455±0.166

    c.f. GR: f=0.674
  - Note: in the case of k_{min}=0.055

    f = 0.587±0.255

Conclusions

- We propose a new model of RSD based on PT.
- Even if nonlinearity is taken into account, the full 2D information are almost identical to the multipole expansion up to hexadecapole (l=4).
- We apply our model to the SDSS DR7 multipole power spectrum in order to constrain 2D BAO scale "(D_A,H)" & growth parameter "f".
- This is a nice example that shows the lectures in this school are extremely useful.