Halo approach and Test of Gravity with Rredshift-Space Distortions

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and collaboration with G. Huetsi, A. Terukina, T. Kanemaru, C. Hikage, A. Oka, et al.

- 1. Introduction of RSD
- 2. Halo approach
- 3. New test of gravity
- 4. Summary and conclusions

1. Introduction

Redshift-space distortions   Test of gravity theory

peculiar velocity of galaxy $\vec{V}$
shifts the redshift by the Doppler effect

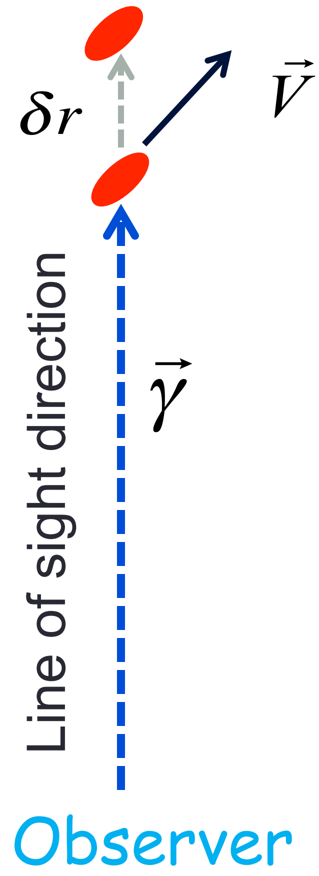
$$\delta z = (1+z)\vec{\gamma}\cdot\vec{V}$$

shift of the radial position in redshift space

$$s = r + \delta r$$

$$\delta r = \frac{\delta z}{H(z)} = \frac{(1+z)\vec{\gamma}\cdot\vec{V}}{H(z)}$$

Galaxies distribution in the redshift-space
is different from that in the real-space



Linear (redshift-space) distortion (Kaiser 1987)

Within the linear theory of density perturbations, V is connected with δ, and this RSD reflects the growth rate of density perturbation

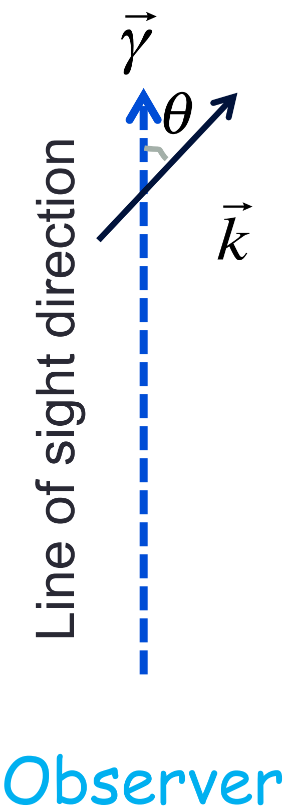
galaxy power spectrum with linear distortion

$$P^s(k,\mu) = (b + f\mu^2)^2 P_{linear}(k)$$

$$f = \frac{d \ln \delta(a)}{d \ln a}$$

μ is the directional cosine between the line of sight direction and the wave number vector

$$\mu = \frac{\vec{k}\cdot\vec{\gamma}}{|\vec{k}|} = \cos\theta$$



Correlation becomes anisotropic !

galaxy density contrast in redshift-space

$$\tilde{\delta}_g^s = \tilde{\delta}_g^r + \mu^2 f \tilde{\delta}$$

$$\tilde{\delta}_g^r = b\tilde{\delta}$$

galaxy density contrast in real-space

$$\frac{\partial \delta(t,x)}{\partial t} + \frac{1}{a}\nabla\cdot\vec{V}(t,x) = 0$$

$$s = r + \delta r = r + \frac{\vec{\gamma}\cdot\vec{V}}{aH}$$

$$\bar{n}_g\left(1+\delta_g^s\right)dss^2 = \bar{n}_g\left(1+\delta_g^r\right)drr^2$$

Multipole power spectrum → anisotropy

$L_\ell(\mu)$ Legendre Polynomial

$$P^s(k,\mu) = \sum_{\ell=0,2,4...} P_\ell(k) L_\ell(\mu)(2\ell+1)$$

Within linear theory

Kaiser (87)

$$P(k,\mu) = (b + f\mu^2)^2 P_{linear}(k)$$

$P_0(k)$ monopole → $P_0(k) = \left(b^2 + \frac{2}{3}bf + \frac{1}{5}f^2\right) P_{linear}(k)$

$P_2(k)$ quadrupole → $P_2(k) = \left(\frac{4}{15}bf + \frac{4}{35}f^2\right) P_{linear}(k)$

$P_4(k)$ hexadecapole → $P_4(k) = \frac{8f^2}{315} P_{linear}(k)$

$P_6(k)$ tetrahexadecapole → $P_6(k) = 0$

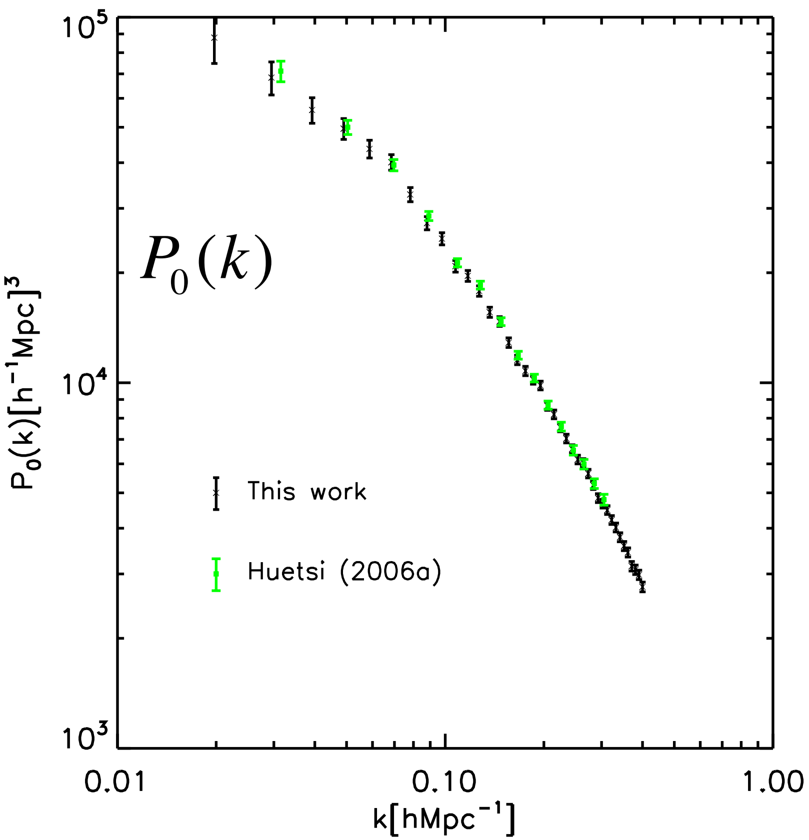
Growth rate f can be measured using multipole spectrum

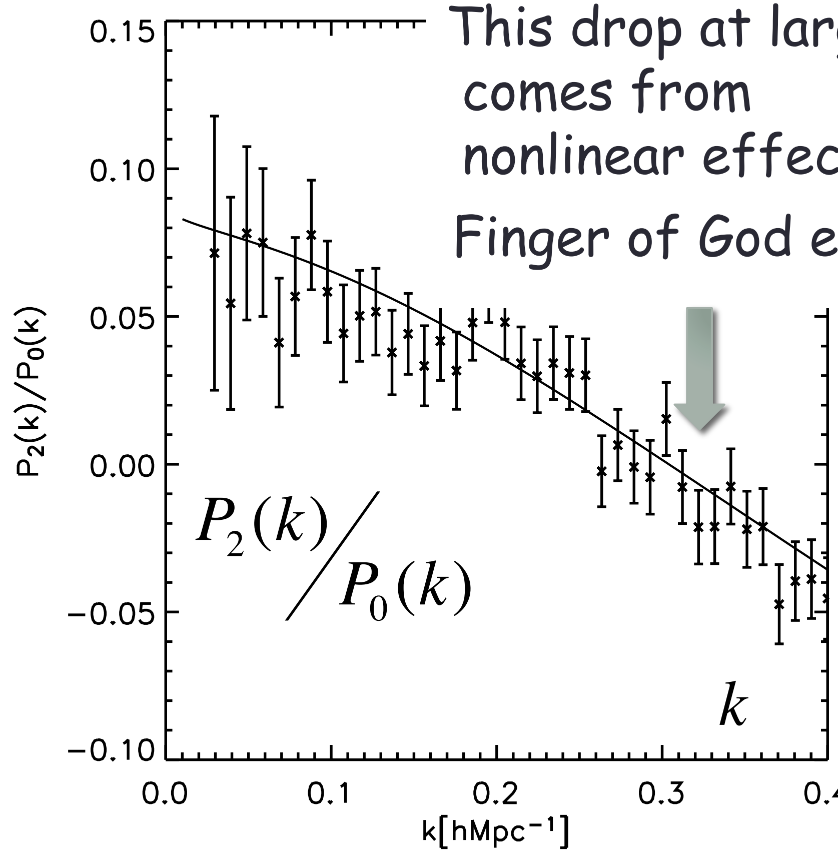
Linear theory predicts $$\frac{P_2(k)}{P_0(k)} = \frac{\frac{4}{15}bf + \frac{4}{35}f^2}{b^2 + \frac{2}{3}bf + \frac{1}{5}f^2} = const.$$

Test of gravity with $P_\ell(k)$

Yamamoto, Sato, Huetsi (08)
(cf. Gozzo et al., 08)

SDSS II DR5 luminous red galaxy (LRG) sample power spectrum





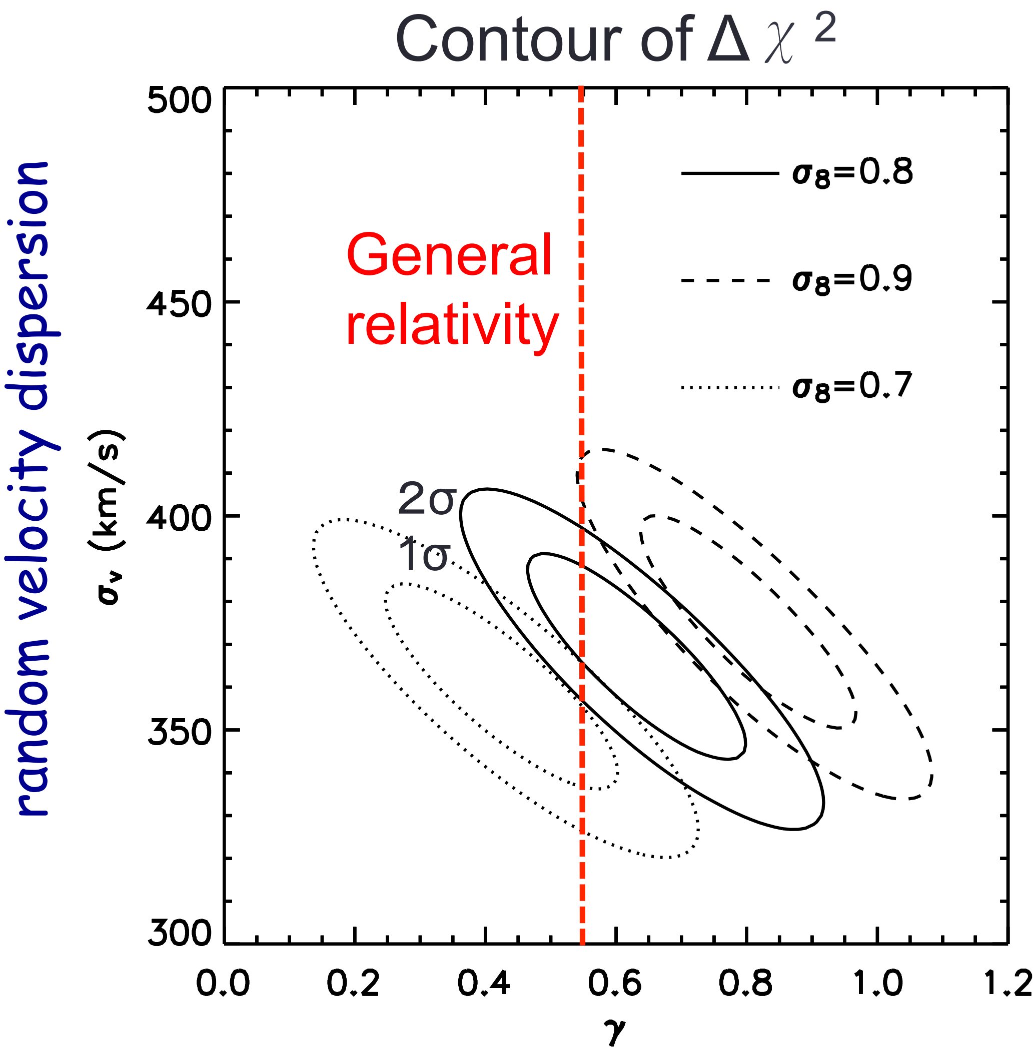
This drop at large k comes from nonlinear effect

Finger of God effect

Test of general relativity

Test of general relativity

KY, Sato, Huetsi (2008)



$$f(a) = \frac{d\ln\delta(a)}{d\ln a}$$

$$= [\Omega_m(a)]^\gamma$$

Within general relativity

$$\gamma = 0.55 - 0.56$$

reproduces the exact formula well.

Test of f(R) gravity

(Yamamoto, Nakamura, Huetsi, Narikawa, Sato, 2010)

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[R + f(R)\right] + \int d^4x\sqrt{-g}L_m$$

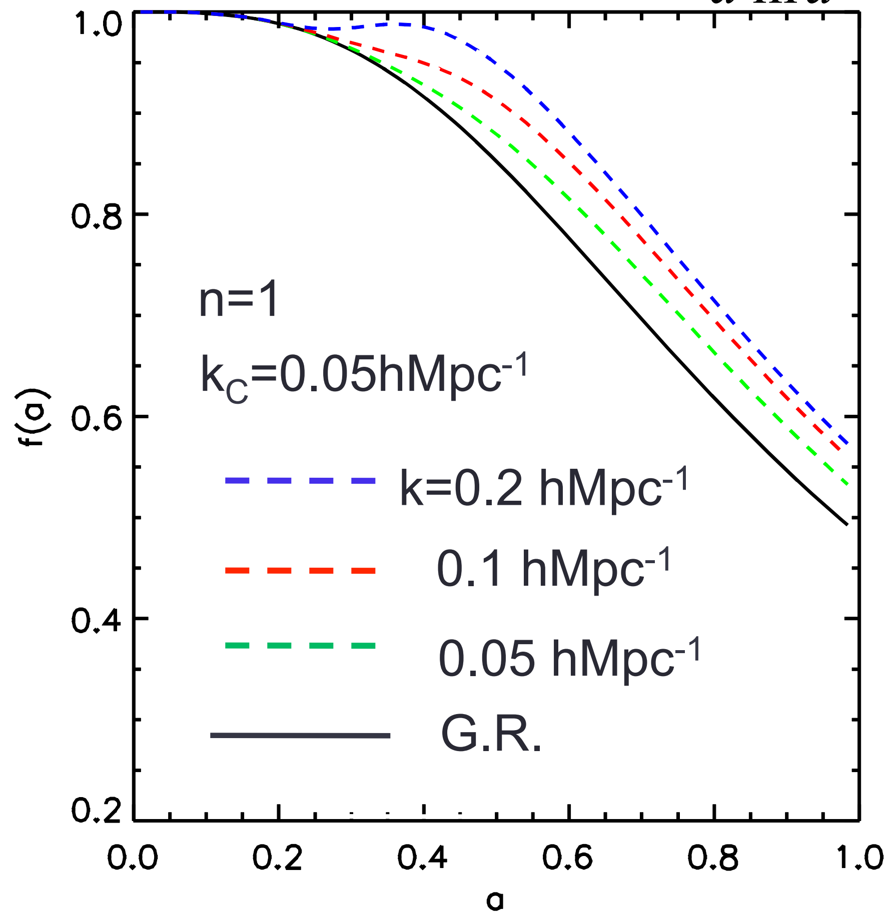
A parameter of the theory is the effective mass of the new degree of freedom,
The effective mass determines a characteristic Compton wavenumber

$\left(k << k_c = m_{eff}^{-1}\right)$ general relativity

$\left(k >> k_c = m_{eff}^{-1}\right)$ Modified gravity

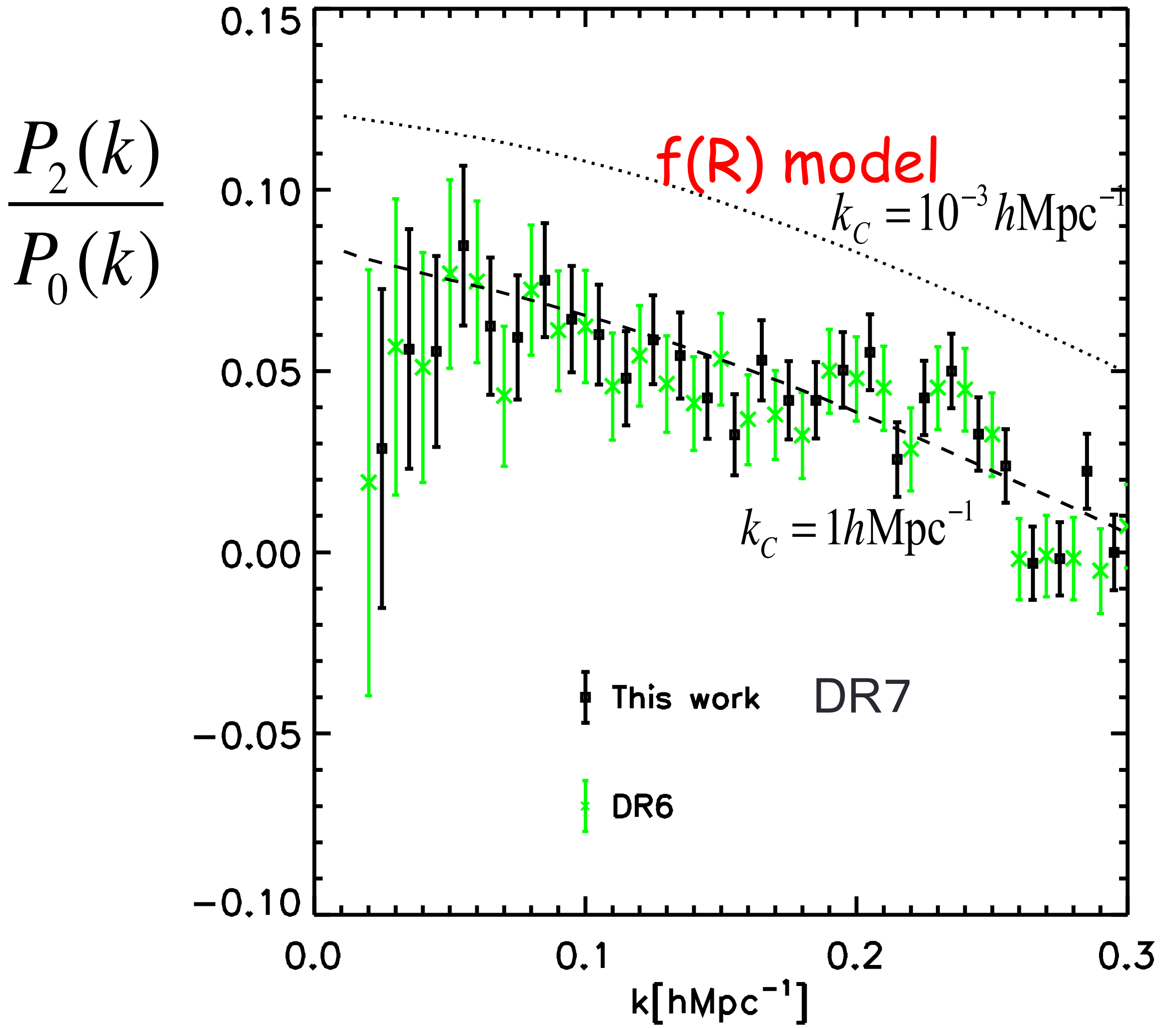
$$\frac{G_{eff}}{G_N} = \frac{4}{3}$$

growth rate $f = \dfrac{d\ln D_1}{d\ln a}$



Constraint of f(R) gravity

(Yamamoto, Nakamura, Huetsi, Narikawa, Sato, 2010)



$$k_C \le 0.04\,h\mathrm{Mpc}^{-1}$$

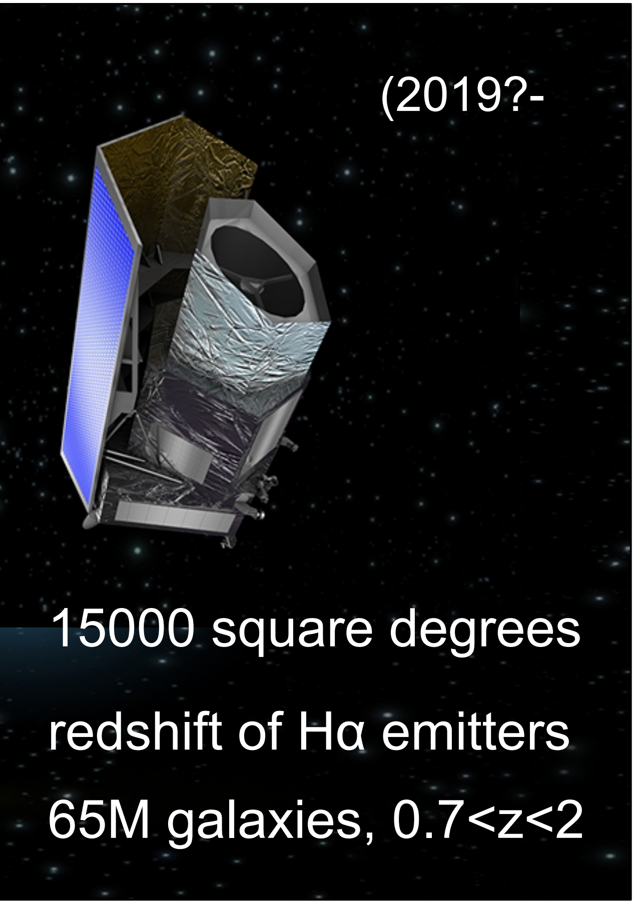
$$(|f_{R0}| \lesssim 10^{-4})$$

More robust constraint

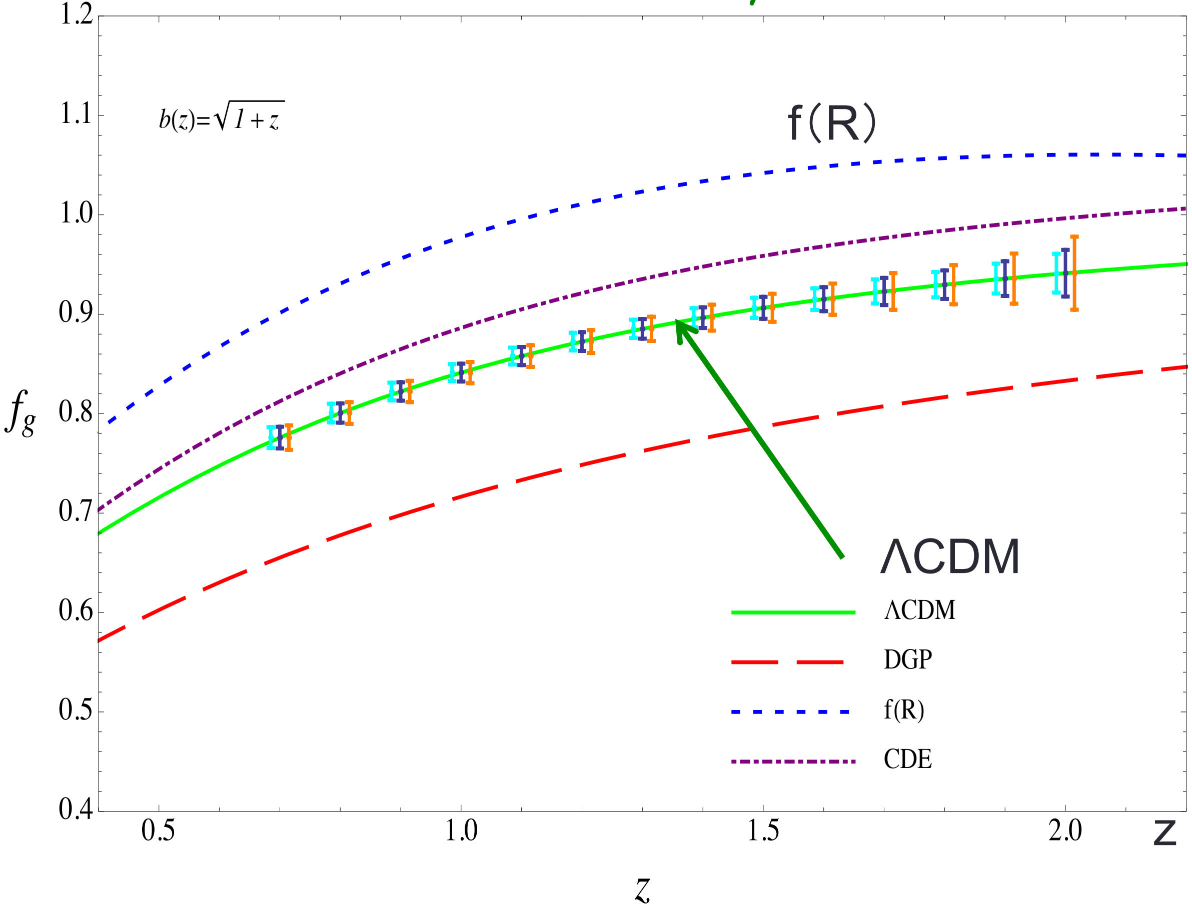
Influences of systematics

(cf. Taruya-san's talk, Oka et al., 2014)

Future prospect with Euclid satellite



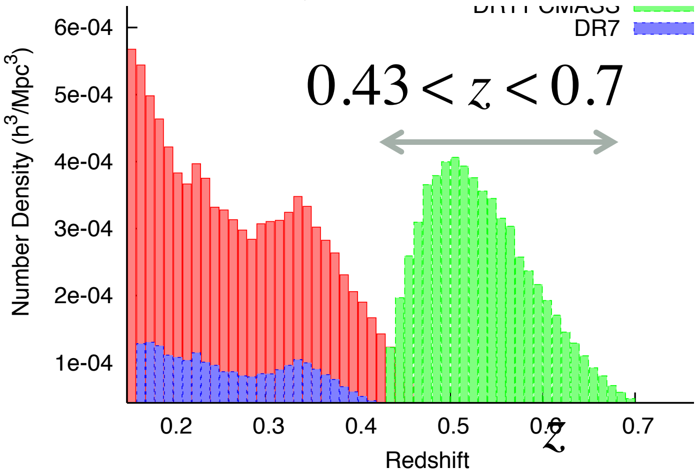
Amendola et al., arXiv:1206.1225



Measurements of the redshift-space distortions is expected to be a promising way for testing gravity.

SDSS BOSS DR11 CMASS sample

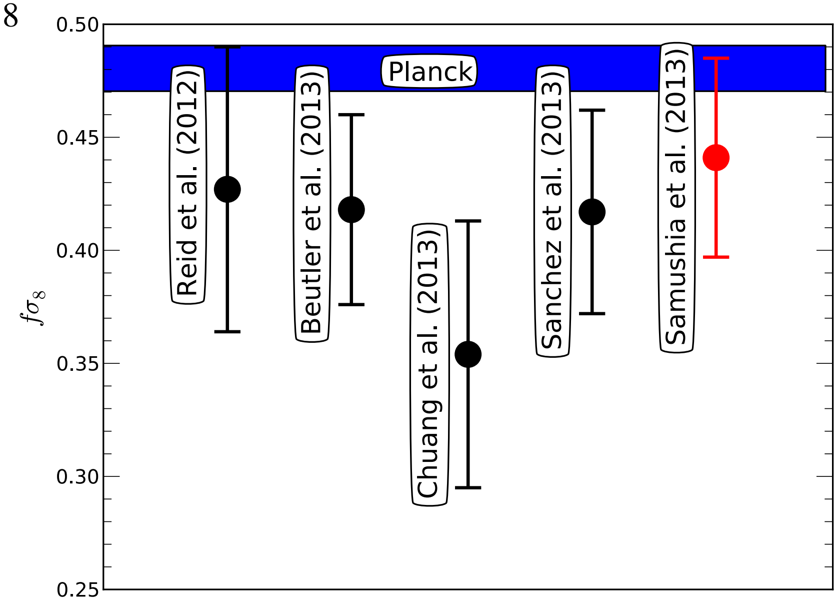
Number density



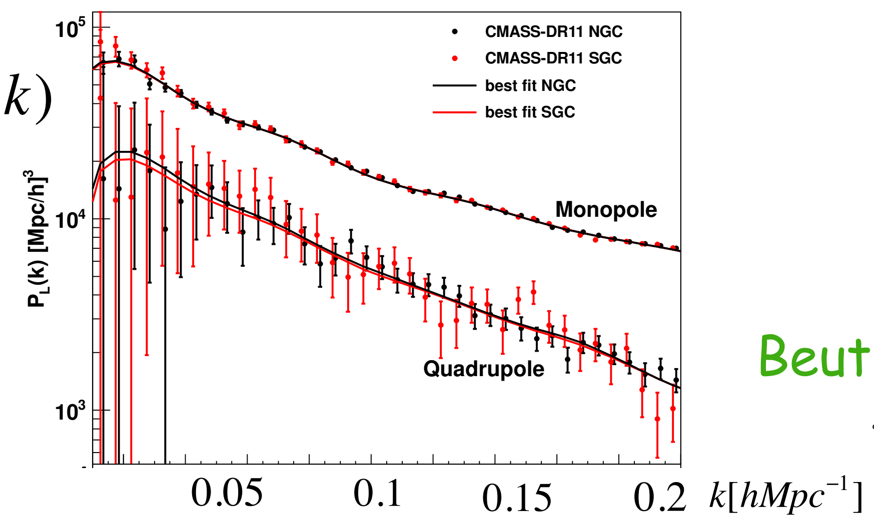
Chuang et al. (2013)

Samushia et al (2013)

$f\sigma_8$



$P_\ell(k)$



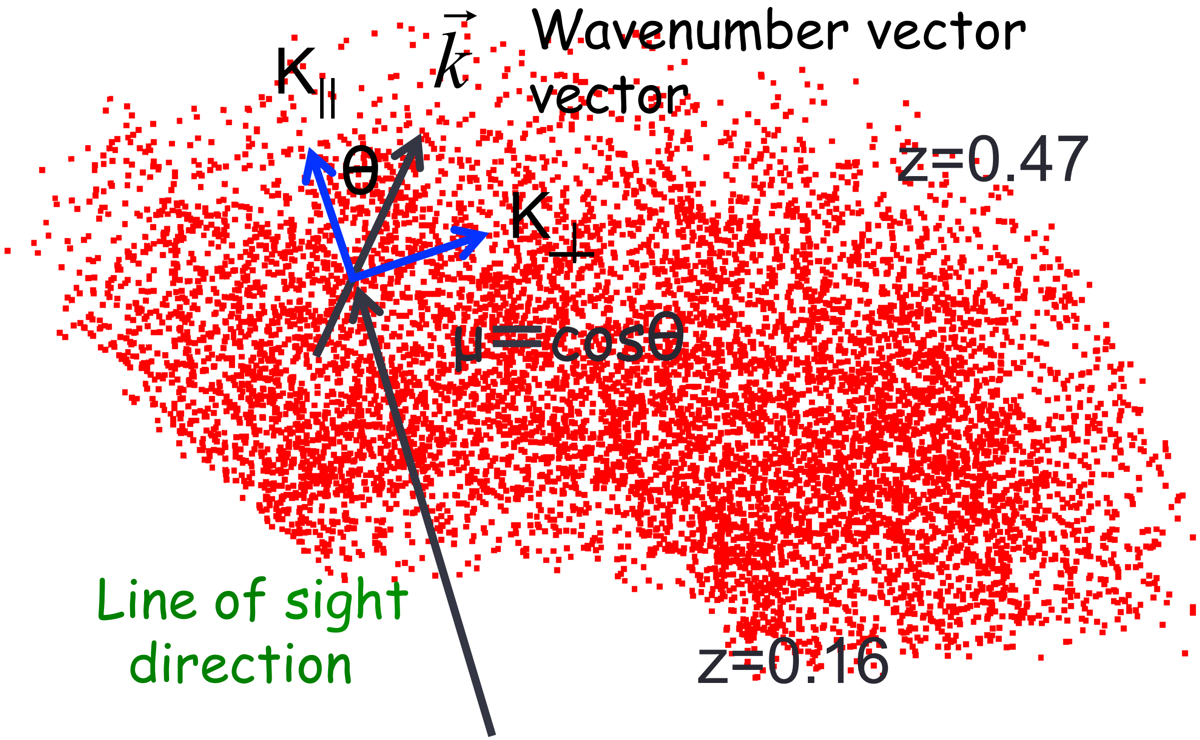
Constraint on $f\sigma_8$ smaller than Planck prediction

Beutler et al.(2013)

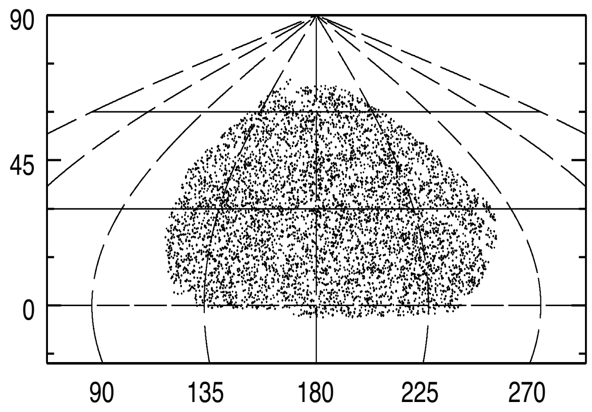
Tension between Planck and Galaxy

Multipole power spectrum analysis of SDSS luminous red galaxy (LRG) sample

(K.Y., Sato, Huesti 2008-)
(K.Y.+ 2010)

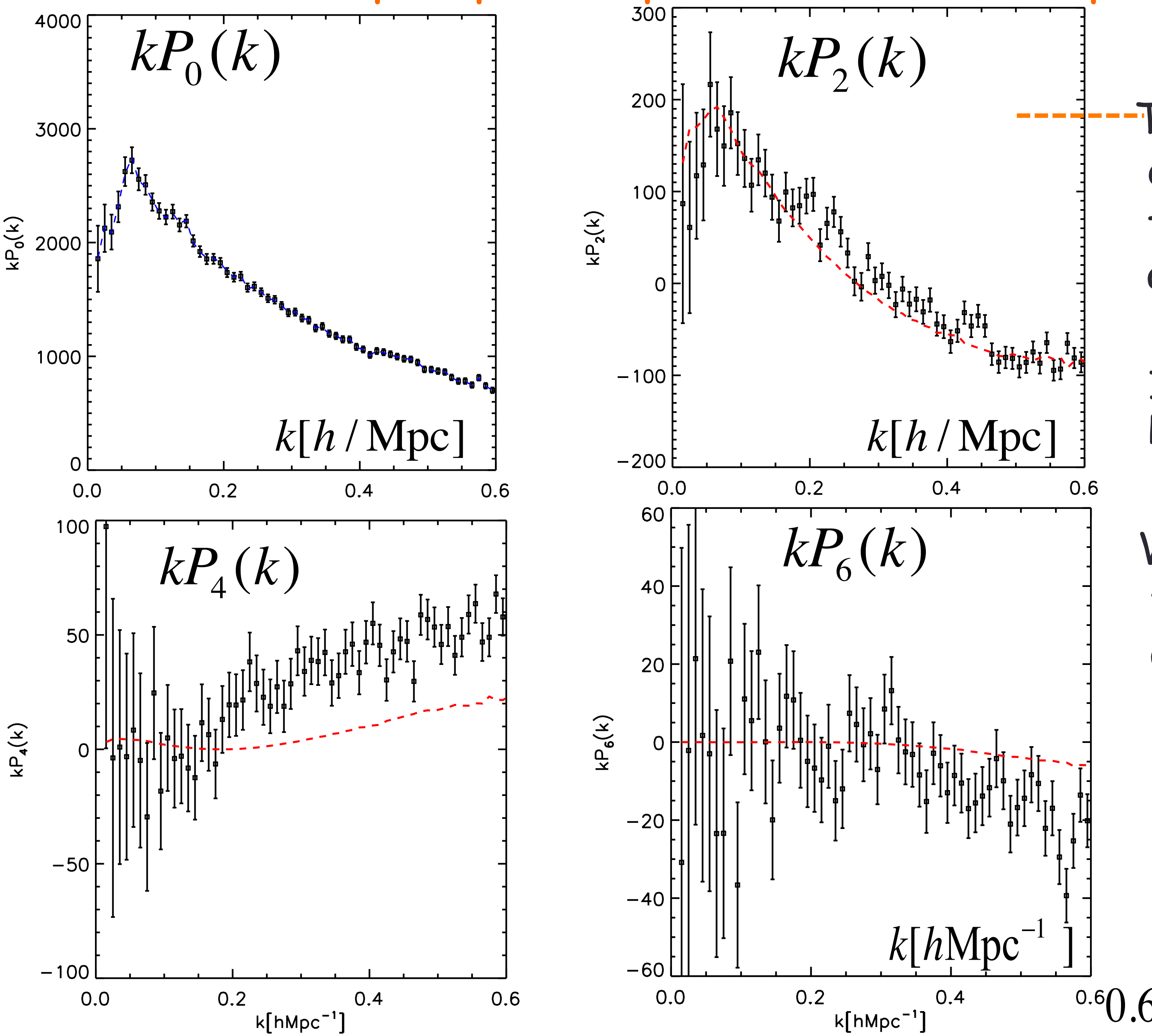


10^5 galaxies
7150 degree^2



An algorithm to measure the multipole power spectrum. (K.Y., et al, 2006)

Problem in multipole power spectrum of LRG sample (SDSS DR7)

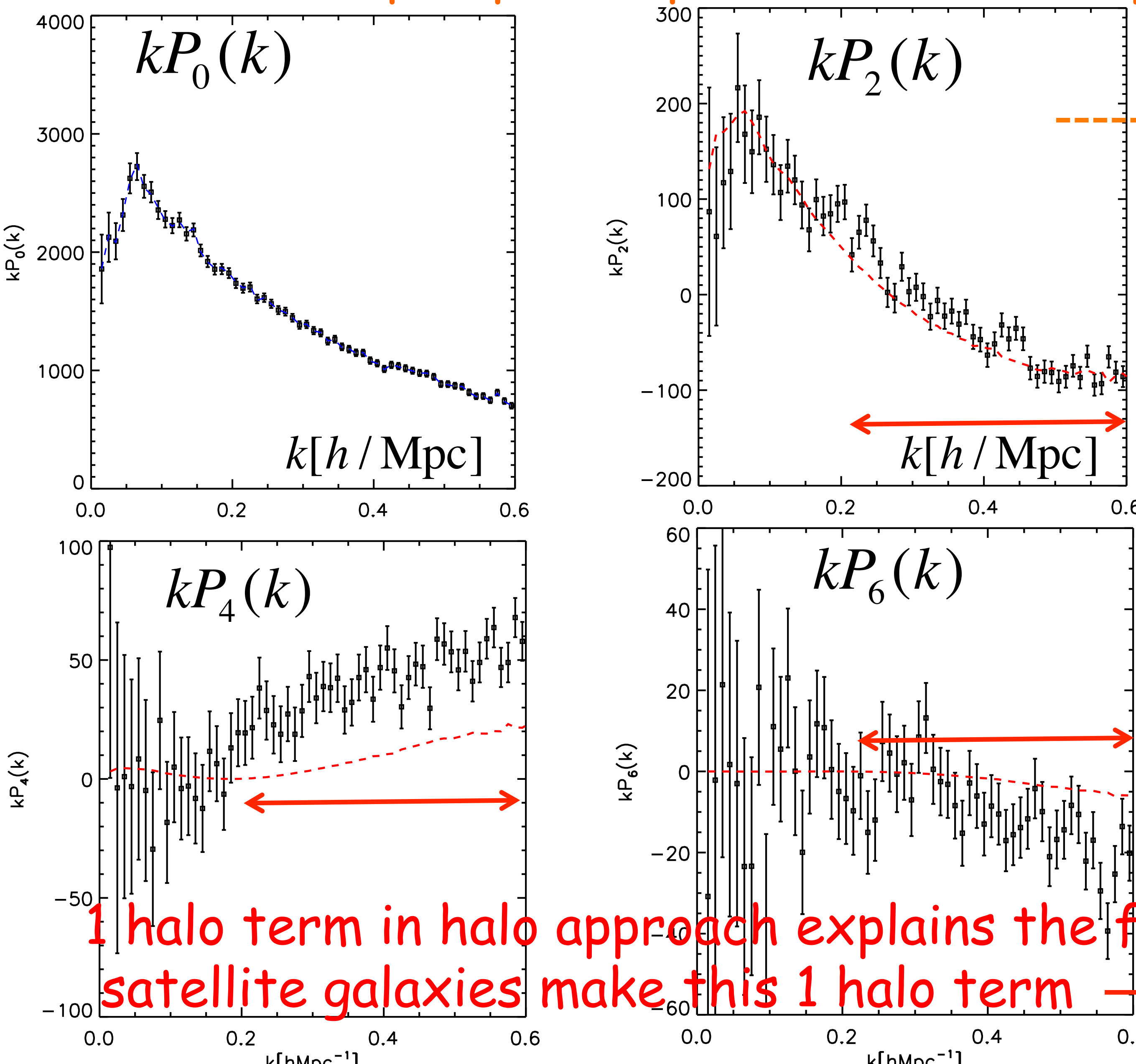


Theoretical model does not fit all the spectra at the same time.

In the linear theory, $P_6(k)=0$

What determines the feature at large k?

Problem in multipole power spectrum of LRG sample (SDSS DR7)



Theoretical model does not fit all the spectra at the same time.

In the linear theory, $P_6(k)=0$

What determines the feature at large k?

(Hikage and KY. 2013)

1 halo term in halo approach explains the feature at large k

satellite galaxies make this 1 halo term → gravity test

2. Halo approach

Every DM and galaxy reside in a dark matter halo, their distribution is described on the basis of the halo density profile $\rho(r, M)$ with mass M and halo's correlation

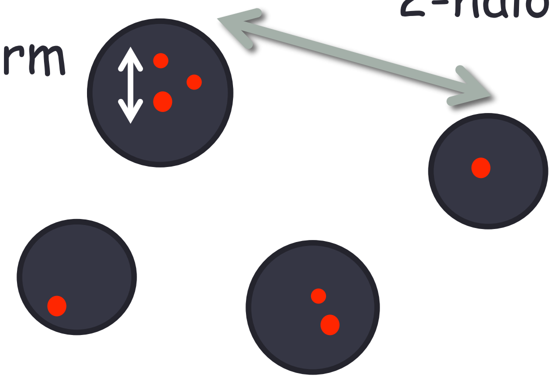
Two point correlation is modeled as the sum of the contribution from the pairs in the same halo (1 halo term), and from the pairs in the different halos (2 halo term)

$$\xi(r) = \xi^{1h}(r) + \xi^{2h}(r)$$

$$P(k) = P^{1h}(k) + P^{2h}(k)$$

1-halo term

$\xi^{1h}(r)$ → $P^{1h}(k)$



2-halo term

$\xi^{2h}(r)$ → $P^{2h}(k)$

1-halo term is the convolution of the density profile of DM or galaxy

$$\xi^{1h}(\vec{r}) = \frac{1}{\bar{\rho}^2} \int dM \frac{dn(M)}{dM} \int d\vec{y} \rho(|\vec{y}|, M) \rho(|\vec{y} + \vec{r}|, M)$$

$$P^{1h}(k) = \frac{1}{\bar{\rho}^2} \int dM \frac{dn(M)}{dM} |u(k, M)|^2$$

Fourier Transform

$$u(k, M) = \frac{1}{(2\pi)^{3/2}} \int d\vec{y} \rho(|y|, M) e^{i\vec{k}\cdot\vec{y}}$$

galaxy correlation in halo model needs

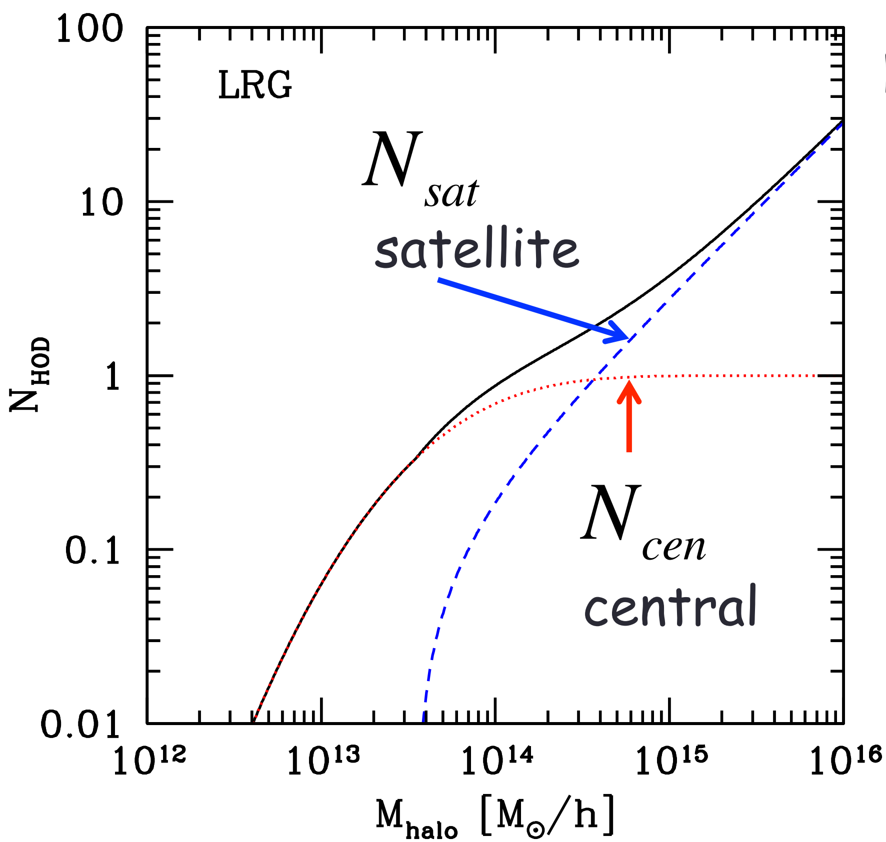
Halo occupation distribution (HOD)

Probability of galaxy number in a halo with mass M

Satellite galaxy (moving in a halo with random velocity)

Central galaxy located in the center of a halo, and the random velocity is negligible.

LRG



Number of LRGs in a halo with mass M

(Zheng, etal. 05, Zehavi, et al Reid, Spergel 09)

$$N_{cen} = \frac{1}{2}\left[1 + erf\left(\frac{\log_{10} M - \log_{10} M_{\min}}{\sigma_{\log M}}\right)\right]$$

$$N_{sat} = \left(\frac{M - M_{cut}}{M_1}\right)^{\alpha}$$

Satellite fraction is 5% in the total LRGs

Power spectrum in redshift-space $P(k,\mu)=P^{1h}(k,\mu)+P^{2h}(k,\mu)$

1-halo term

Central-Satellite Satellite-Satellite

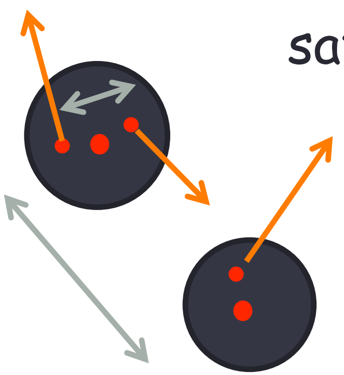
$$P^{1h}(k,\mu)=\frac{1}{\bar{n}^2}\int dM\,\frac{dn(M)}{dM}\left(2N_{cen}N_{sat}\,p(k,\sigma_V,M)+N_{sat}^2\,p(k,\sigma_V,M)^2\right)$$

Finger of God effect

2-halo term

$$P^{2h}(k,\mu)\cong\frac{1}{\bar{n}^2}\left[\int dM\,\frac{dn(M)}{dM}\langle N_{cen}\rangle\left(1+\langle N_{sat}\rangle p(k,\sigma_V,M)\right)\left(b(M)+f\mu^2\right)\right]^2 P_m(k)$$

Linear distortion



satellite galaxies have random velocity

Finger of God

RSD

Probability distribution function of random velocity V of satellite galaxy in a halo with mass M

$$F(V_\parallel)=\frac{1}{\sqrt{2\pi}\sigma_V(M)}\exp\left[-\frac{V_\parallel^2}{2\sigma_V^2(M)}\right]$$

Randomly mapped

$$s_\parallel=r_\parallel+V_\parallel/aH$$

$$p(k,\sigma_V,M)\cong u(k,M)\exp\left[-\frac{\sigma_V^2(M)k^2\mu^2}{2a^2H^2}\right]$$

Power spectrum in redshift-space $P(k,\mu)=P^{1h}(k,\mu)+P^{2h}(k,\mu)$

1-halo term

Central-Satellite — Satellite-Satellite

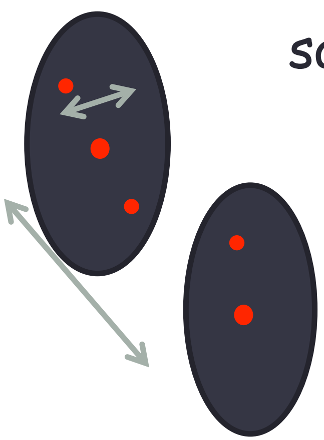
$$P^{1h}(k,\mu)=\frac{1}{\bar{n}^2}\int dM\,\frac{dn(M)}{dM}\left(2N_{cen}N_{sat}\,p(k,\sigma_V,M)+N_{sat}^2\,p(k,\sigma_V,M)^2\right)$$

Finger of God effect

2-halo term

$$P^{2h}(k,\mu)\cong\frac{1}{\bar{n}^2}\left[\int dM\,\frac{dn(M)}{dM}\langle N_{cen}\rangle\left(1+\langle N_{sat}\rangle\,p(k,\sigma_V,M)\right)\left(b(M)+f\mu^2\right)\right]^2 P_m(k)$$

Linear distortion



satellite galaxies have random velocity → Finger of God RSD

Probability distribution function of random velocity V of satellite galaxy in a halo with mass M

$$F(V_\parallel)=\frac{1}{\sqrt{2\pi}\sigma_V(M)}\exp\left[-\frac{V_\parallel^2}{2\sigma_V^2(M)}\right]$$

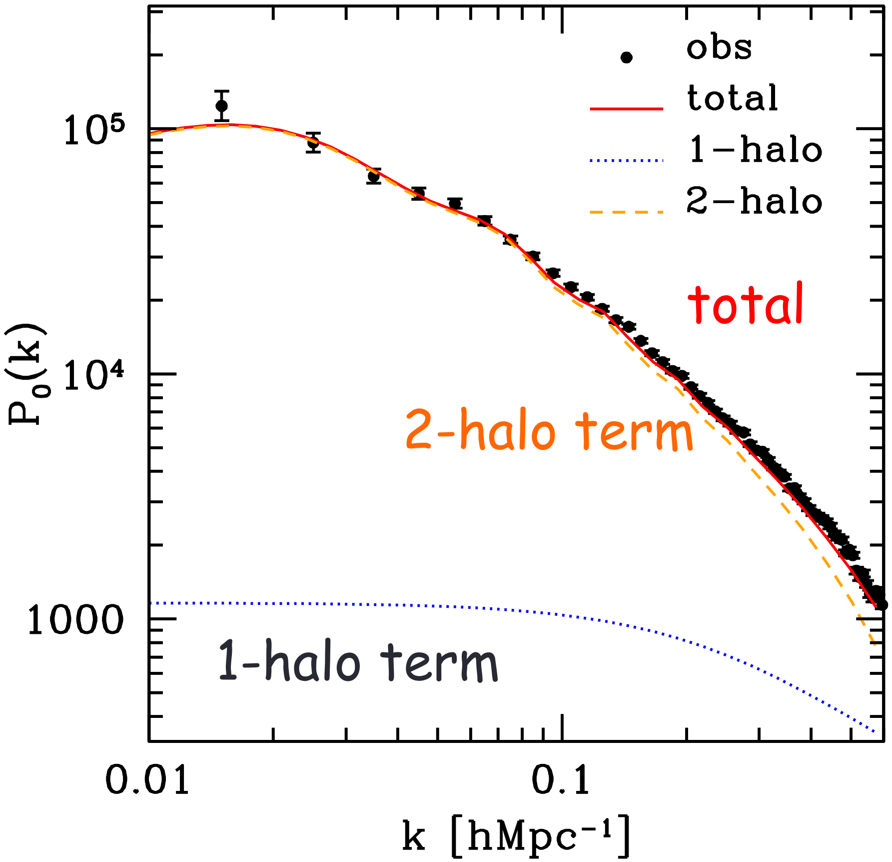
Fourier transform of elongated satellite distribution

$$s_\parallel=r_\parallel+V_\parallel/aH$$

$$p(k,\sigma_V,M)\simeq u(k,M)\exp\left[-\frac{\sigma_V^2(M)k^2\mu^2}{2a^2H^2}\right]$$

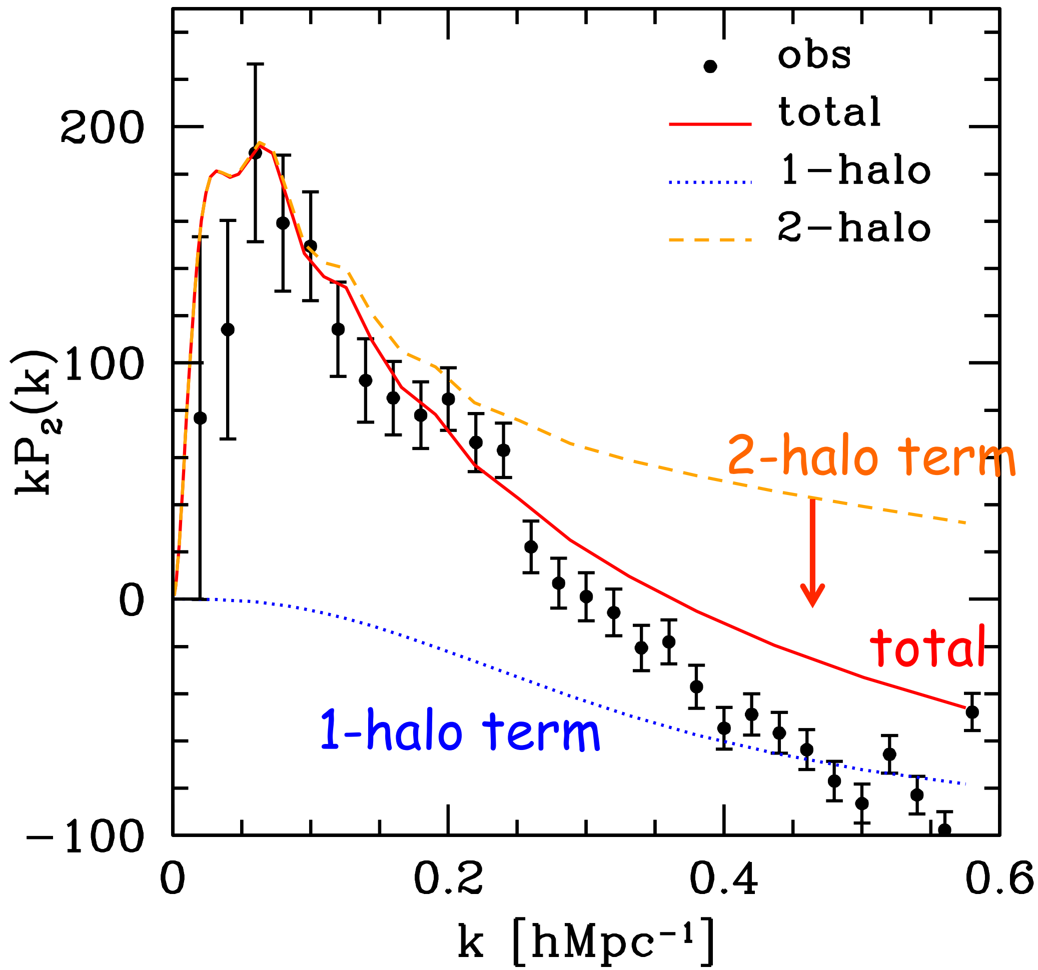
Monopole power spectrum

$P_0(k)$ Comparison with LRG sample



No significant contribution of 1-halo term to the monopole spectrum (a few times 10 % level)

$kP_2(k)$ Quadrupole spectrum

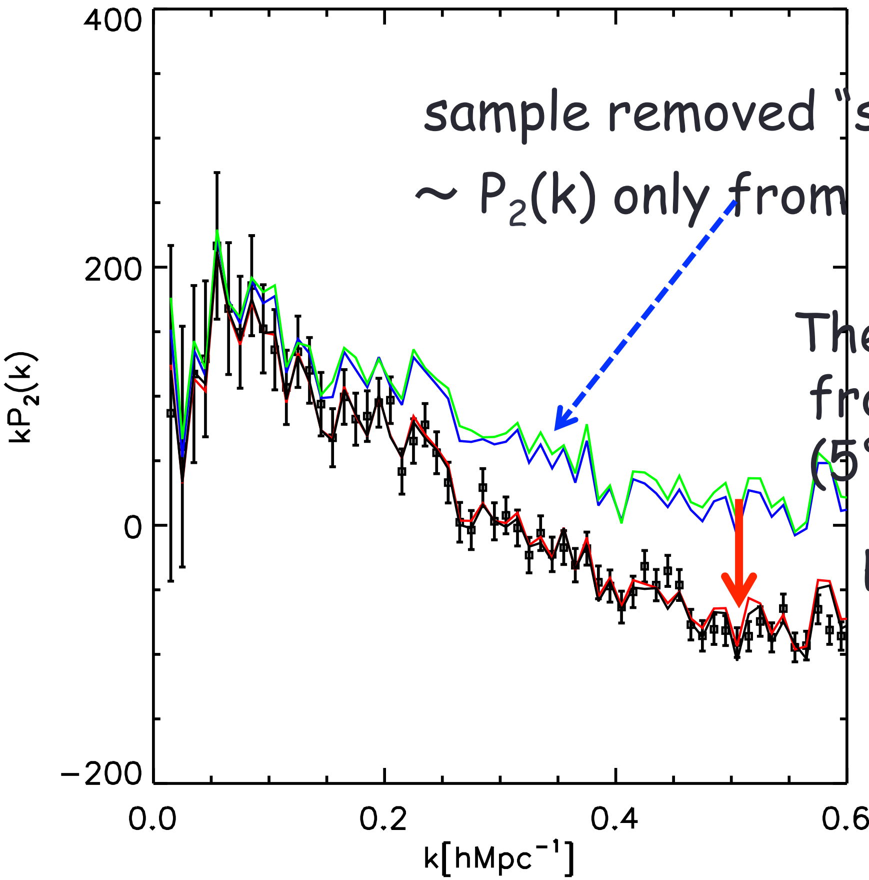


Significant contribution of 1-halo term to quadrupole spectrum at large k ($k>0.2hMpc^{-1}$)

Possible contribution at quasi-linear regime ($k<0.2hMpc^{-1}$)

Significant contribution of 1-halo term to the quandrupole is confirmed by observational data

$kP_2(k)$



sample removed "satellite" galaxies

~ $P_2(k)$ only from 2 halo term

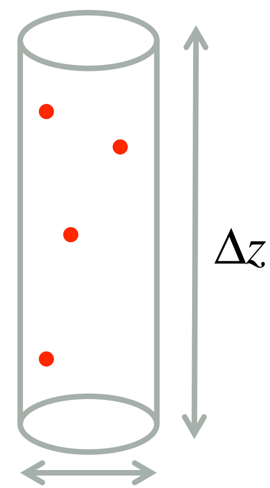
The difference comes from satellite galaxy (5% of total LRGs)

Effect of 1-halo term

Count In Cylinder technique

(Reid, Spergel 2008)

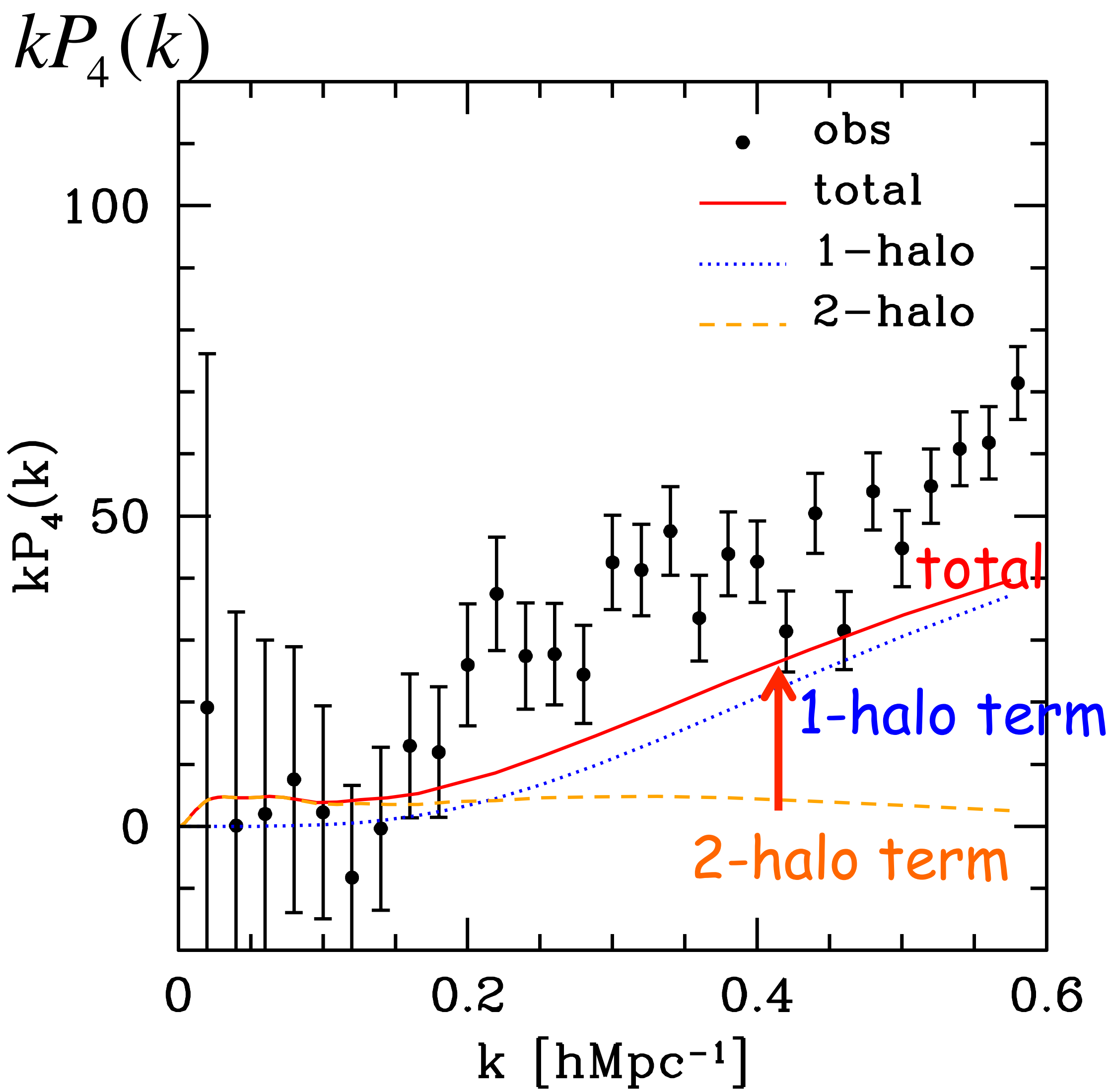
multiple system definition



$$\Delta r_{\perp} < 0.8h^{-1}Mpc$$

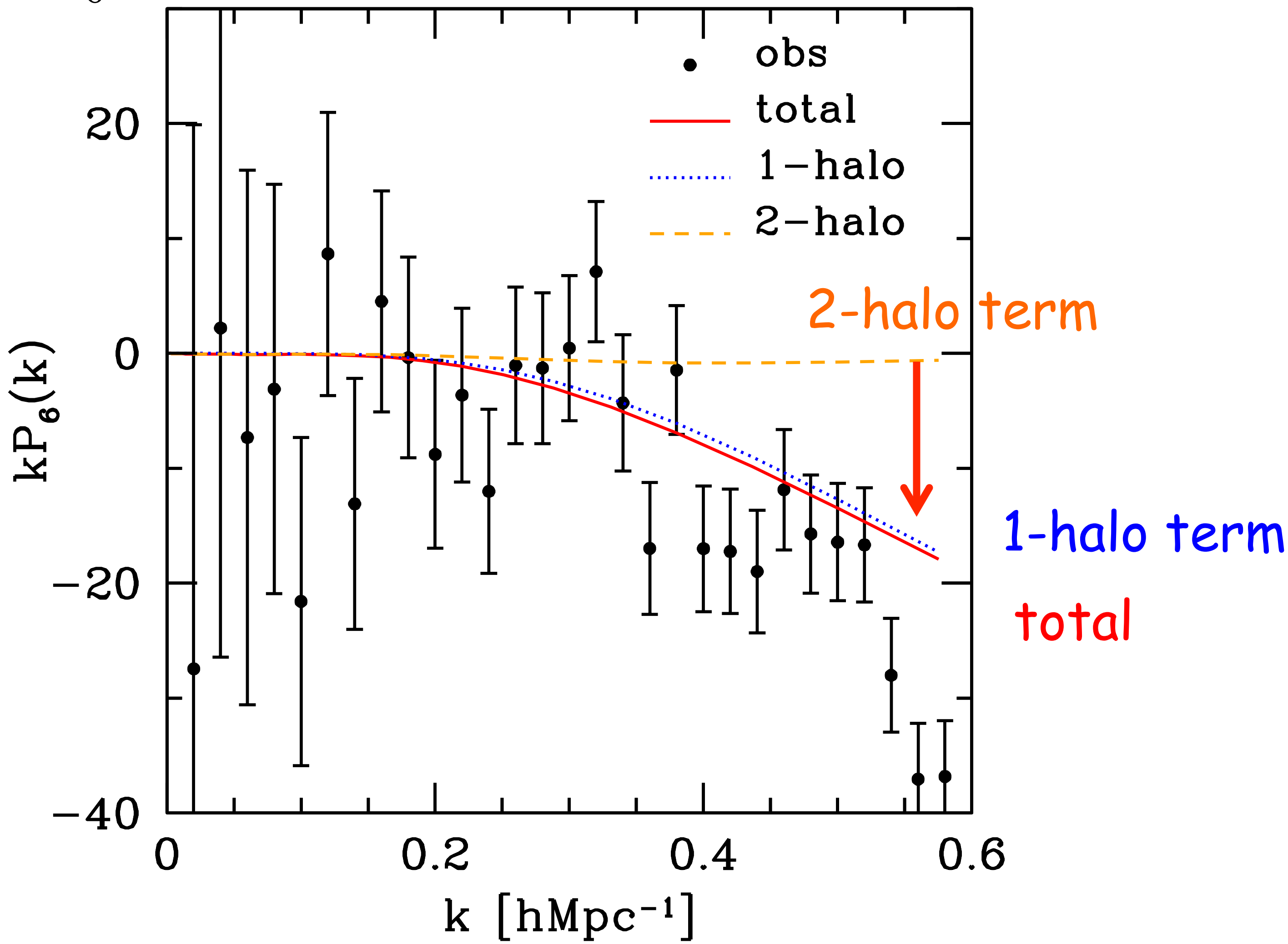
$$\frac{\Delta z}{1+z} < 0.006$$

1-halo term dominates $P_\ell(k)$ for $\ell \geq 4$



1-halo term dominates $P_\ell(k)$ for $\ell \geq 4$

$kP_6(k)$



Information from 1-halo term

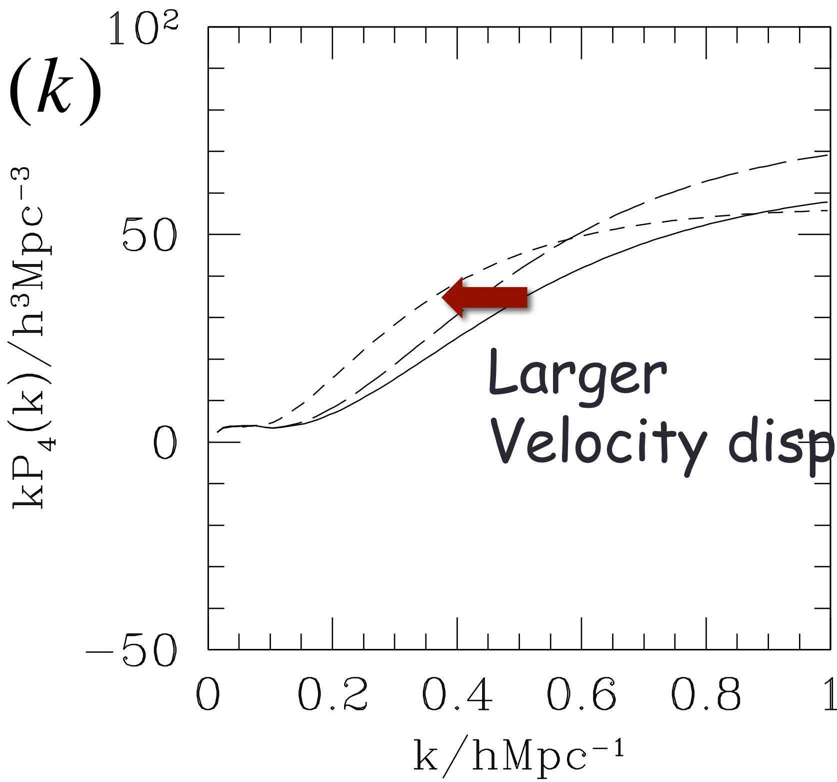
Central - Satellite pair

$$P^{1h}(k,\mu) \cong \frac{1}{\bar{n}^2}\int dM \frac{dn(M)}{dM} 2\langle N_{cen}\rangle\langle N_{sat}\rangle u(k,M)\exp\left[-\frac{\sigma_V^2(M)k^2\mu^2}{2a^2H^2}\right]$$

Satellite fraction(HOD)

Random velocity dispersion of satellite galaxies

$kP_4(k)$



Larger Satellite fraction

Larger Velocity dispersion

k

Information from 1-halo term

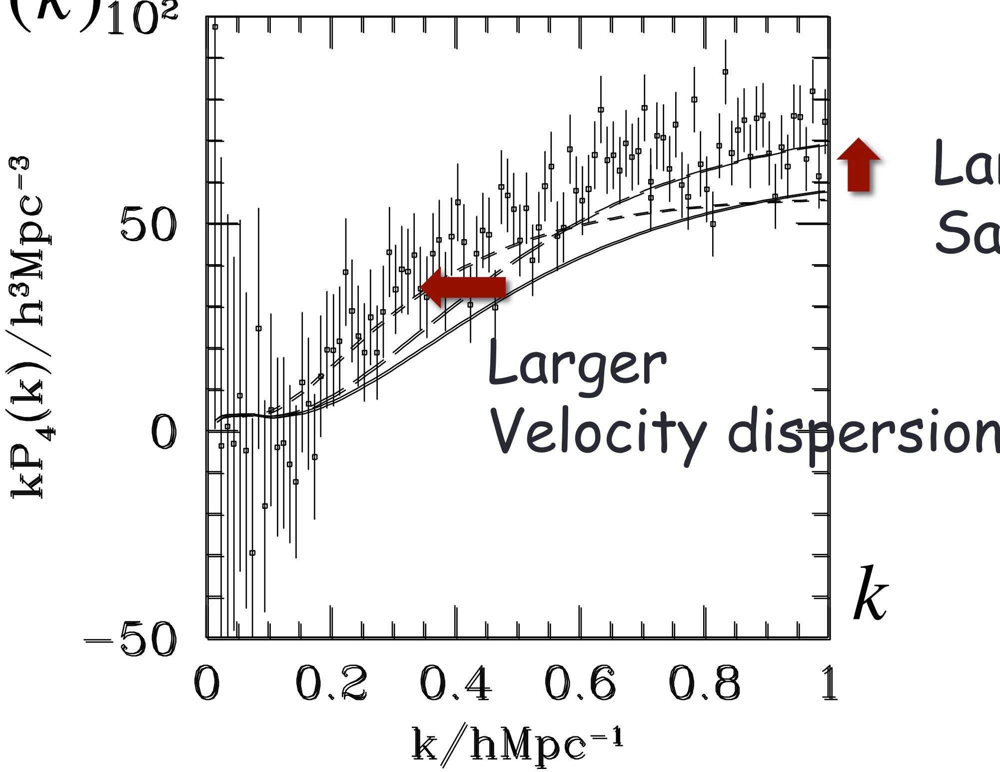
$$P^{1h}(k,\mu) \cong \frac{1}{\bar{n}^2}\int dM \frac{dn(M)}{dM} 2\langle N_{cen}\rangle\langle N_{sat}\rangle u(k,M)\exp\left[-\frac{\sigma_V^2(M)k^2\mu^2}{2a^2H^2}\right]$$

Satellite fraction(HOD)

(Reid Spergel, LRG)
(White, CMASS)

Random velocity dispersion of satellite galaxies

$kP_4(k)$



k

Larger
Satellite fraction

3. New test of gravity with multipole spectrum

Test of gravity with random velocity of satellite galaxies

$k > 0.2h^{-1}Mpc$ Random velocity dispersion in a halo with mass M

$$\sigma_V^2 = \sigma_V^2(M) \quad \sigma_V^2(M) \propto \frac{GM}{r_{vir}} \propto M^{2/3}$$ (if random motion is virialized)

↕ (if this relation is modeled precisely)

1-halo term and multipole power spectrum

↕

Observations

Test of gravity with RSD uses (quasi)-linear regime

$k < 0.2h^{-1}Mpc$ Linear growth rate $f = \frac{d \ln D_1(a)}{d \ln a}$

Simple model of the random velocity of satellite galaxies

Hikage, Takada, Spergel(2012)

$$\sigma_V^2(M) \propto \frac{GM}{r_{vir}} \propto M^{2/3}$$

Assume the singular isothermal like velocity dispersion

$$\sigma^2(r) = \frac{GM(<r)}{2r}$$

Average over the satellite probability distribution function (normalized NFW density profile $\hat{\rho}(r)$)

$$\sigma_V^2(M) = \int_0^{r_{vir}} dr r^2 \hat{\rho}(r) \sigma^2(r)$$

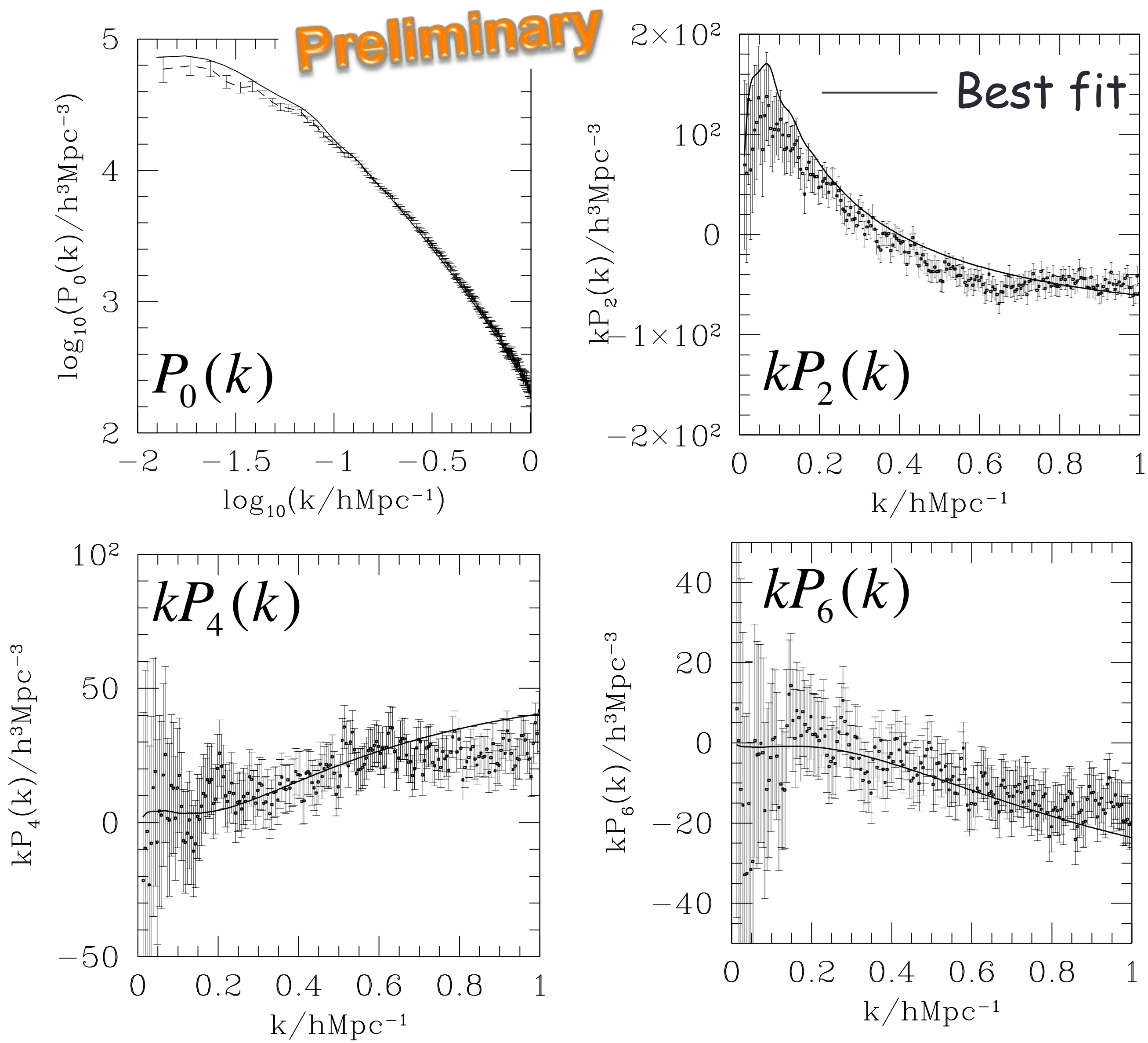
$$\cong \beta \frac{GM}{2r_{vir}} \qquad \beta = \begin{cases} 0.7 & (z=0.57) \\ 0.8 & (z=0.35) \\ 1 & (z=0) \end{cases}$$

↕

MCMC analysis comparing with $P_L(k)$ of BOSS CMASS DR9

CMASS DR9 power spectrum

(North, 2600 deg.^{2}, 2×10^5 gals.)



MCMC analysis with

$$0.15hMpc^{-1} < k < 1hMpc^{-1}$$

$$b(k) = b_0 \frac{1 + A_2 k^2}{1 + A_1 k}$$

$$1 - f_{coll} \cong 0.12 \pm 0.02$$

$$\beta \cong 0.77 \pm 0.05$$

$$\beta = 0.71$$

Simple model's theoretical prediction the Lambda CDM

(cosmology, HOD fixed)

Conclusion

1-halo term makes quite large contribution to the higher multipole $P_l(k)$.

$P_4(k)$, $P_6(k)$ are dominated by 1-halo term, $P_2(k)$ is significantly contaminated

1 halo term comes from the satellite (LRG case, satellite is 5%)

1-halo term can never be described by the fluid approximate equations.

Impact and future work

$k < 0.2 h^{-1} Mpc$

- There may be contamination of the satellite galaxies in ongoing and future redshift survey, (SDSSBOSS), Subaru PFS and EUCLID

$k > 0.2 h^{-1} Mpc$

- New test of gravity on halo scale with multipole spectrum at high k This method might be used as a test of dark matter properties.

- More precise modeling of the halo approach comparing with simulations