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Redshift space distortion of BOSS galaxies and its cosmological constraints

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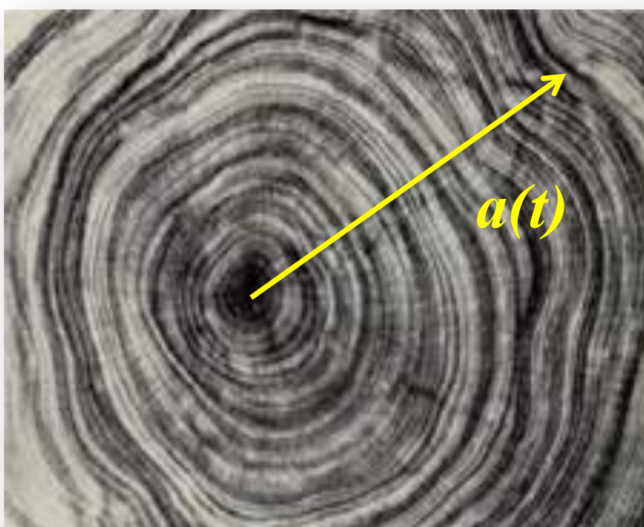
The Hubble diagram of Supernova Ia: accelerated expansion

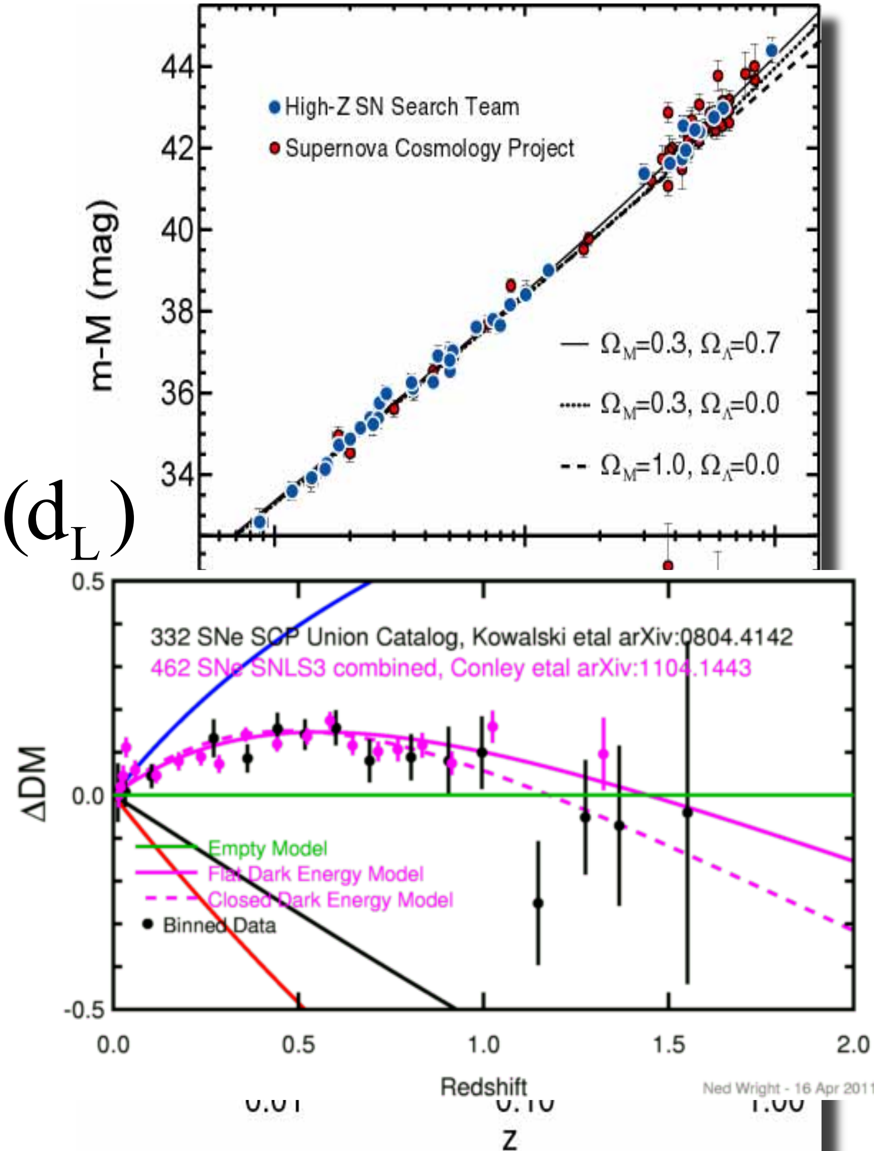
Luminosity Distance

$$\boxed{d_L = (1+z)\int_0^z \frac{c\, dz'}{H(z',\Omega_m,\Omega_\Lambda)}}$$

$$H \equiv \frac{\dot{a}}{a}$$

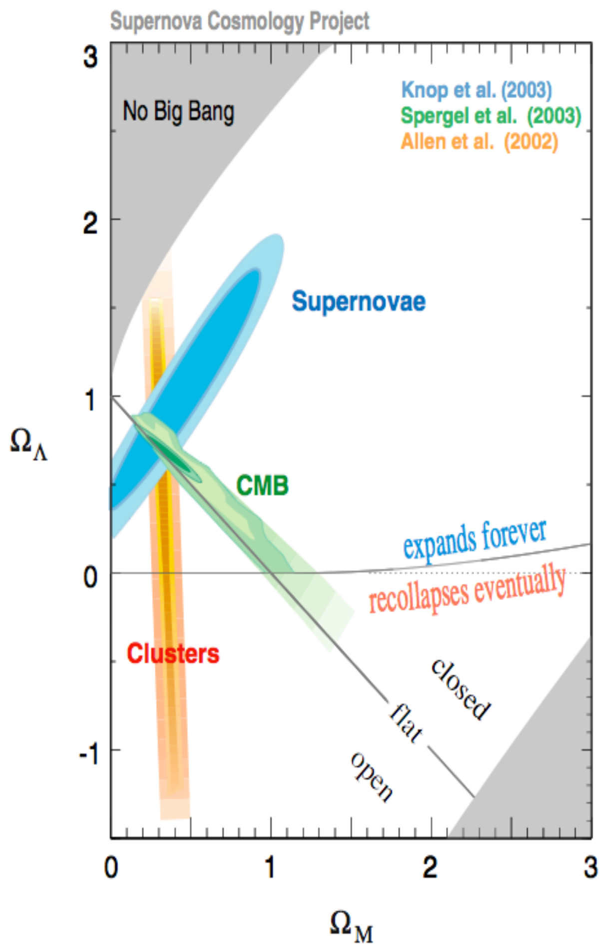
$$5\log(\mathrm{d_L})$$





Redshift z

Concordance Cosmology: Cosmological constant



<u>**Supernova**</u>

Accelerated Expansion

- **Ω_Λ ~ 1 ($p=w\rho c^2$, e.g. $w=-1$ vacuum energy)**

<u>**LSS and Clusters**</u>

- **Ω_m ~0.3**

<u>**CMB**</u>

- **flat ($\Omega_{TOT}=1$)**
- **Ω_m ~0.3 → Ω_Λ ~0.7**

•<u>**They together (with many others)**</u>

- **Ω_m ~0.3 Ω_Λ~0.7**

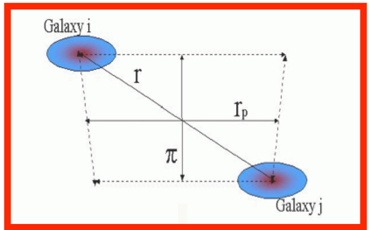
Either side of the GR equation could be a solution

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^2} T_{\mu\nu}}$$

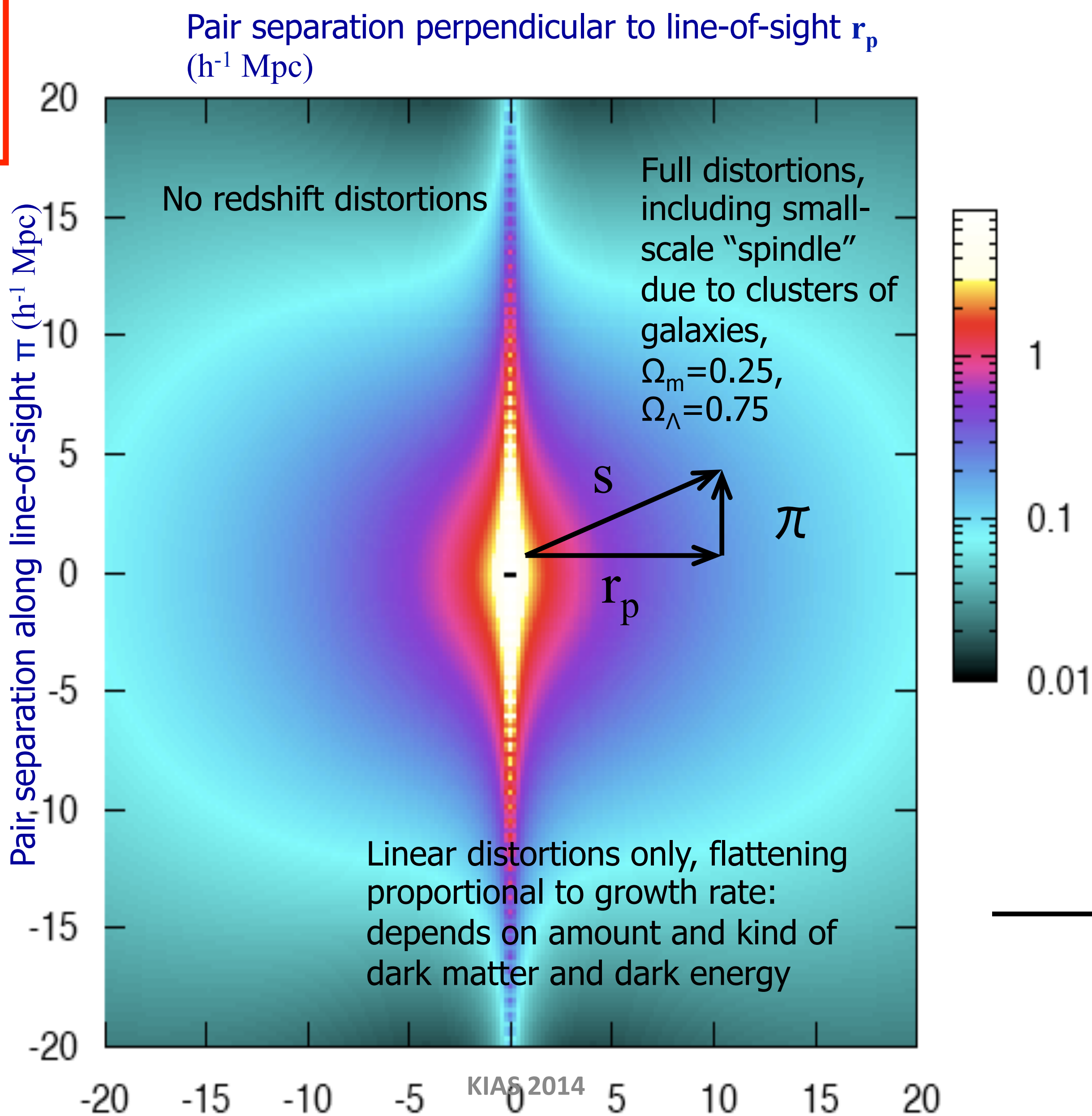
R.H.S: Dark Energy $T_{\mu\nu} \to T_{\mu\nu} + T_{\mu\nu}(DE)$

L.H.S : Modified Gravity $R \to F(R)$

Redshift-space galaxy-galaxy correlation function $\xi(r_p,\pi)$



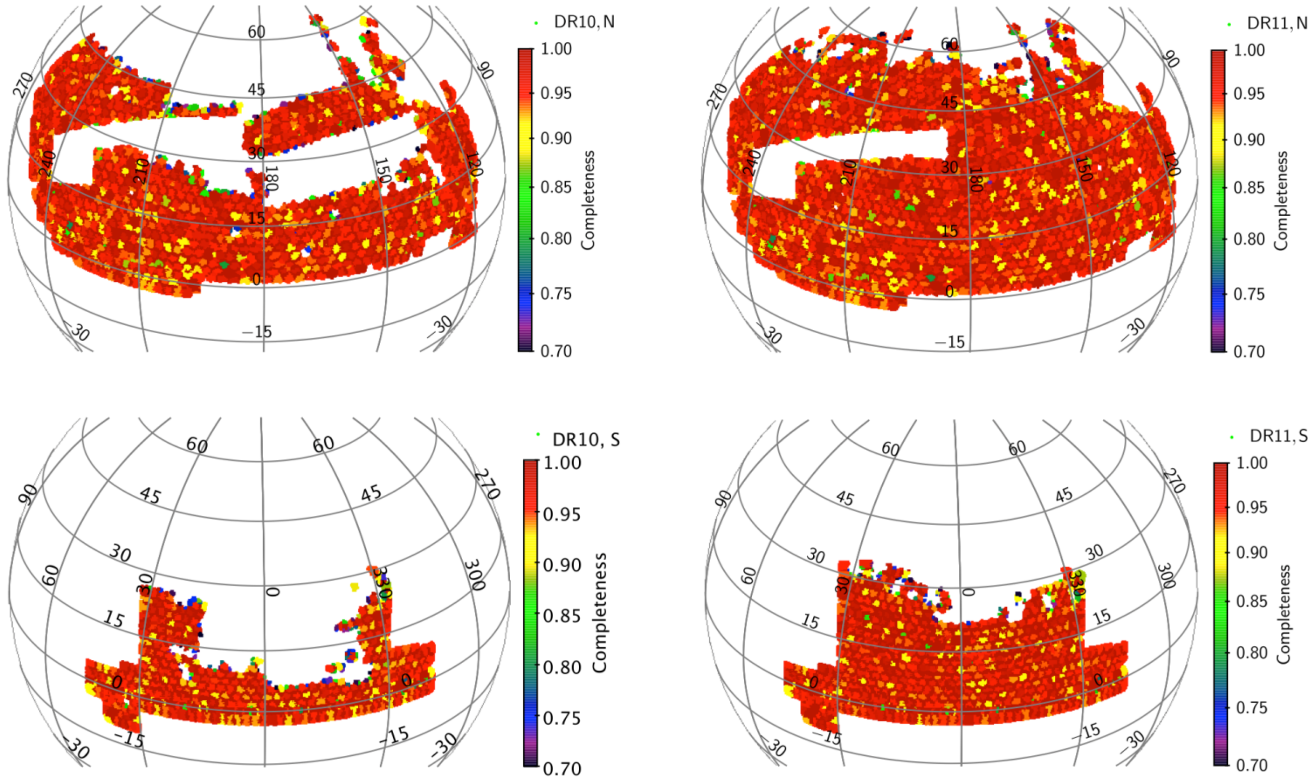
Line of sight to observer



Linear Growth rate $f = b_L\,\beta$

Compression parameter β(Kaiser 1987)

SDSS BOSS CMASS sample DR11



The sample contains about 600000 massive galaxies at redshift 0.6, perhaps most suitable for measuring RS P(K)

Challenge in measuring RS power spectrum

- It is generally preferred to measure the power spectrum in redshift space (RS), as the RS P(k) is coupled weakly at different scales, and the nonlinearities (such as mapping, galaxy bias, structure evolution)can be handled on quailinear scales （hopefully）
- But it is not easy to directly measure the RS P(K) because of two problems 1) lines of the sights to galaxies not parallel; 2) convolved with a complex observational window function plus a shot noise
- Use the moving-LOS method by Yamamoto et al.(2006,PASJ) to solve problem 1.
- It seems there is no good way to solve problem 2 especially on the scale comparable to that of the survey

The method of Jing & Boerner (2001): simple and accurate

- **Both the window function and the shot noise can be corrected in the correlation function (CF) measurement**
- **RS P(k) from the CF**

$$
\begin{aligned}
P_g^s(k,\mu) &= \int \xi_g^s(s_\perp, s_\parallel) e^{i\mathbf{k}\cdot\mathbf{s}} d^3\mathbf{s} \\
&= \int \xi_g^s(s_\perp, s_\parallel) e^{i(k_\parallel s_\parallel + k_\perp s_\perp \cos(\phi))} s_\perp ds_\perp d\phi ds_\parallel \\
&= \int \xi_g^s(s_\perp, s_\parallel) K(k_\perp, k_\parallel; s_\perp, s_\parallel) s_\perp ds_\perp ds_\parallel \ , \quad (3)
\end{aligned}
$$

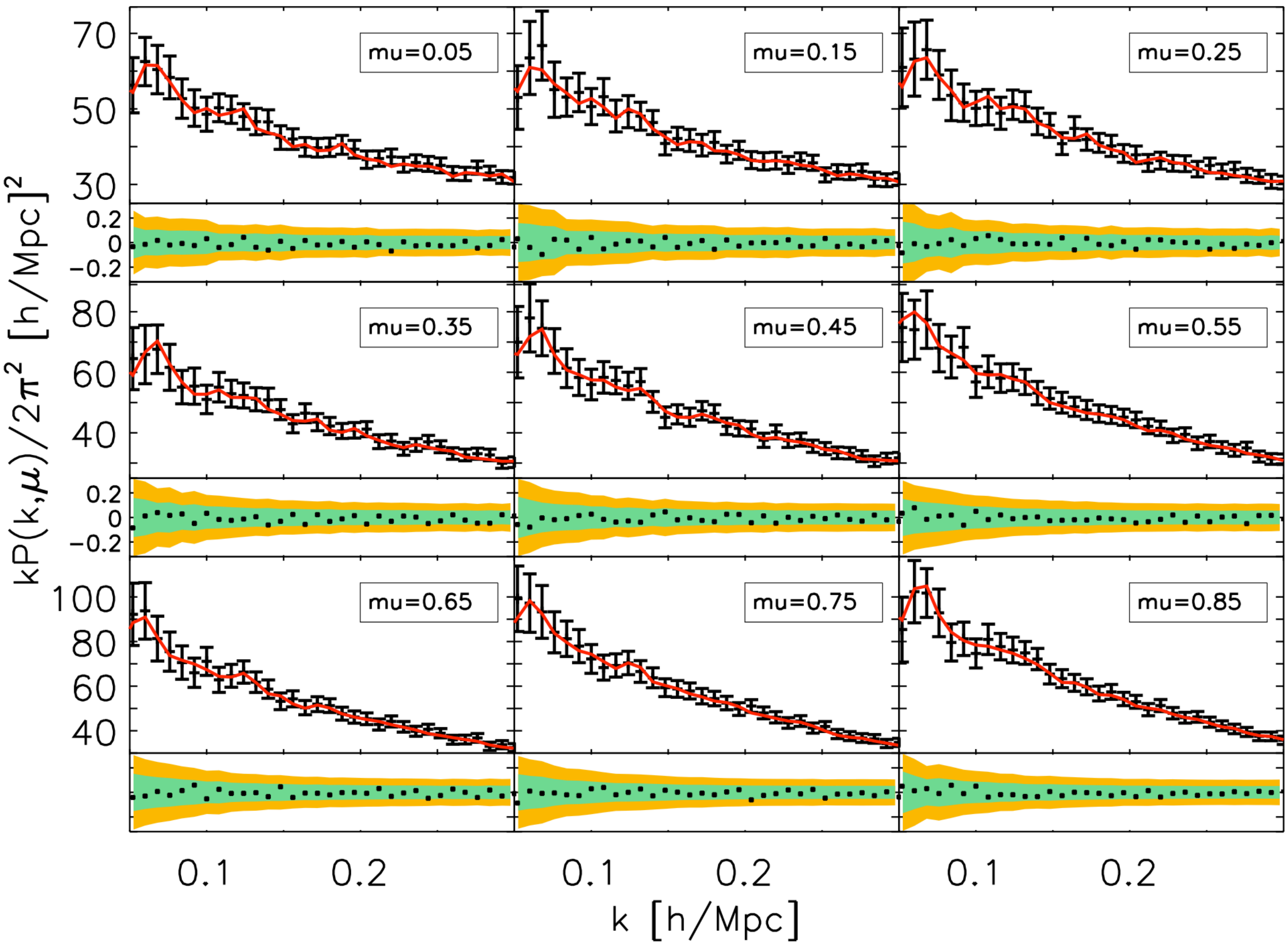
where $k_\parallel = k \cdot \mu$ and $k_\perp = \sqrt{k^2 - {k_\parallel}^2}$. Notice that μ here is not related to μ_s in the correlation function. The kernel K is defined as $K(k_\perp, k_\parallel; s_\perp, s_\parallel) = \cos(k_\parallel s_\parallel) J_0(k_\perp s_\perp)$ with $J_0(x) = \int e^{ix\cos(\phi)} d\phi$ the zero-th order Bessel function. In practice, we need to cut

- **One worry is that the errors of P(k) could be correlated on different scales, but we will see the correlations are weak**

Mock catalog test

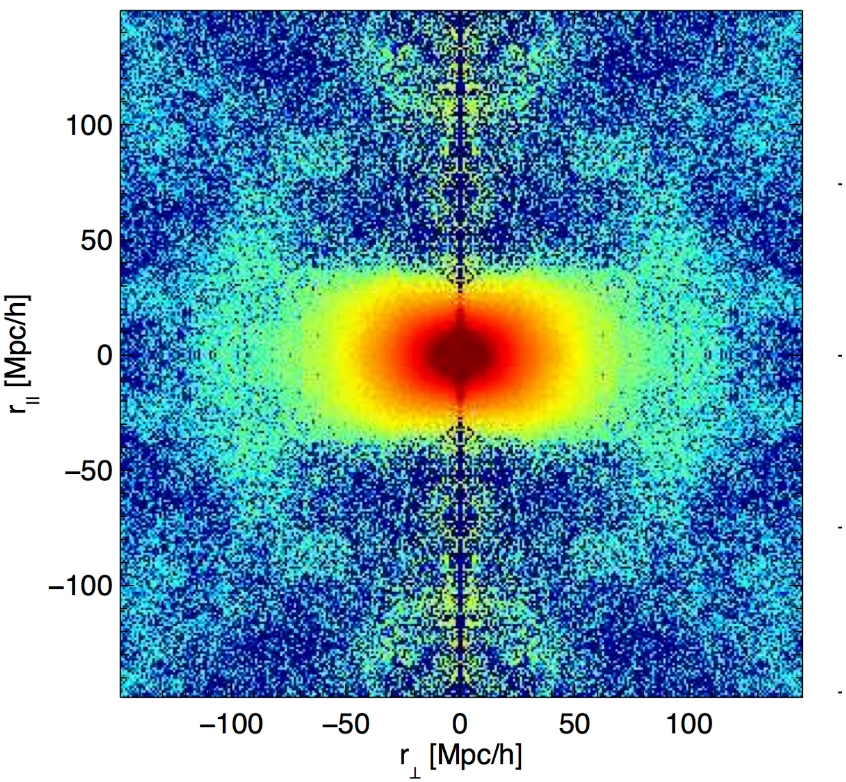
- Subhalo catalog, from an LCDM simulation with Np=3072**3 and L=1200 Mpc/h
- Using the Galaxy-Subhalo Matching method of Wang & Jing（2010）， we have constructed a CMASS mock catalog (Cubic volume)
- Result：P(K) from the FFT of CF and that directly from FFT are in good agreement, indicating one can get P(K) if the input CF is correct.

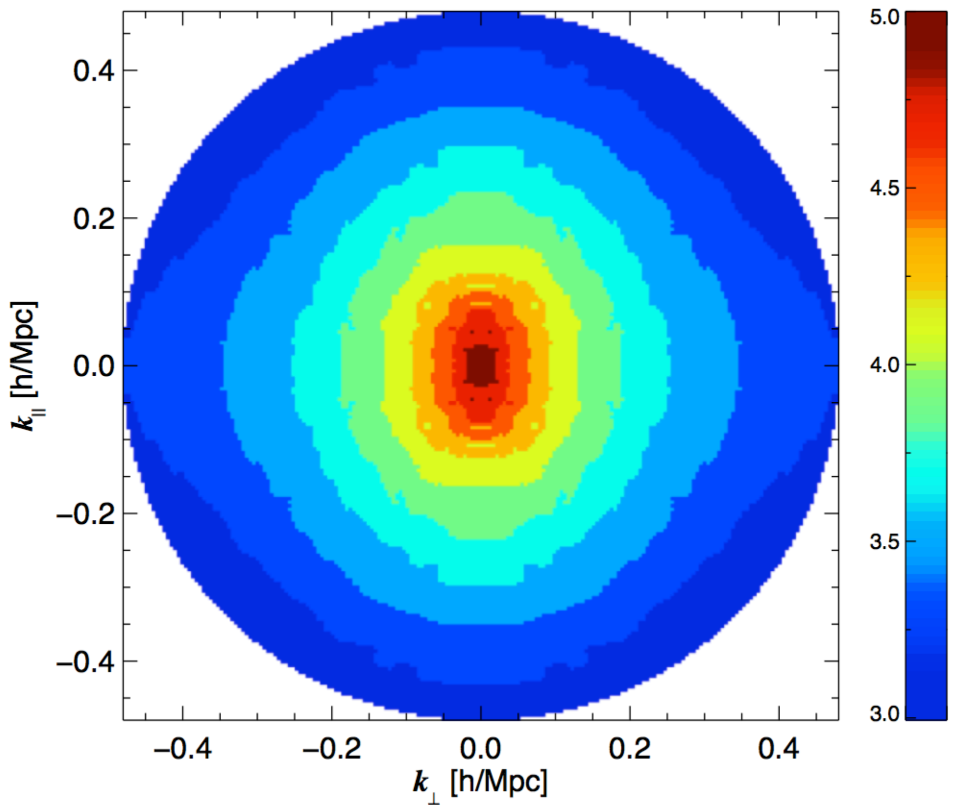
JB2001 method（red lines）vs direct FFT (black points with error bars）



Li, Zhigang, JYP et al 2016, ApJ, accepted

Applied to CMASS sample DR11





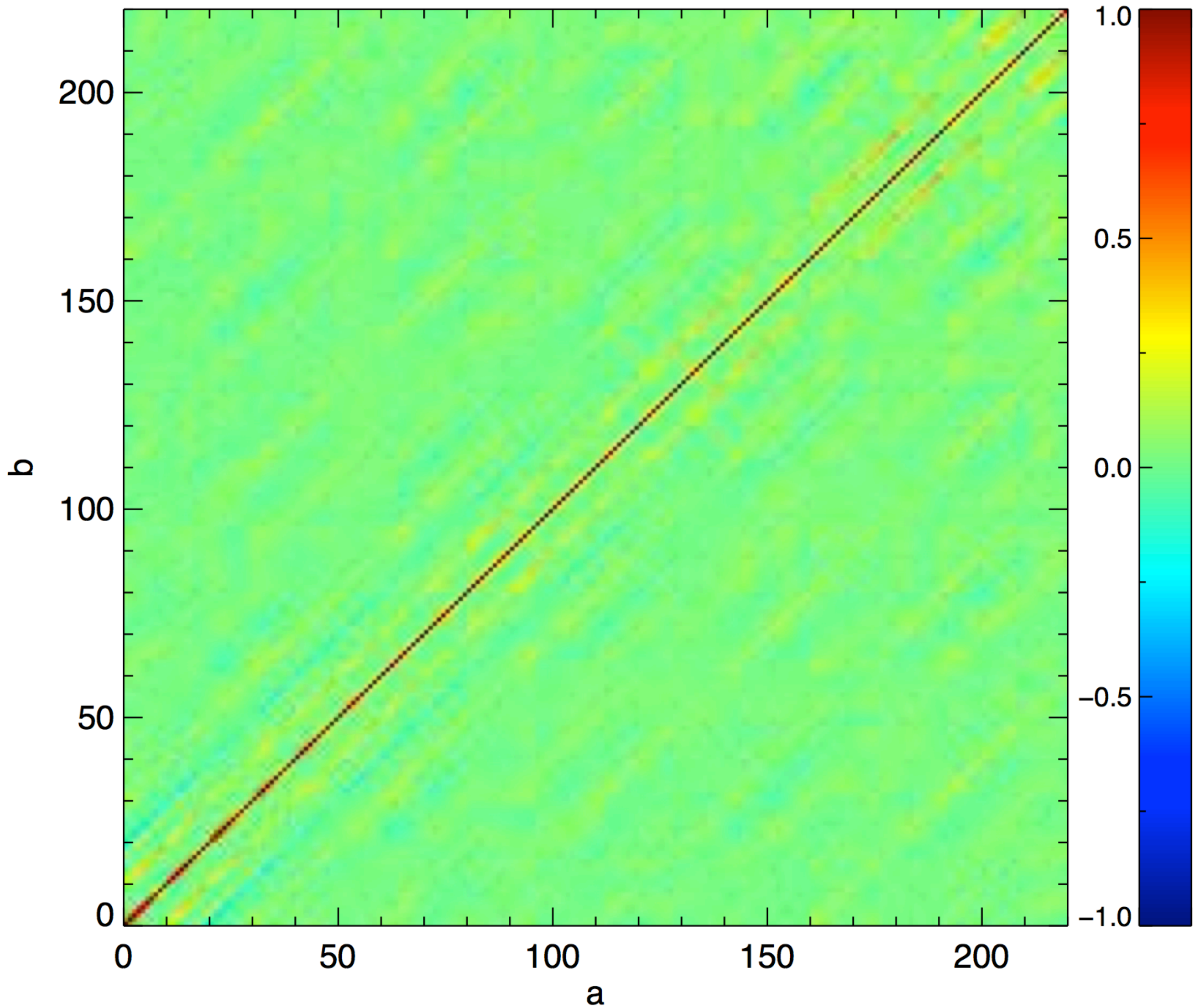
Correlation function in redshift space

Power spectrum in redshift space

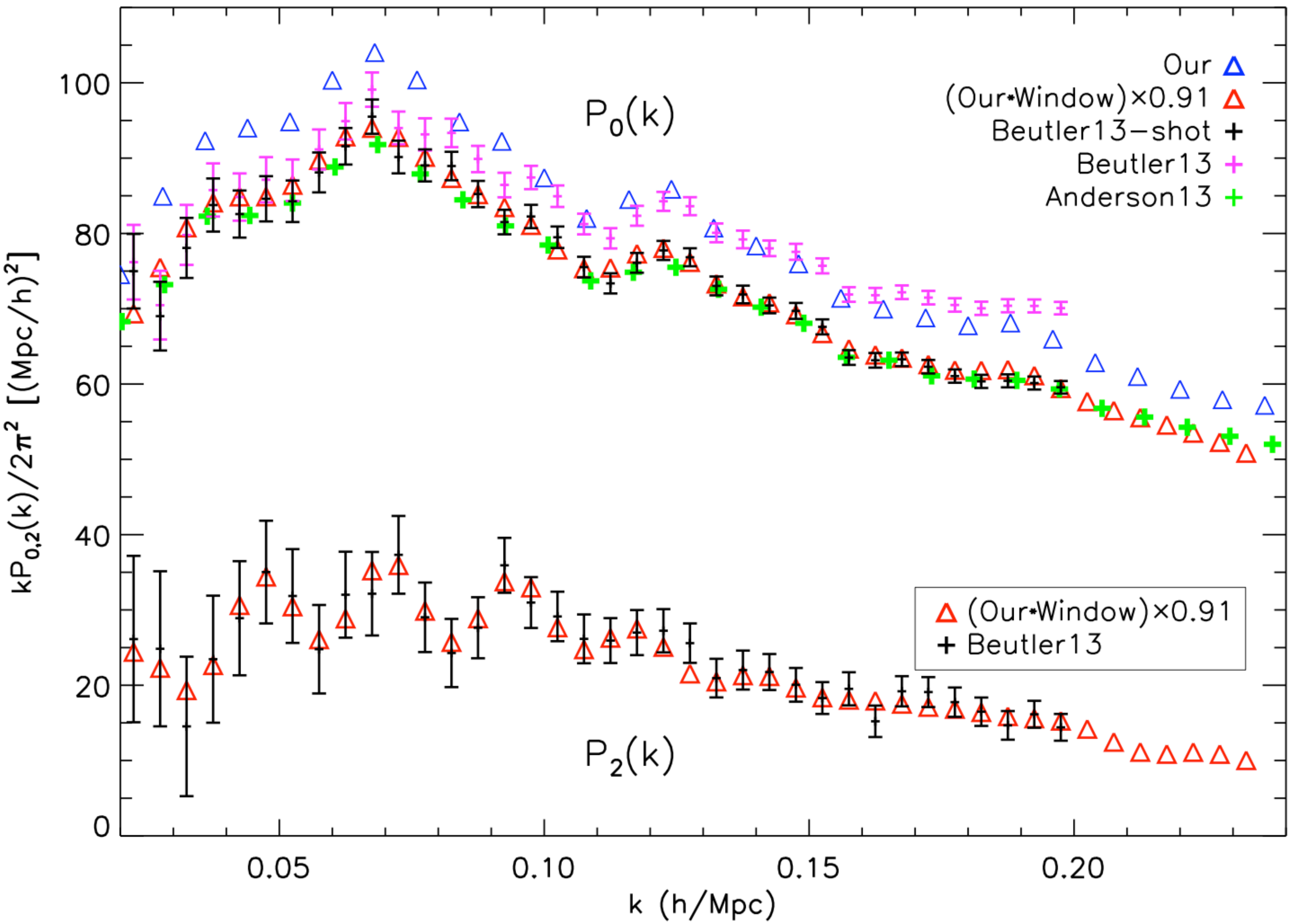
Error Matrix estimated from mocks

1. Estimate the error matrix of P(k) with MultiDark Patchy mock catalogs

2. Found different modes correlate weakly, the method not introduces mode-mode coupling

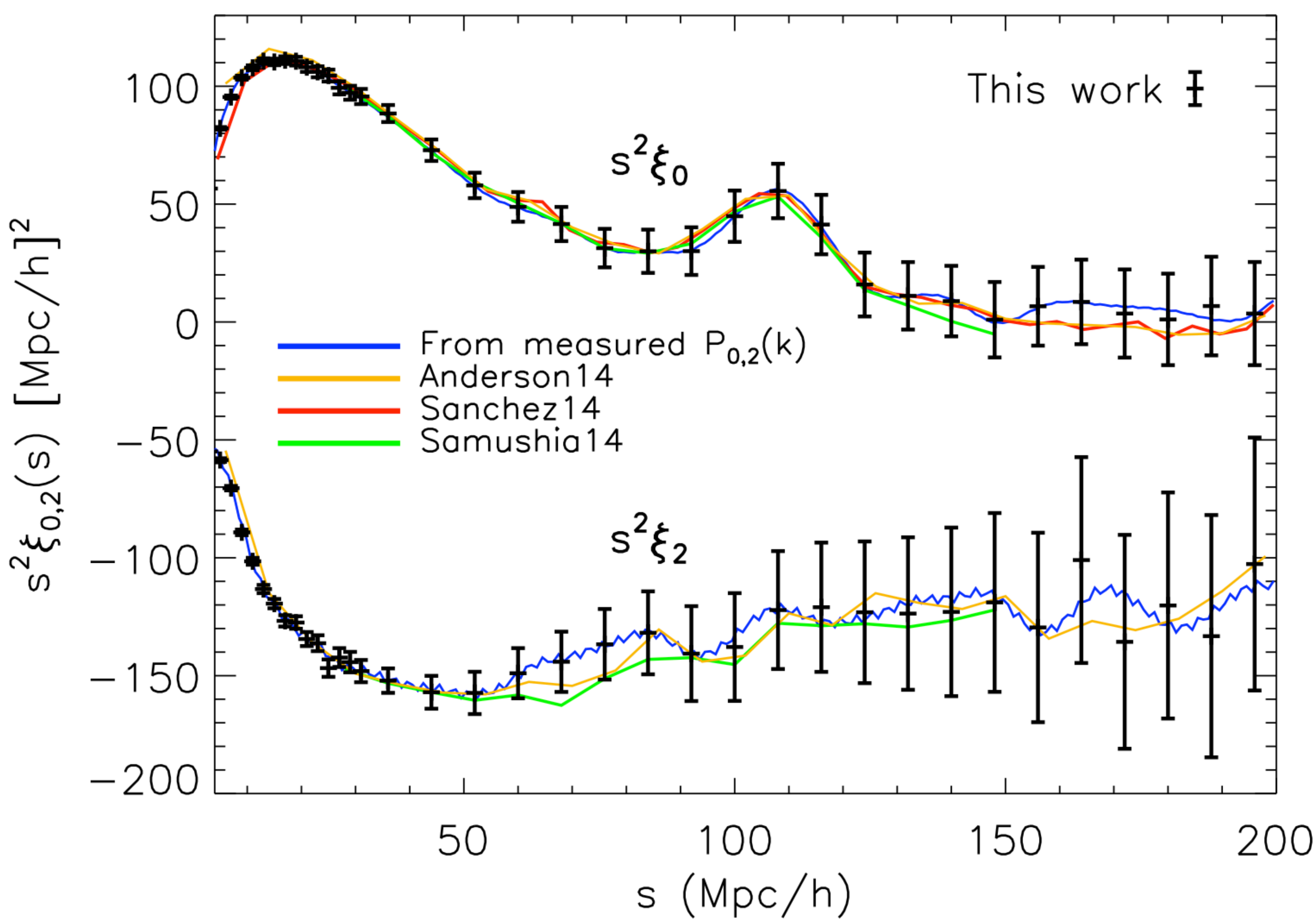


Comparing with previous works



Previous works: window function or shot noise may not be properly corrected

Reproduced RS CFs in previous studies



Incomplete list of approximations/simplifications in RSD modeling

$$\mathbf{x}^s = \mathbf{x} + \frac{\mathbf{v}\cdot\hat{x}}{H}\hat{x} \xrightarrow{\text{Distant observer}} \mathbf{x}^s = \mathbf{x} + \frac{v_z}{H}\hat{z}$$

Neglecting AP/relativistic effects/lensing distortion

Single streaming
No magnification bias

$$P^s(\mathbf{k}) = \int \langle (1+\delta_1)(1+\delta_2)e^{ik_z(v_{1z}-v_{2z})/H}\rangle e^{i\mathbf{k}\cdot\mathbf{r}}d^3x$$

Cumulant expansion theorem

$$P_g^s(k,u) = \left[P_g(k)(1+\beta\tilde{W}(k)u^2)^2 + u^4 P_{\theta_S\theta_S}(k) + \cdots\right] D^{\rm FOG}(ku)$$

Linear density-velocity relation, no velocity bias

Deterministic density-velocity

Negligible high order corrections

$$P_g^s(k,u) = P_g(k)(1+\beta u^2)^2 D^{\rm FOG}(ku)$$

Further approximations often used in observations

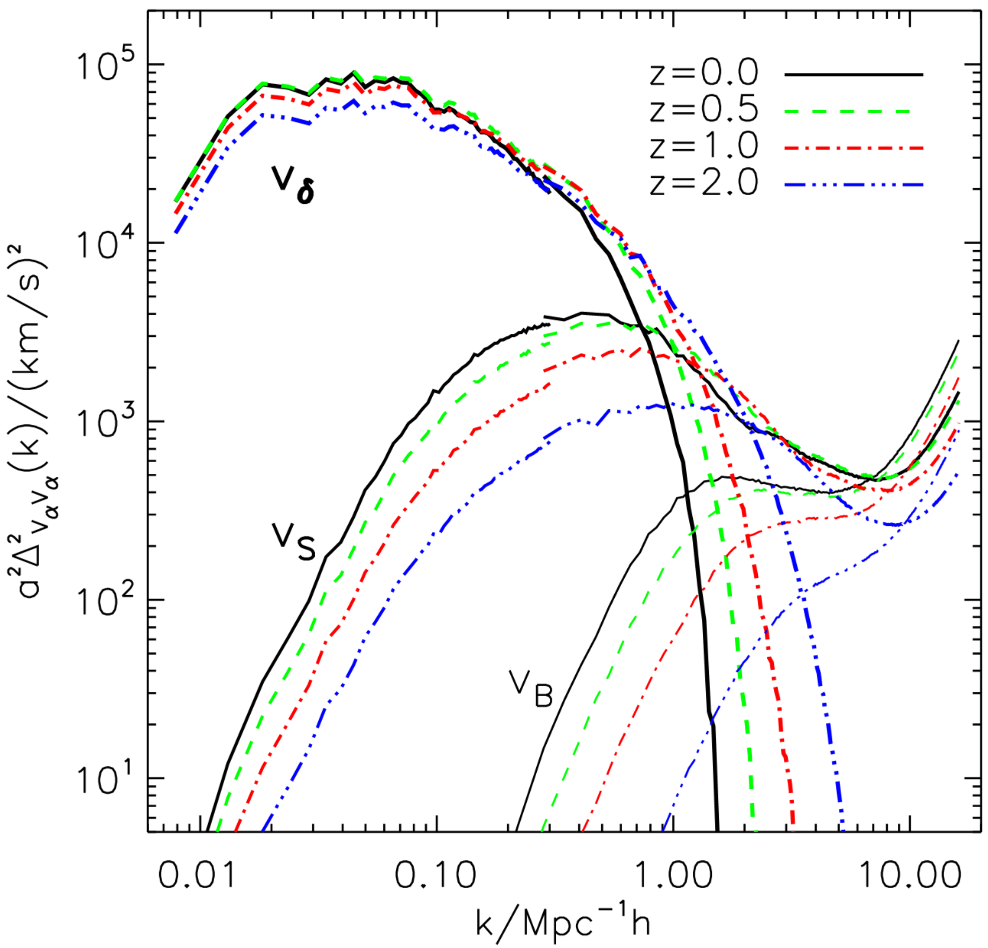
- **Scale independent galaxy density bias**
- **$D^{\rm FOG}$**: Gaussian, Lorentz, more complicated? Meaning of σ_v?

Disentangle RSD: A generic velocity decomposition

- Velocity decomposition into three eigen-modes:
  - Gradient part v_E
    - v_δ: correlated with density: mostly linear, dominant at large scale
    - v_S: uncorrelated: significant at intermediate scale
  - Curl part v_B
    - Highly nonlinear, small scale

- Different origins
- Different scale/z dependence
- Different RSD

Zhang,, Pan, Zheng, 2013



Zheng et al. 2013

A formula of Zhang et al.(2013)

$$\begin{aligned} P^s_{\delta\delta}(k,u) \ = \ & \Big\{ P_{\delta\delta}(k)(1+f\tilde{W}(k)u^2)^2 + u^4 P_{\theta_S\theta_S}(k) \\ & + C_{NG}(k,u) + C_G(k,u) + C_S(k,u) \Big\} \\ & \times D^{\rm FOG}_\delta(ku) D^{\rm FOG}_S(ku) D^{\rm FOG}_B(ku) \ . \qquad (26) \end{aligned}$$

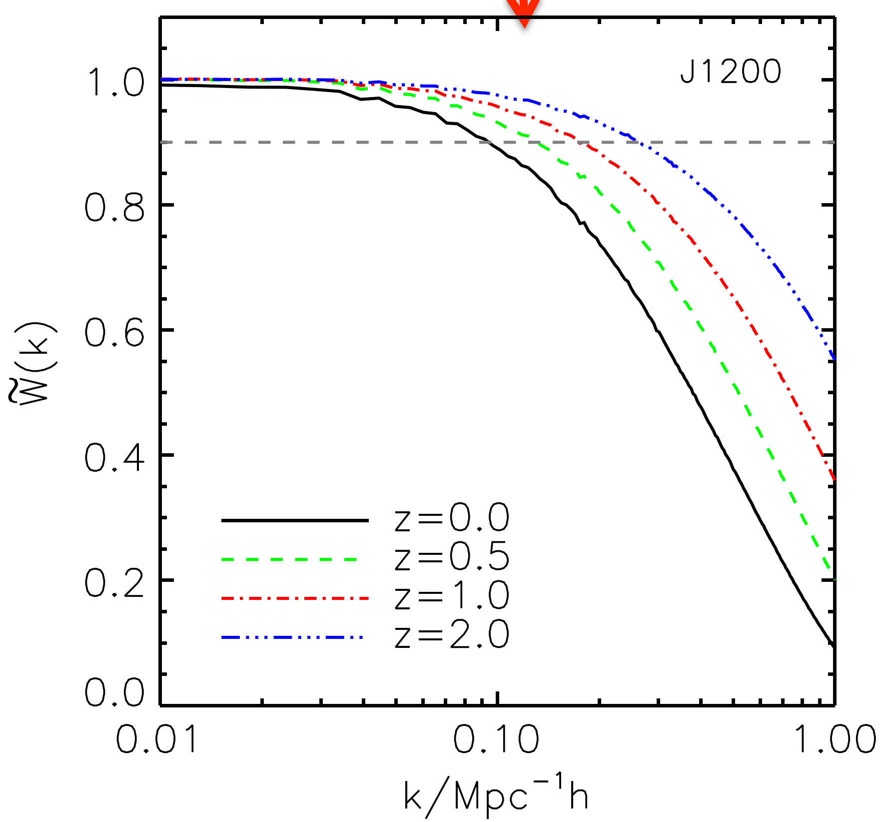
$$\theta(\mathbf{x}) \equiv -\nabla \cdot \mathbf{v}(\mathbf{x})/H \equiv -\nabla \cdot \mathbf{v}_E(\mathbf{x})/H$$

$$W(\mathbf{k}) = W(k) = \frac{P_{\delta\theta}(k)}{P_{\delta\delta}(k)}$$

$$\tilde{W}(k) \equiv \frac{W(k)}{W(k\to 0)} = \frac{W(k)}{f} = \frac{1}{f}\frac{P_{\delta\theta}(k)}{P_{\delta\delta}(k)}$$

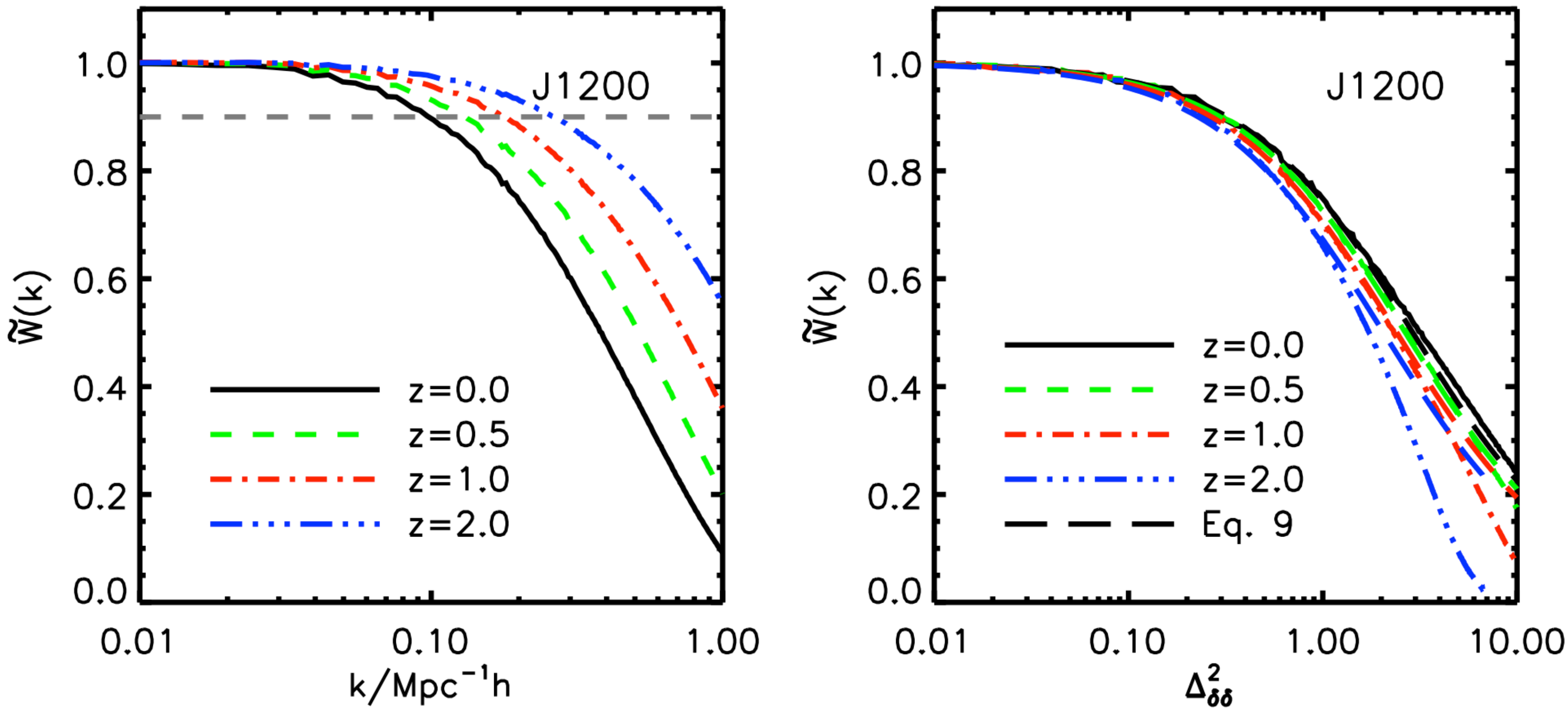
Disentangle RSD: nonlinear velocity-density

$$P^s(k,u) = \left[P(k)(1 + f\tilde{W}(k)u^2)^2 + P_{\theta_s\theta_s}(k)u^4 + C_G(k,u) + C_{NG,3}(k,u)\right] D^{\mathrm{FOG}}(ku)$$



Zheng et al. 2013

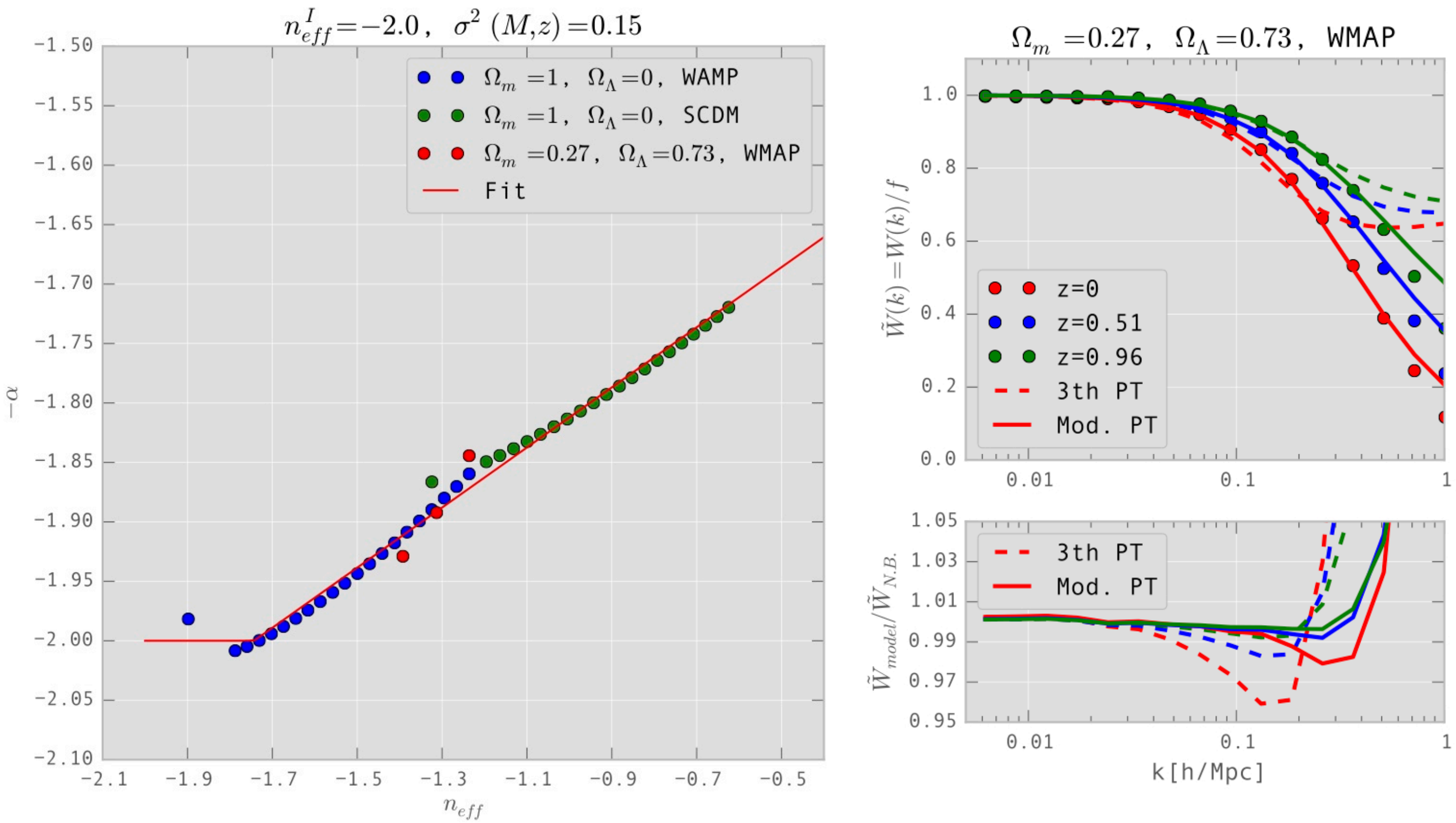
- Velocity growth is suppressed w.r.t density.
- Leading order correction to the Kaiser formula
- **10% at k=0.1h/Mpc and z=0**



J1200
1.0
0.8
0.6
0.4
0.2
0.0
$\tilde{W}(k)$
0.01
0.10
1.00
$k/\mathrm{Mpc}^{-1}h$
z=0.0
z=0.5
z=1.0
z=2.0
J1200
10.00
$\Delta^2_{\delta\delta}$
Eq. 9

Cheng,D.L. et al in preparation

Accurate model for W(k)



1. **Mainly depend on power spectrum, only weakly on cosmology**
2. **With third-order PT + simulations, we can predict W(K) at the accuracy better than1%**

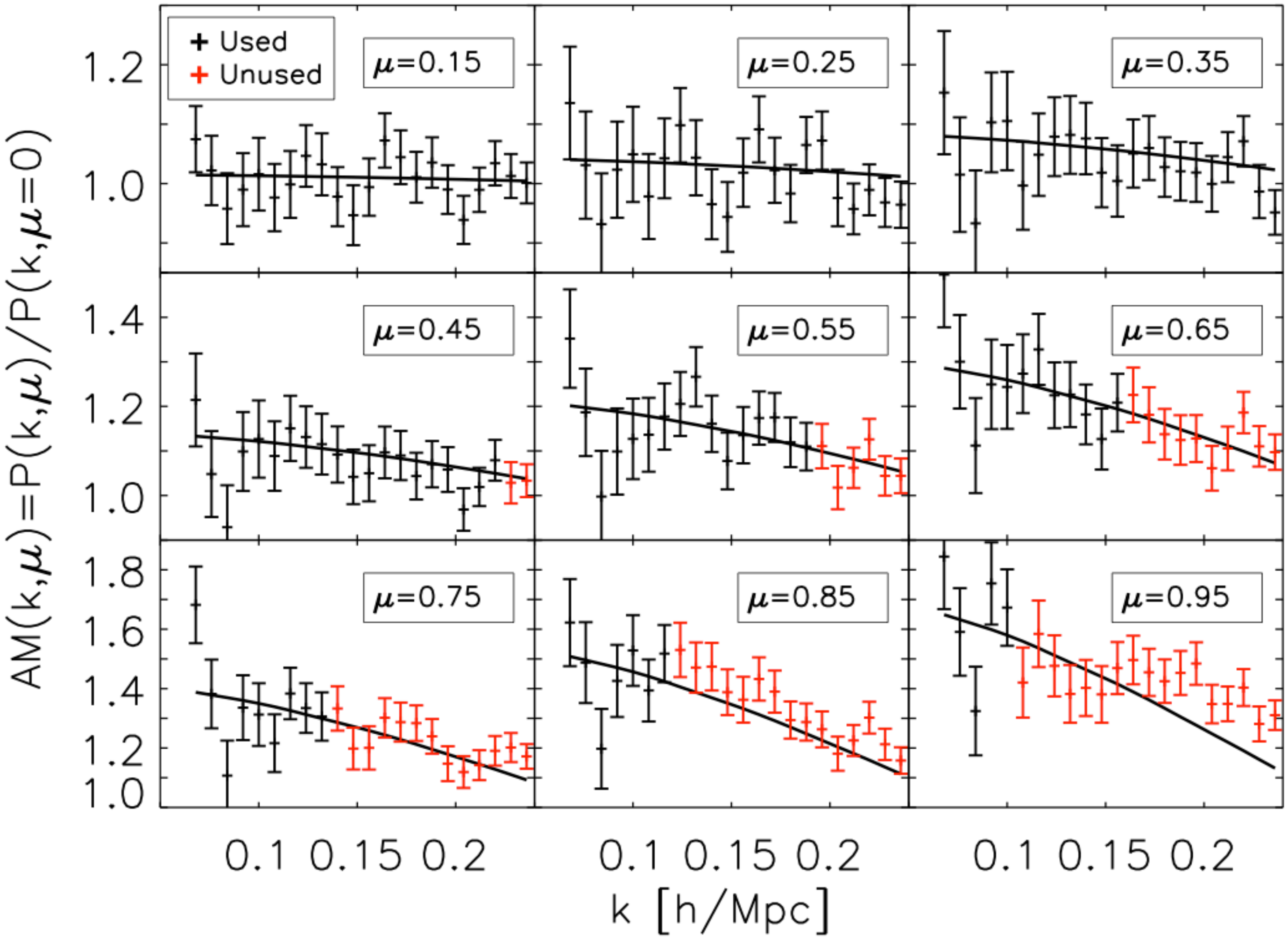
Anisotropy Measure (AM)

- One of the main aims to measure RS P(k)is to measure the motion of galaxies, thus the growth rate of structures;
- To minimize to uncertainties of galaxy bias and non-linar evolution, we define the anisotropy measure：

$$\mathrm{AM}(k,\mu) \equiv \frac{P_g^s(k,\mu)}{P_g^s(k,\mu=0)} \ .$$

- To the major order, it is related to the galaxy motion on $\mathrm{AM}^{\mathrm{md}}(k,\mu) = (1+\beta W(k)\mu^2)^2 \exp\{-(k\mu\tilde{\sigma}_v)^2\}$.

Anisotropy Measure of CMASS galaxies



kμ<0.1 h/Mpc for our model fitting, in order to minimize high order effects (which will be considered in a future work)

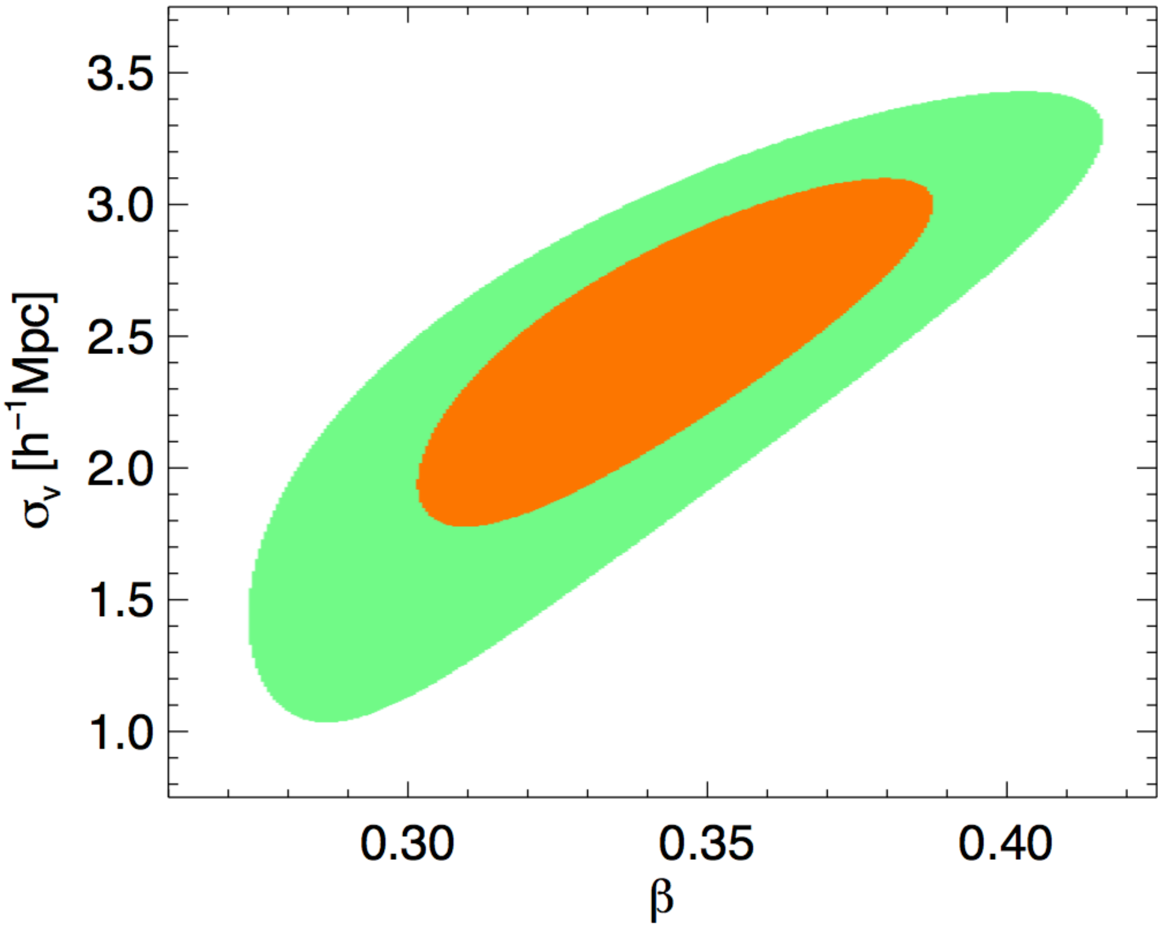


FIG. 6.— Two dimensional likelihood function of β and $\tilde{\sigma}_v$ for BOSS-DR11 CMASS galaxies. The orange contours show 68% confidence level, while the green contours show 95% confidence level.

Our main result of the growth rate at z=0.57

$$f(z_{\rm eff})\sigma_8(z_{\rm eff}) = 0.440 \pm 0.037$$

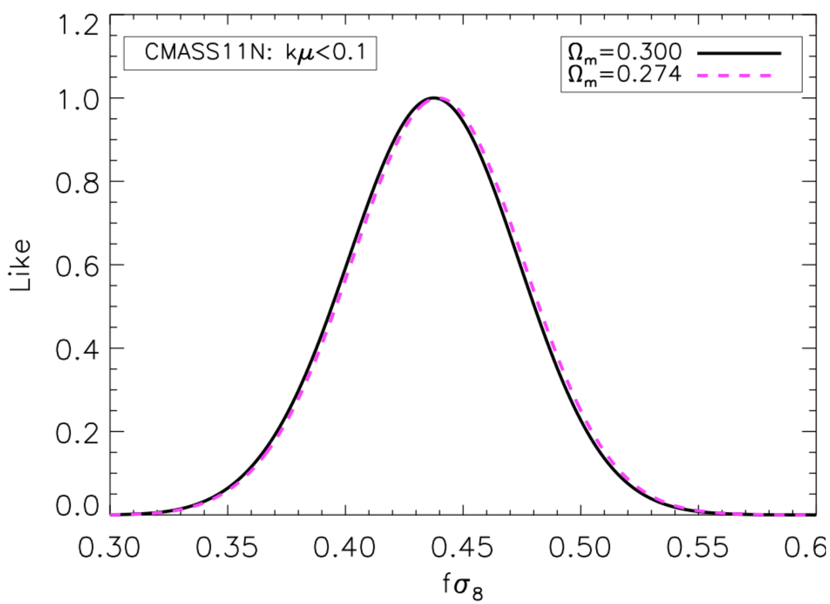


FIG. 7.— Normalized likelihood function of $f(z_{\rm eff})\sigma_8(z_{\rm eff})$ BOSS-DR11 CMASS galaxies. The black solid curve shows sults assuming $\Omega_m = 0.3$ in measuring $b_g\sigma_8(z_{\rm eff})$ and the mage dashed curve corresponds to $\Omega_m = 0.274$. The figure shows ne gible difference for these two cases.

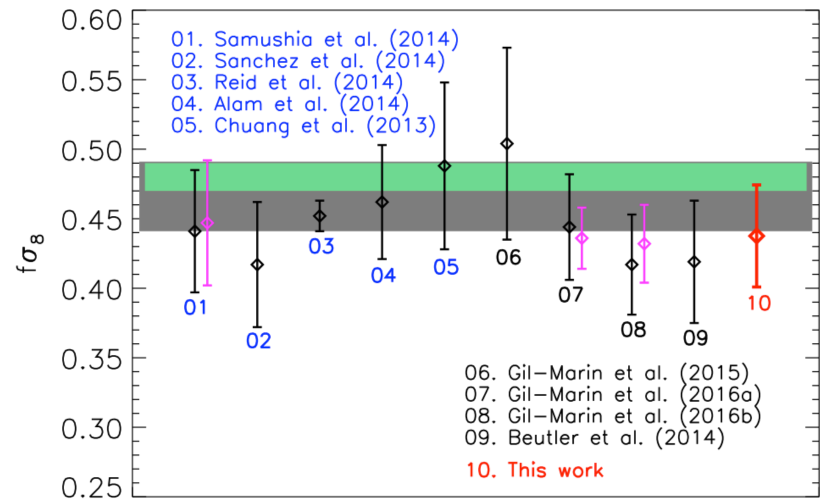
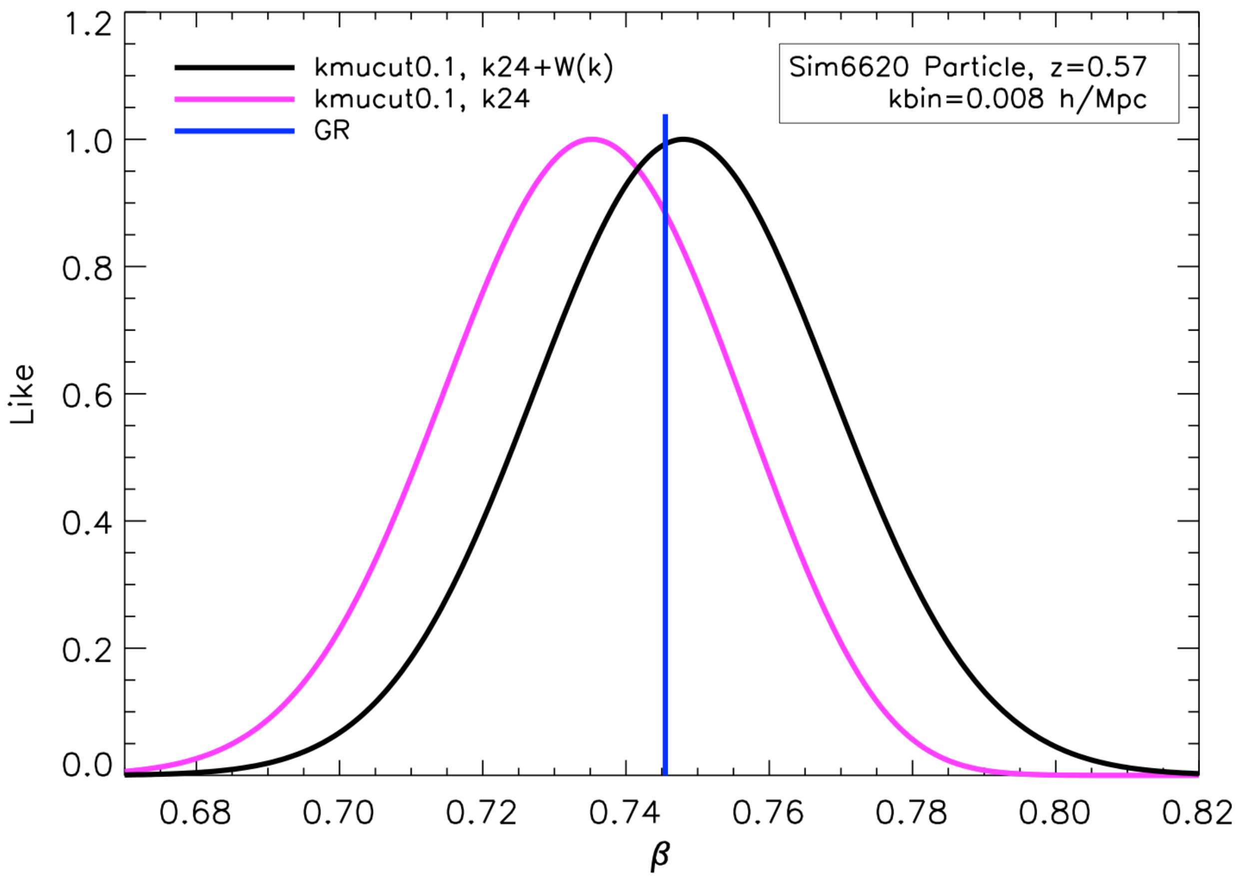


FIG. 8.— Constraints on $f(z_{\rm eff})\sigma_8(z_{\rm eff})$ from BOSS CMASS DR10, DR11 and DR12 release. Our result are shown in red diamond. Black diamonds show the results from various literatures. Magenta diamonds show those analysis that do not include the AP effect or use fiducial parameters for the AP effect. The green band show the $1\,\sigma$ confidence level allowed by Planck15 assuming ΛCDM+GR model and grey band for WMAP9 assuming ΛCDM+GR model.

Simulation test for w(k)



It is necessary to include nonlinearity($W(k)$), which can bias the f measure to a lower value (for our cut k and μ, it is 5-10%)

Summary

- RSD is potentially a powerful tool to study dark energy and modified gravity
- Our method of measuring RS power spectrum from RS correlation function is simple and accurate
- It is necessary to include the quasi-nonlinear effect W(k) in the velocity field even at scale $k<0.24$ and $k\mu<0.1$
- Applied to SDSS DR11, we get

$$f(z_{\rm eff})\sigma_8(z_{\rm eff}) = 0.440 \pm 0.037$$

Li, Zhigang, JYP et al 2016, ApJ, accepted; arXiv:1609.03697

Outlook

- Modeling: high order effects; full simulations
- Observations: SDSS DR12, and future surveys

Thank you!

Acknowledgements：Zhigang Li, Pengjie Zhang, Dalong Cheng