Redshift Distortion as a probe for cosmology: improving theoretical modeling

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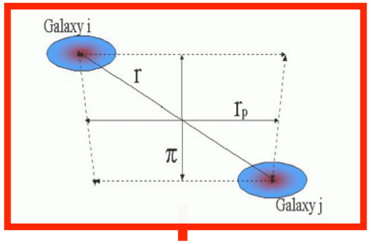
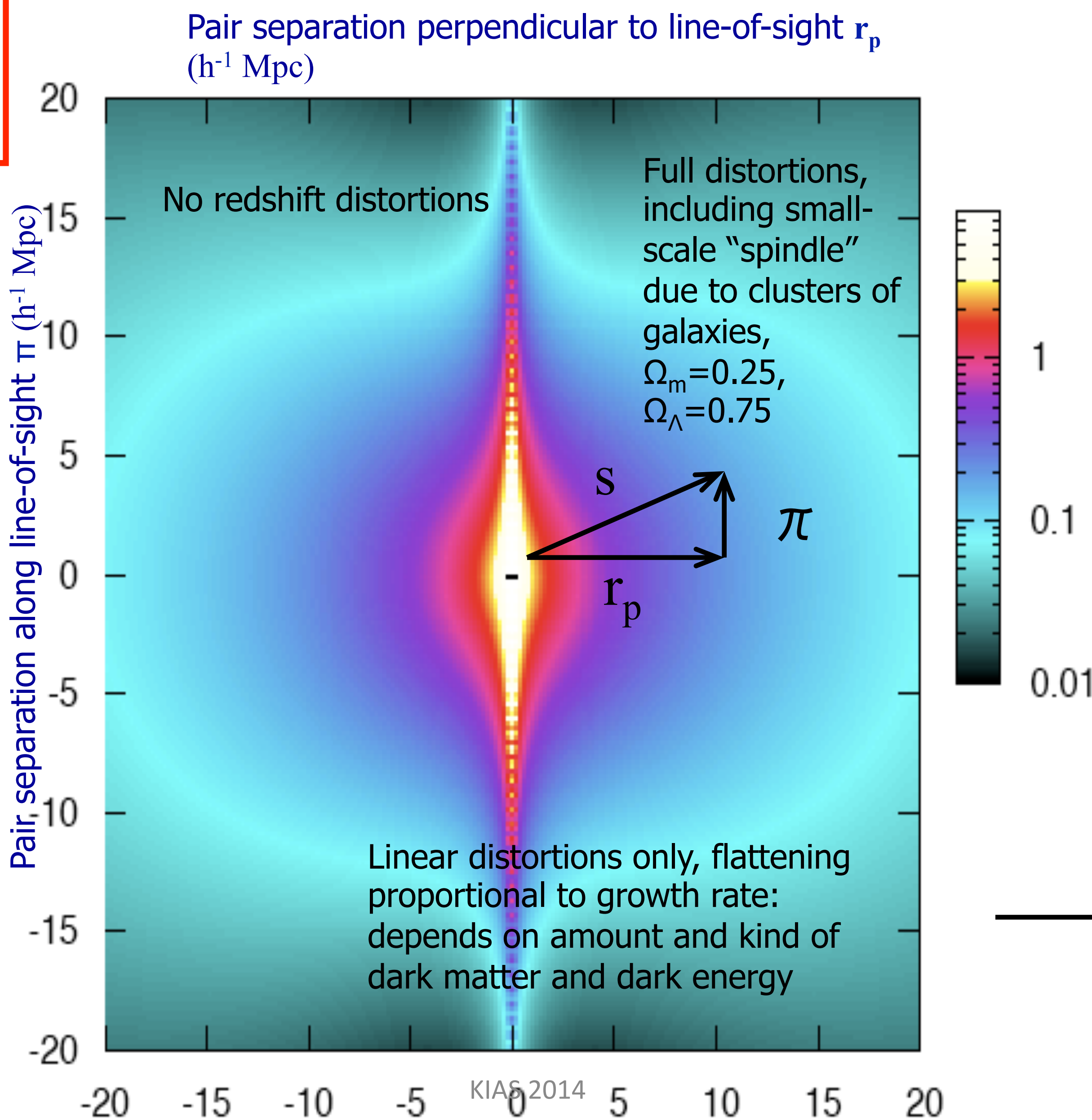
Y. Zheng, P. Zhang, Y. Jing, W. Lin, and J. Pan, Phys. Rev. D 88, 103510 (2013), 1308.0886
P. Zhang, Y. Zheng, Y. Jing, (2014, **paperSI**), PRD
Y. Zheng, P. Zhang, Y. Jing, (2014, **paperSII**), PRD
Y. Zheng, P. Zhang, Y. Jing, (2014, **paperB**), PRD, submitted

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



Line of sight to observer



$f = b_L\,\beta$

Compression parameter β(Kaiser 1987)

But we need to look at both sides of the story…

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

Modify gravity theory [e.g. ***R* → *f(R)***]

"…the Force be with you"

Add dark energy

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Probing Gravity at Cosmological Scales by Measurements which Test the Relationship between Gravitational Lensing and Matter Overdensity

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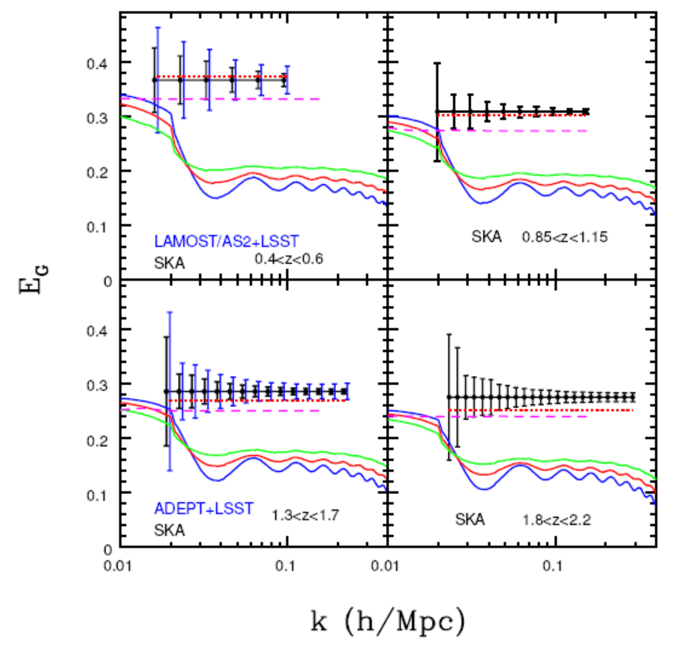
The standard cosmology is based on general relativity (GR) and includes dark matter and dark energy and predicts a fixed relationship between the gravitational potentials responsible for gravitational lensing and the matter overdensity. Alternative theories of gravity often make different predictions. We propose a set of measurements which can test this relationship, thereby distinguishing between dark energy or matter models and models in which gravity differs from GR. Planned surveys will be able to measure E_G, an observational quantity whose expectation value is equal to the ratio of the Laplacian of the Newtonian potentials to the peculiar velocity divergence, to percent accuracy. This will easily separate alternatives such as the cold dark matter model with a cosmological constant, Dvali-Gabadadze-Porrati, TeVeS
$f(R)$ gravity.

4个引力模型: GR，f(R)，DGP，TeVeS



张鹏杰等提出在宇宙学尺度上检验广义相对论与其他引力论的Eg方法

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 18 June 2010 (MN LaTeX style file v2.2)

Designing a space-based galaxy redshift survey to probe dark energy

Yun Wang[1*], Will Percival[2], Andrea Cimatti[3], Pia Mukherjee[4], I

- We also consider the dependence on the information used: the full galaxy power spectrum P(k), P(k) marginalized over its shape, or just the Baryon Acoustic Oscillations (BAO). We find that the inclusion of growth rate information (extracted using redshift space distortion and galaxy clustering amplitude measurements) leads to a factor of 3 improvement in the FoM, assuming general relativity is not modified. This inclusion partially compensates for the loss of information when o… straints, rather t…

$$P_{obs}(k_\perp^{ref}, k_\parallel^{ref}) = \frac{\left[D_A(z)^{ref}\right]^2 H(z)}{\left[D_A(z)\right]^2 H(z)^{ref}} b^2 \left(1+\beta\,\mu^2\right)^2 \cdot \left[\frac{G(z)}{G(0)}\right]^2 P_{matter}(k)_{z=}$$

Key assumption:
K_max=0.1 Mpc/h for z=0 and k_max=0.2 for z>1

Challenge

to model RSD at 1% accuracy
at k<0.1-03 h/Mpc

A nominal way in Literature

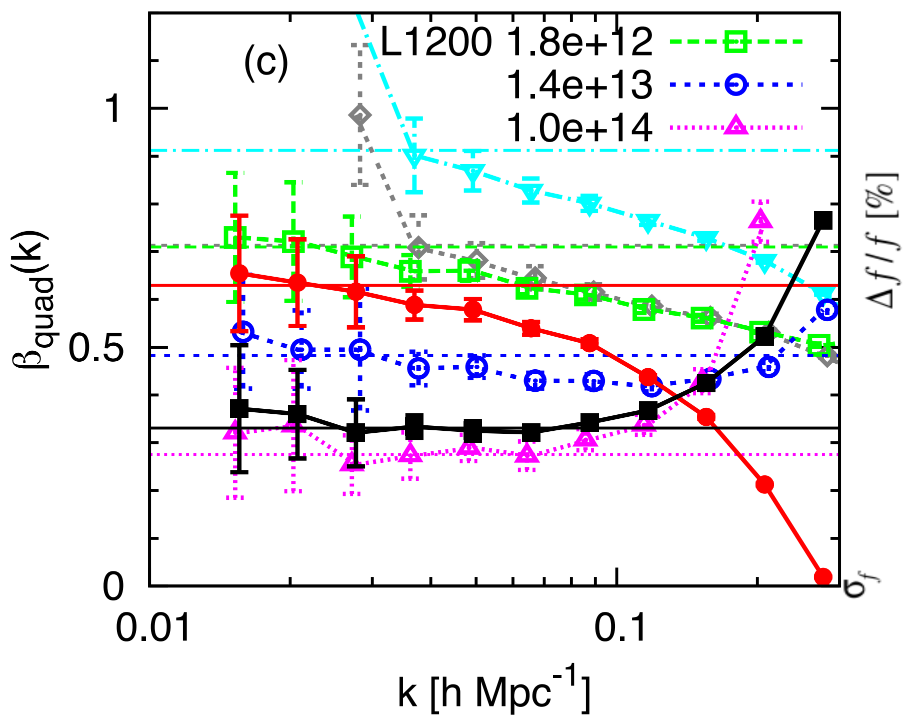
$$P^s_{\delta\delta}(k,u) \simeq P_{\delta\delta}(k)(1+fu^2)^2 D^{\mathrm{FOG}}(ku)$$

$$f \equiv d\ln D/d\ln a$$

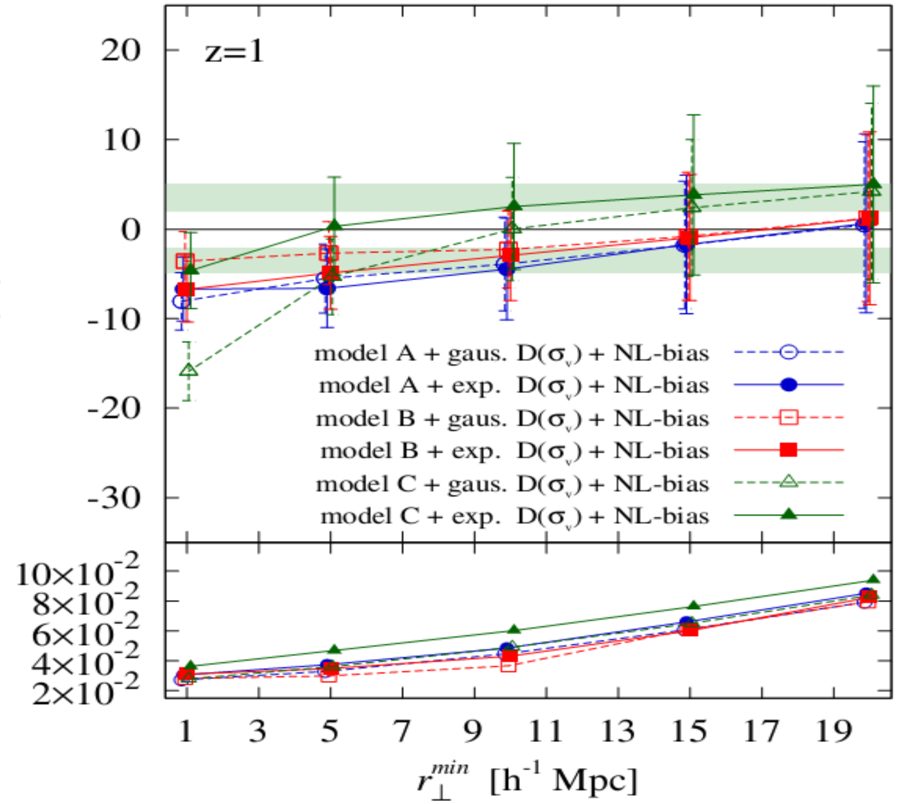
$$u \equiv k_{||}/k$$

One can change this easily for a deterministic linear bias b

Systematic error detected at 10% level



Okumura & Jing, 2010



Torre & Guzzo, 1202.5559

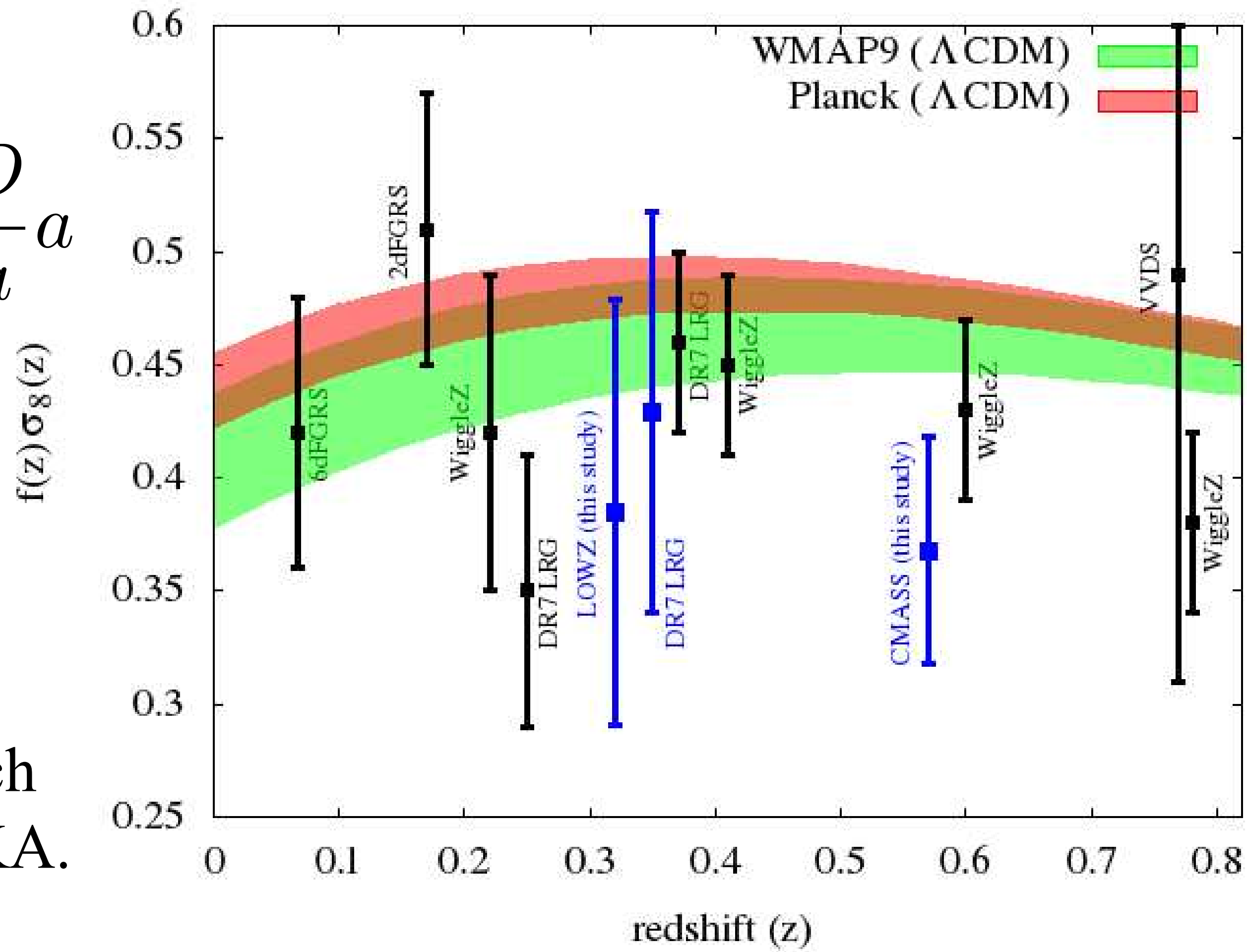
Beta=f/b

And many more works

Often further compressed into a single number

$$f(z)\sigma_8(z) \propto \frac{dD}{da}a$$

$$f \equiv \frac{d\ln D}{d\ln a}$$



Chuang et al. 1312.4889

Can achieve 1% for stage IV surveys such as MS-DESI and SKA.

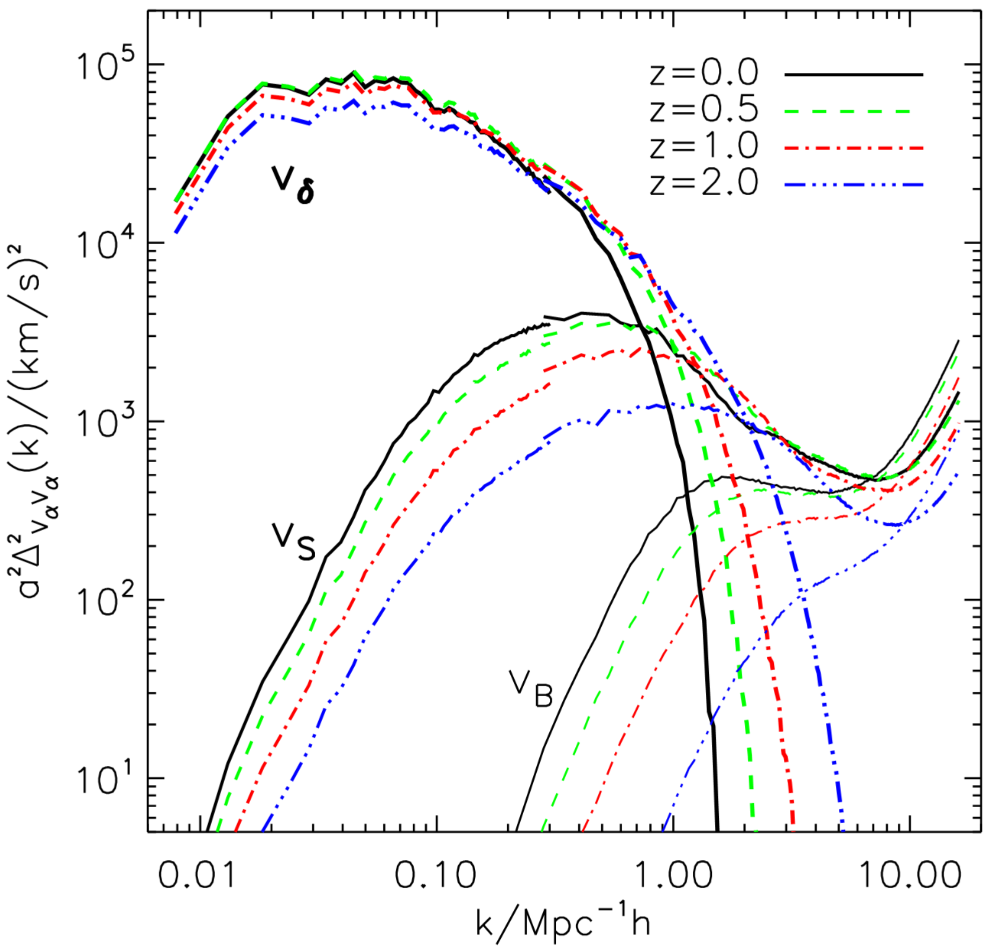
Challenging to achieve 1% accuracy

- Many works to improve RSD model
  - e.g. Peebles 1980,…, Kaiser 1987,…, Hamilton 1992,…, Scoccimarro, 2000, …, White 2001,…, Yang et al. 2002,…, Kang et al. 2002,…, Szapudi 2004,…, Zu et al. 2007,…, Tinker 2007, …, Matsubara 2008,…,Taruya et al. 2010,…, Kwan et al. 2011,…, Seljak & McDonald, 2011,..,Reid & White 2011,…Jennings et al. 2012,…
- Entangled complexities
  - **Nonlinear mapping between real and redshift space**
    - Redshift space 2pt is the sum of all N-pt in real space
  - **Nonlinearity in the dark matter density and velocity statistics**
    - Non-Gaussianity, no compact expression of redshift space ps
    - Stochastic velocity-density relation
  - **Nonlinear galaxy-dark matter relation**
    - Stochastic scale dependence density bias
    - Velocity bias
- Disentangle them!
  - ZPJ, Pan & Zheng, 2012; Zheng et al. 2013; ZPJ, Zheng & Jing, 2014, Zheng et al. in preparation,…
  - **Pengjie Zhang (SJTU), Yi Zheng (SHAO, Shanghai; Daejeong, Korea)**

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

The way to measure the three components in simulation

$$\mathbf{v}_E(\mathbf{k}) = \frac{(\mathbf{k}\cdot\mathbf{v}(\mathbf{k}))}{k^2}\mathbf{k}, \qquad (7)$$

$$\mathbf{v}_B(\mathbf{k}) = \mathbf{v}(\mathbf{k}) - \mathbf{v}_E(\mathbf{k}) \ .$$

ompose $\mathbf{v}_E$ into $\mathbf{v}_\delta$ and $\mathbf{v}_S$ [Eq. (3)],

$$\mathbf{v}_\delta(\mathbf{k}) = -i\frac{\delta(\mathbf{k})W(k)}{k^2}\mathbf{k} \ , \qquad (8)$$

$$\mathbf{v}_S(\mathbf{k}) = \mathbf{v}_E(\mathbf{k}) - \mathbf{v}_\delta(\mathbf{k}) \ .$$

Incomplete list of approximations/simplifications in RSD modeling

$$\mathbf{x}^s = \mathbf{x} + \frac{\mathbf{v}\cdot\hat{x}}{H}\hat{x}$$

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

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

Linear density-velocity relation, no velocity bias

Deterministic density-velocity

Negligible high order corrections

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

Further approximations often used in observations

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

Challenging to achieve 1% accuracy

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A formula of Zhang et al.(2013)

$$P^s_{\delta\delta}(k,u) = \Big\{P_{\delta\delta}(k)(1+f\tilde{W}(k)u^2)^2 + u^4 P_{\theta_S\theta_S}(k) + C_{NG}(k,u) + C_G(k,u) + C_S(k,u)\Big\} \times D^{\mathrm{FOG}}_{\delta}(ku) D^{\mathrm{FOG}}_{S}(ku) D^{\mathrm{FOG}}_{B}(ku)\ . \quad (26)$$

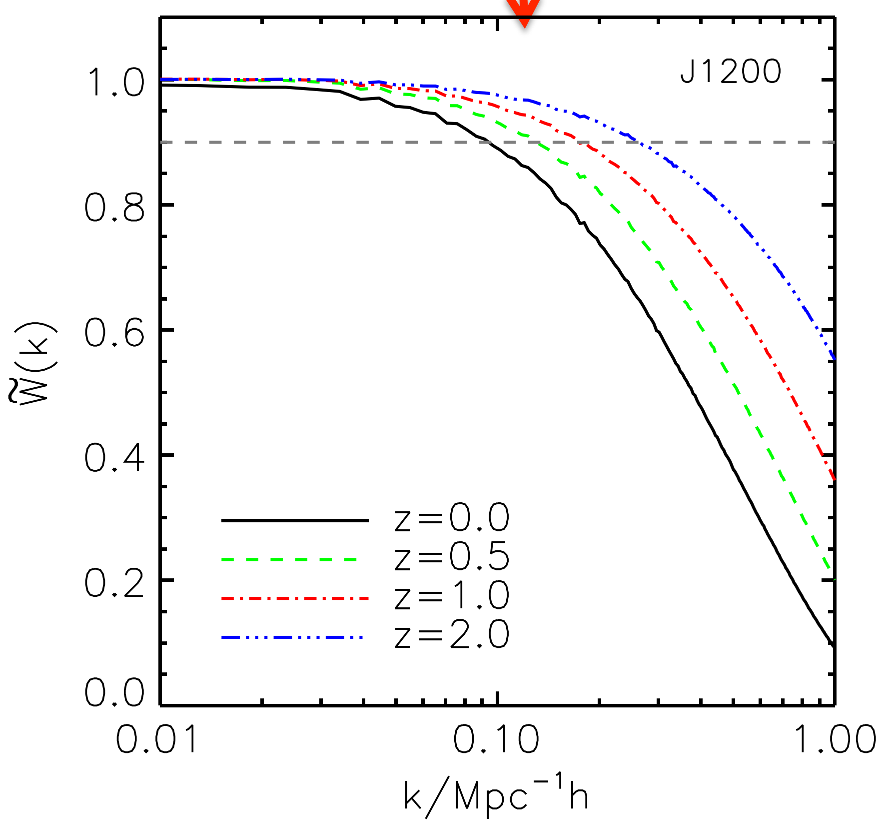
$$\theta(\mathbf{x}) \equiv -\nabla\cdot\mathbf{v}(\mathbf{x})/H \equiv -\nabla\cdot\mathbf{v}_E(\mathbf{x})/H.$$

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

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

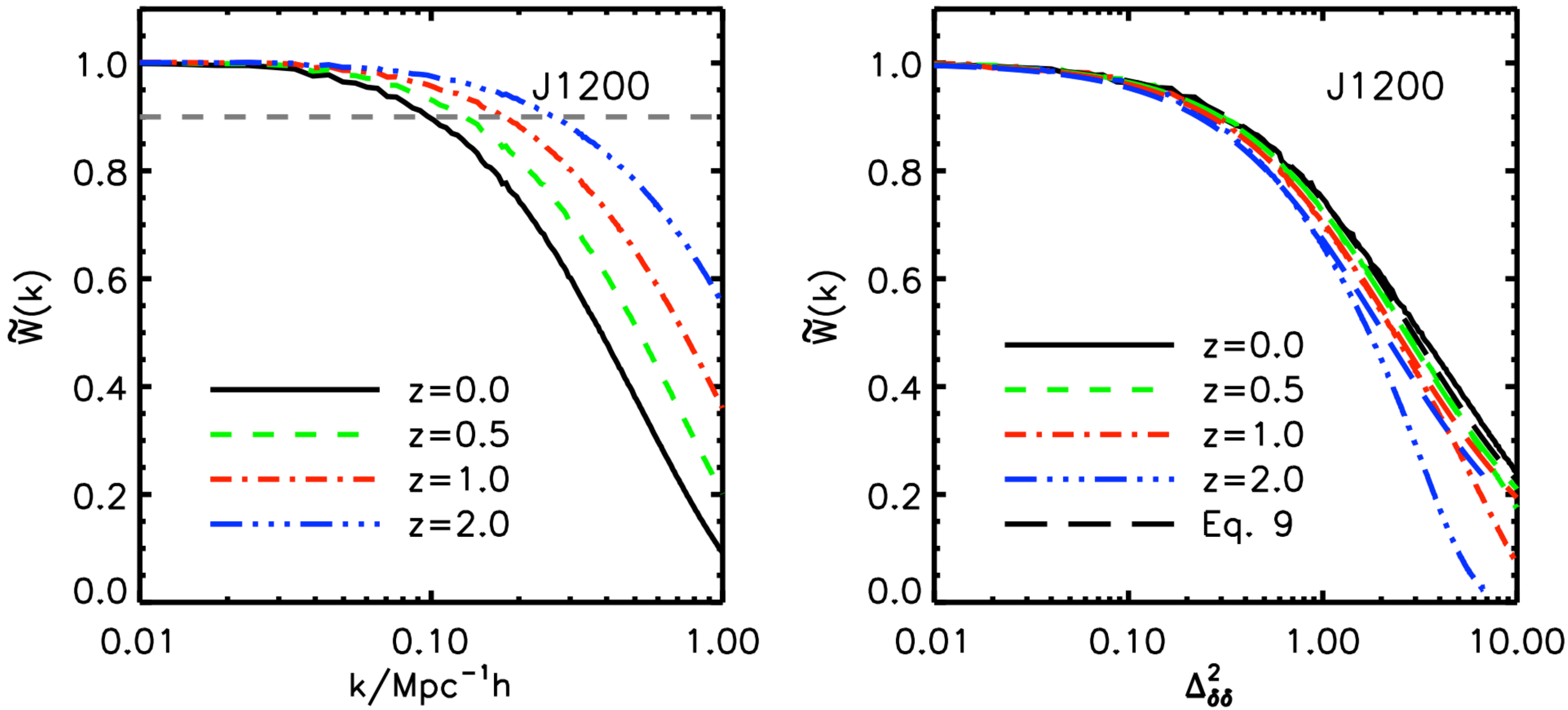
Disentangle RSD: nonlinear velocity-density

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



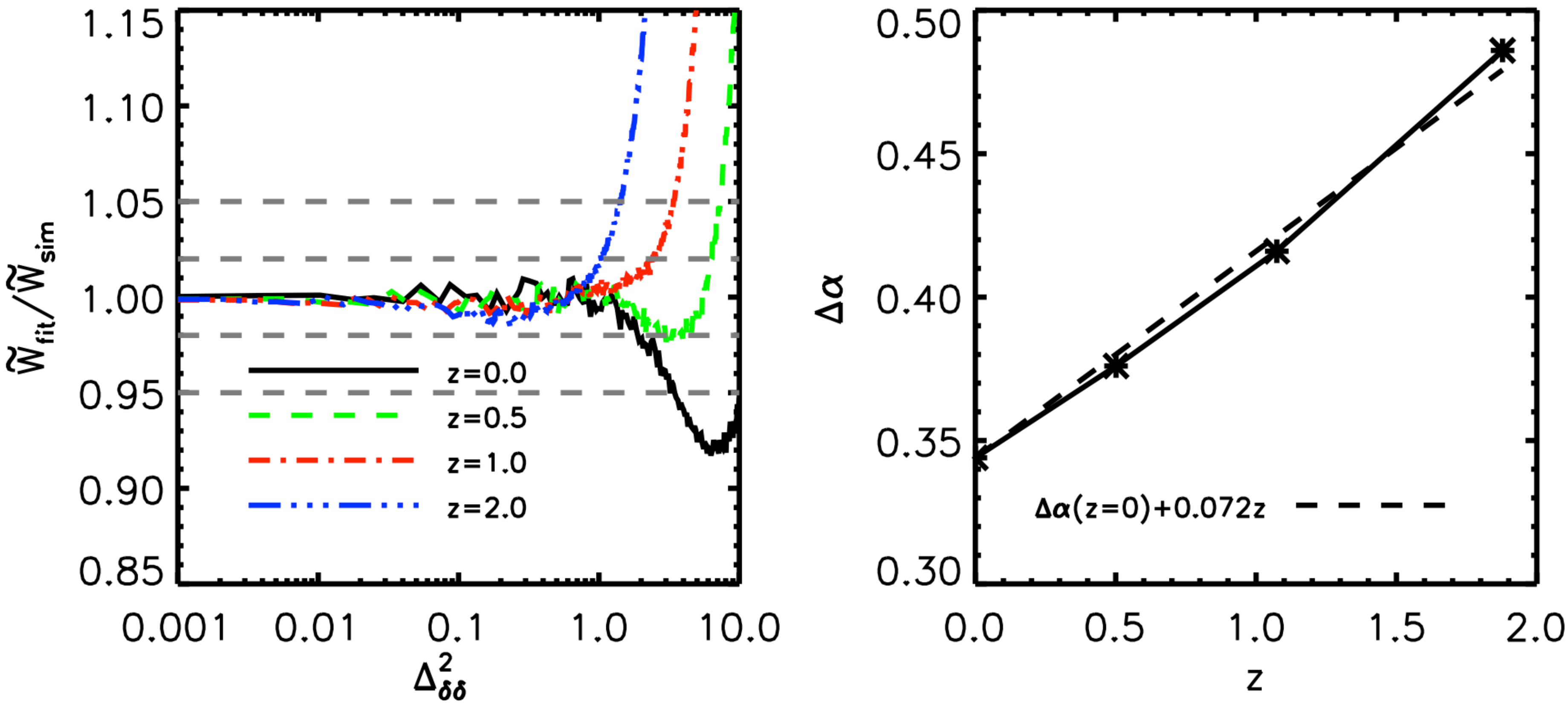
Zheng et al. 2013

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

$$\tilde{W}(k,z) = \frac{1}{1+\Delta\alpha(z)\Delta^2_{\rm NL}(k,z)} \equiv \frac{1}{1+\Delta\alpha(z)\Delta^2_{\delta\delta}(k,z)} . \quad (13)$$

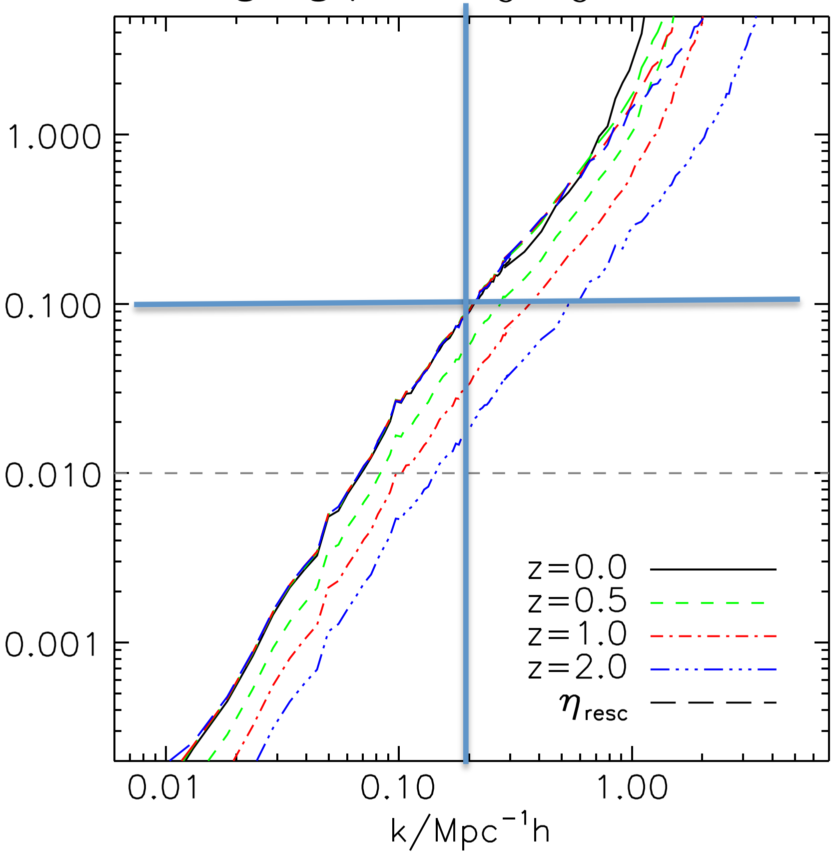
Redshift	$\Delta\alpha$	χ^2	χ^2_{dof}	$N_{\rm data}$
$z = 0$	0.344	1.001	0.026	38
$z = 0.5$	0.376	1.0	0.019	54
$z = 1$	0.416	1.001	0.012	82
$z = 2$	0.486	1.01	0.007	145


1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.001
0.01
0.1
1.0
10.0
$\Delta^2_{\delta\delta}$
$\tilde{W}_{fit}/\tilde{W}_{sim}$
z=0.0
z=0.5
z=1.0
z=2.0
0.50
0.45
0.40
0.35
0.30
0.0
0.5
1.0
1.5
2.0
z
$\Delta\alpha$
$\Delta\alpha(z=0)+0.072z$

Disentangle RSD: stochastic velocity-density

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

$P_{\theta_s\theta_s}/P_{\theta_\delta\theta_\delta}$



Zheng et al. 2013

- Stochastic velocity v_S has a leading order contribution with u^4 directional dependence
- **O(1%) effect at k=0.1h/Mpc and z=0-2.**

Disentangle RSD: Finger of God

$$D_B(k_z, \mathbf{r}) \equiv \left\langle \exp\left(i \frac{k_z(v_{1z,B} - v_{2z,B})}{H} \right) \right\rangle$$

Similarly for s and delta velocity components

Zheng et al. 2013

One-point distribution function

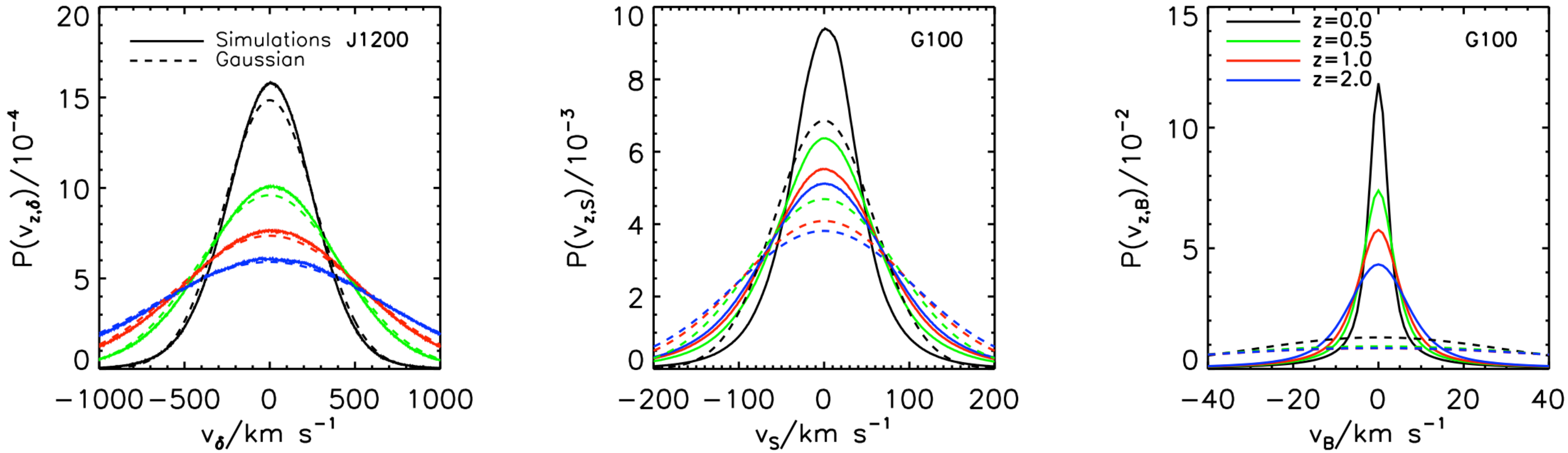


FIG. 8: The PDFs of $\mathbf{v}_{\delta,S,B}$ along the z axis are shown by solid lines. The dashed lines show Gaussian distributions with the same velocity mean and dispersion of corresponding velocity PDFs. Different line colors represent different redshifts. Apparently, $\mathbf{v}_\delta$ is the most Gaussian velocity component since it mainly correlates with linear matter density field and the window function $\tilde{W}$ suppresses non-Gaussianities from small scales. In contrast, $\mathbf{v}_B$ is strongly non-Gaussian, consistent with the fact that most contribution comes from strongly nonlinear and non-Gaussian scales.

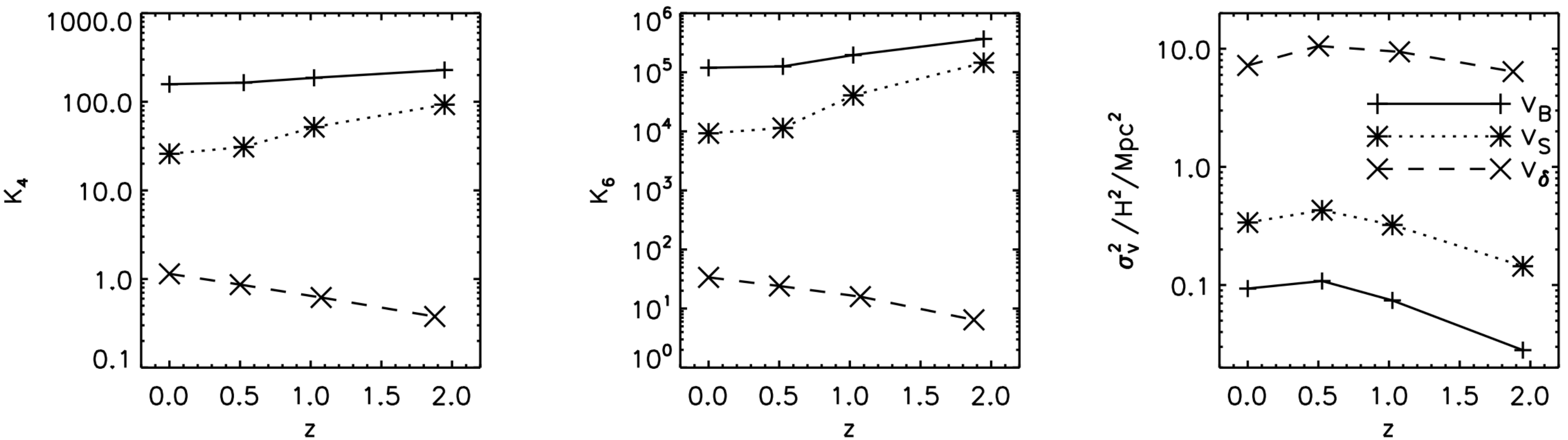
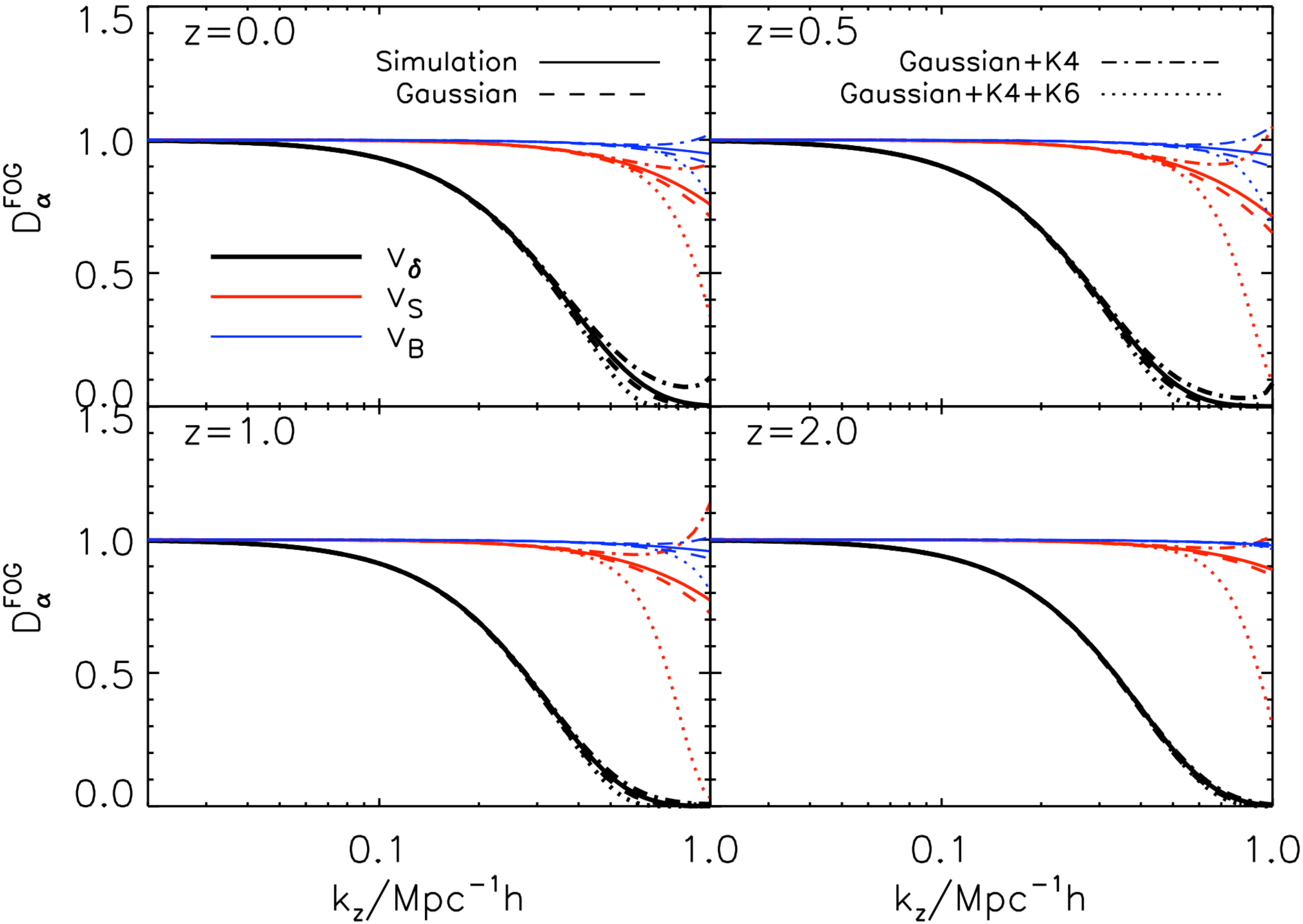


FIG. 9: *Left and middle panels*: The fourth and sixth order of reduced cumulants of $\mathbf{v}_{\delta,S,B}$. They confirm the non-Gaussianity results shown in Fig. 8. Towards lower redshift, non-Gaussianities of $\mathbf{v}_{S,B}$ decrease, likely due to ongoing halo virialization and the associated velocity randomization, while non-Gaussianity of $\mathbf{v}_\delta$ increases due to nonlinear structure evolution. *Right panel*: $\sigma^2_{v_\alpha}/H^2$ determines the leading-order damping to redshift space clustering caused by the FOG effect [Eq. (23), Fig. 10].

$$K_4 \equiv \frac{\langle v^4\rangle}{\langle v^2\rangle^2} - 3 \, ,$$

$$K_6 \equiv \frac{\langle v^6\rangle}{\langle v^2\rangle^3} - 10\frac{\langle v^3\rangle^2}{\langle v^2\rangle^3} - 15\frac{\langle v^4\rangle}{\langle v^2\rangle^2} + 30$$


z=0.0
z=0.5
z=1.0
z=2.0
Simulation
Gaussian
Gaussian+K4
Gaussian+K4+K6
v_δ
v_S
v_B
D_α^{FOG}
1.5
1.0
0.5
0.0
0.1
1.0
$k_z/\mathrm{Mpc}^{-1}h$

locity dispersion,

$$\sigma_{v_\alpha}^2 = \xi_{v_{z,\alpha} v_{z,\alpha}}(r=0) = \frac{1}{3}\int \Delta^2_{v_\alpha v_\alpha}(k)\frac{dk}{k}\ . \qquad (22)$$

To the first order, the damping functions take Gaussian form,

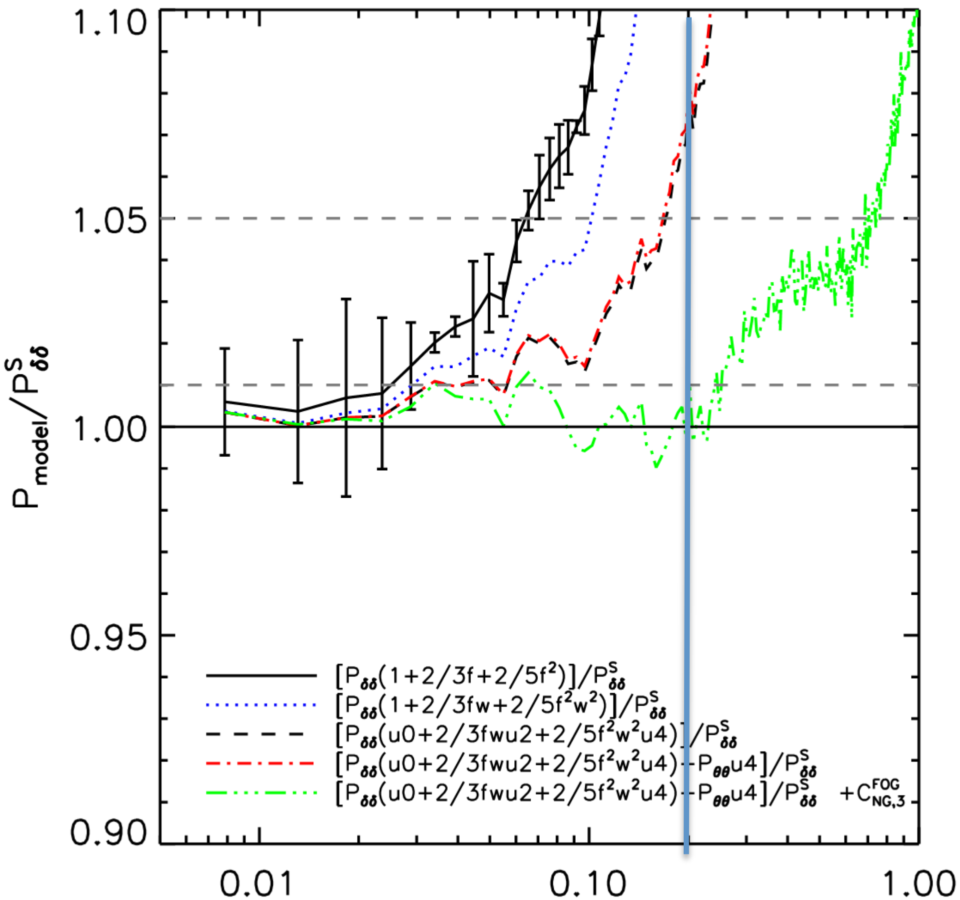
$$\sqrt{D_\alpha^{\rm FOG}(k_z)} = \exp\left(-\frac{x}{2}\right) = \exp\left(-\frac{(k_z\sigma_{v_\alpha})^2}{2H^2}\right)\ . \quad (23)$$

$$\begin{aligned} D^{\rm FOG}(k_z) &\equiv D_\delta^{\rm FOG}(k_z) D_S^{\rm FOG}(k_z) D_B^{\rm FOG}(k_z) \quad (24) \\ &\simeq \exp\left(-\frac{k_z^2(\sigma_{v_\delta}^2+\sigma_{v_S}^2+\sigma_{v_B}^2)}{H^2}\right) \\ &\simeq \exp\left(-\frac{k_z^2\sigma_{v_\delta}^2}{H^2}\right)\ . \end{aligned}$$

Gaussian, not Lorentz

Disentangle RSD: 1% at k<0.2 Mpc/h

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



- **C_G, $C_{NG,3}$ arise from v_δ .**
- **Fully determined by W! No degrees of freedom (ZPJ et al. 2012)**
- **Including them improves the accuracy, without sacrifice on constraining power.**
- Many more tests to fully quantify its accuracy (Zheng et al. 2014, in preparation)

Now galaxy bias

- Spatial sampling bias
- Dynamical velocity bias
- Spatial +velocity coupling bias
- …..
- First, go to dark matter halos

Challenging to achieve 1% accuracy

- Many works to improve RSD model
  - e.g. Peebles 1980,…, Kaiser 1987,…, Hamilton 1992,…, Scoccimarro, 2000, …, White 2001,…, Yang et al. 2002,…, Kang et al. 2002,…, Szapudi 2004,…, Zu et al. 2007,…, Tinker 2007, …, Matsubara 2008,…,Taruya et al. 2010,…, Kwan et al. 2011,…, Seljak & McDonald, 2011,..,Reid & White 2011,…Jennings et al. 2012,…
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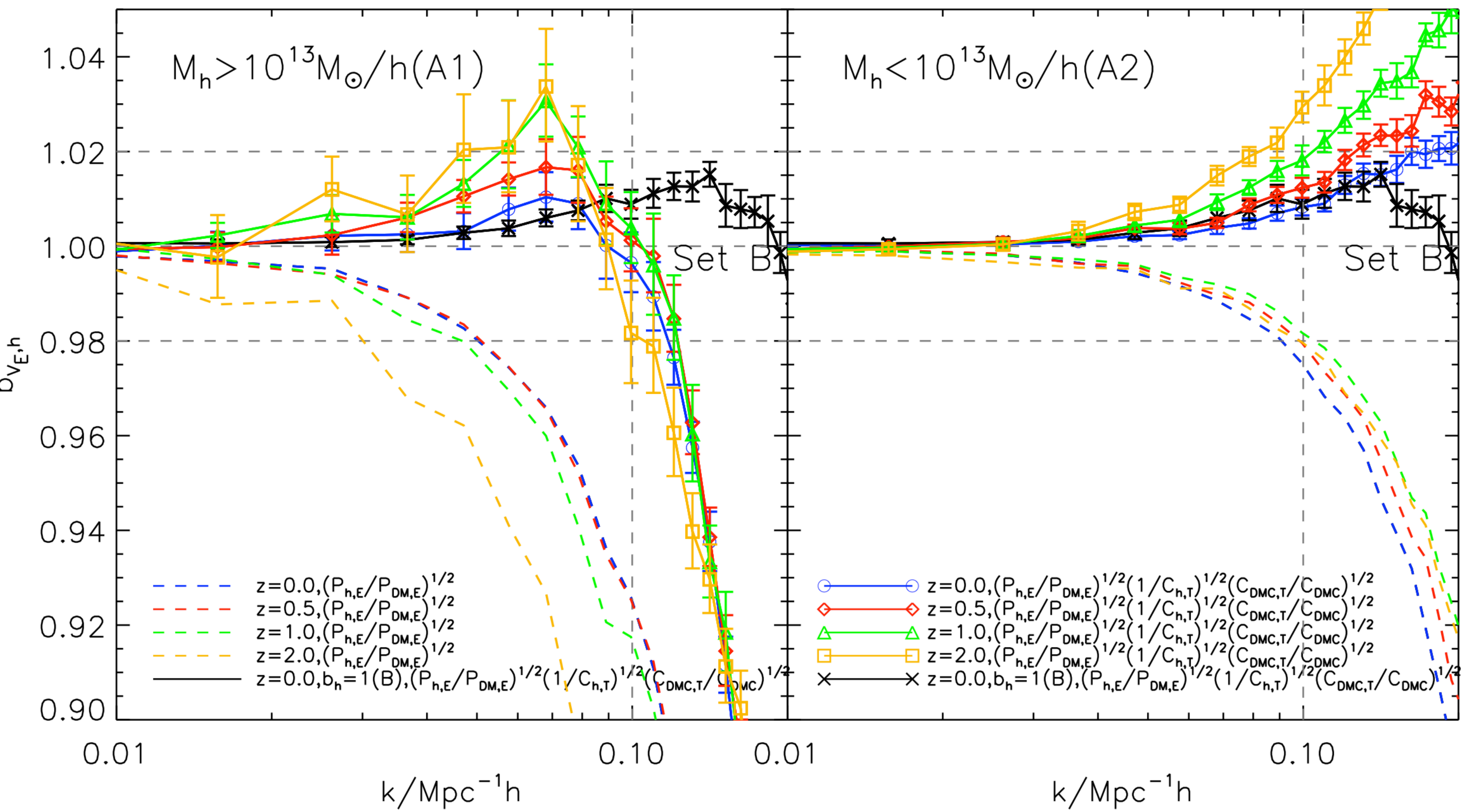
Velocity bias at z≥0: No velocity biass for k<0.1 h/Mpc



Zheng et al. 2014

Conclusions

- 1% level accuracy presents a key challenge to the theoretical modeling of RSD;
- A way of decomposing velocity into 3 components can filter out unwanted and simplify the modeling; our results point to a promising start: 1% accuracy is achievable for k<0.1-0.3 h/Mpc;
- Finger-of-God effect is a Gaussian form, determined by the velocity power spectrum of the density induced gradient part;
- No significant halo velocity bias for k<0.1 h/Mpc

Future

- Now we are applying the model to BOSS sample;
- Including subhalos to study galaxy velocity power spectrum;
- We are using scale-free models to improve our model accuracy;
- Hydro simulations (big enough?)