(Cosmological group at KASI)
http://cosmology.kasi.re.kr/

Halo redshift space distortion

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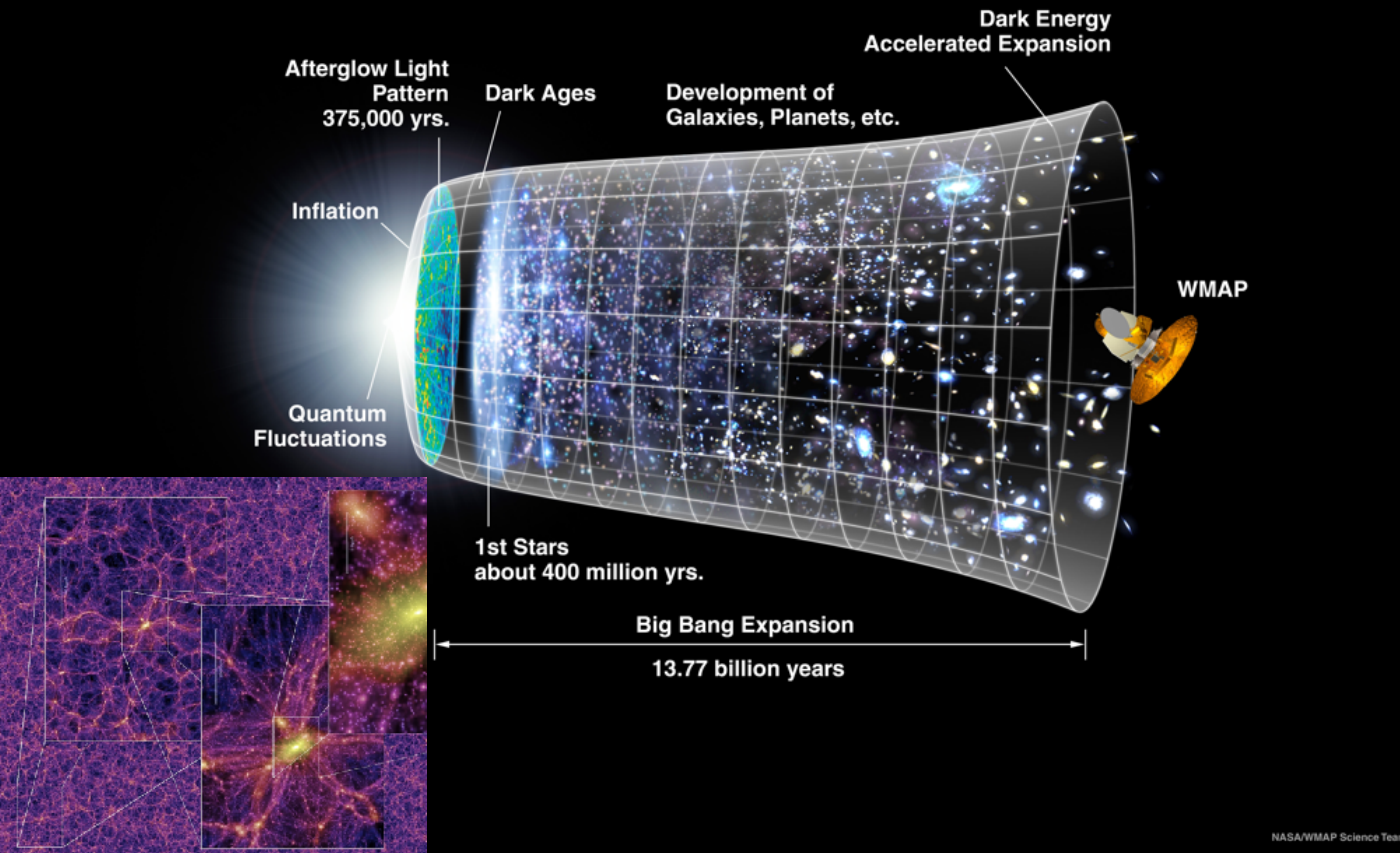
Y. Zheng, Y. Song, arXiv: 1603.00101, JCAP accepted
Y. Zheng, Y. Song and M.Oh, in preparation, 2017
Y. Song, Y. Zheng, M. Oh, and A. Taruya, in preparation, 2017

In general



Afterglow Light Pattern 375,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Dark Energy Accelerated Expansion
Inflation
Quantum Fluctuations
WMAP
1st Stars about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

$$\boxed{\underbrace{R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R}_{\text{Modified gravity}} = \underbrace{-\kappa T_{\mu\nu}}_{\text{Dark Energy}},}$$

1. Background level:

$$ds^2 = c^2\,dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\,d\phi^2\right)\right]$$

$$\boxed{H^2 = \frac{8\pi G}{3}\left(\textstyle\sum_i \rho_i\right) - \frac{c^2 k}{R^2}}$$

2. Perturbation level:

$$ds^2 = -(1+2\psi)dt^2 + (1-2\phi)a^2(t)d\vec{x}^2,$$

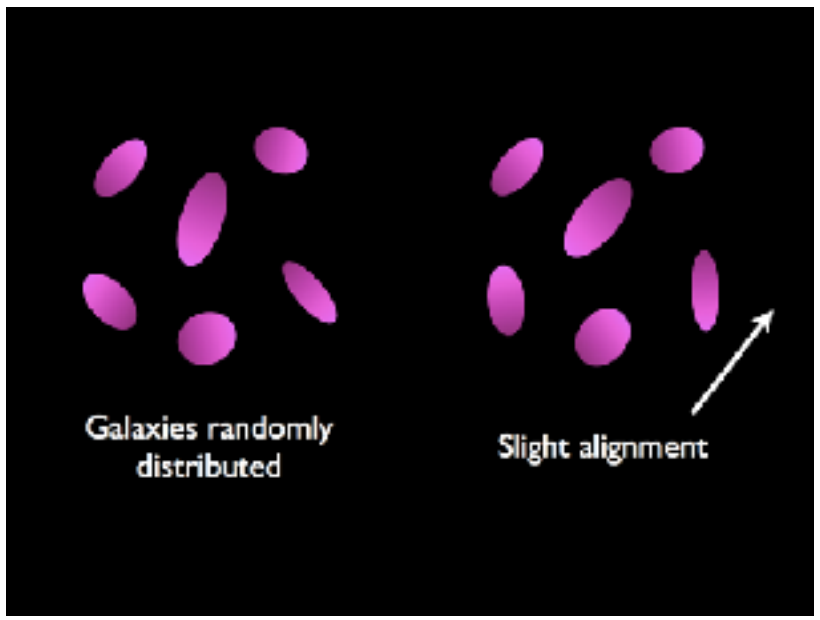
$$\boxed{\begin{aligned} k^2\phi &= -4\pi G a^2 \bar{\rho}_{\rm GR}\left[\delta_{\rm GR} + 3(1+w)Ha\,\frac{\theta_{\rm GR}}{k^2}\right], \\ &\simeq -4\pi G a^2 \bar{\rho}_{\rm GR}\,\delta_{\rm GR}, \end{aligned}}$$

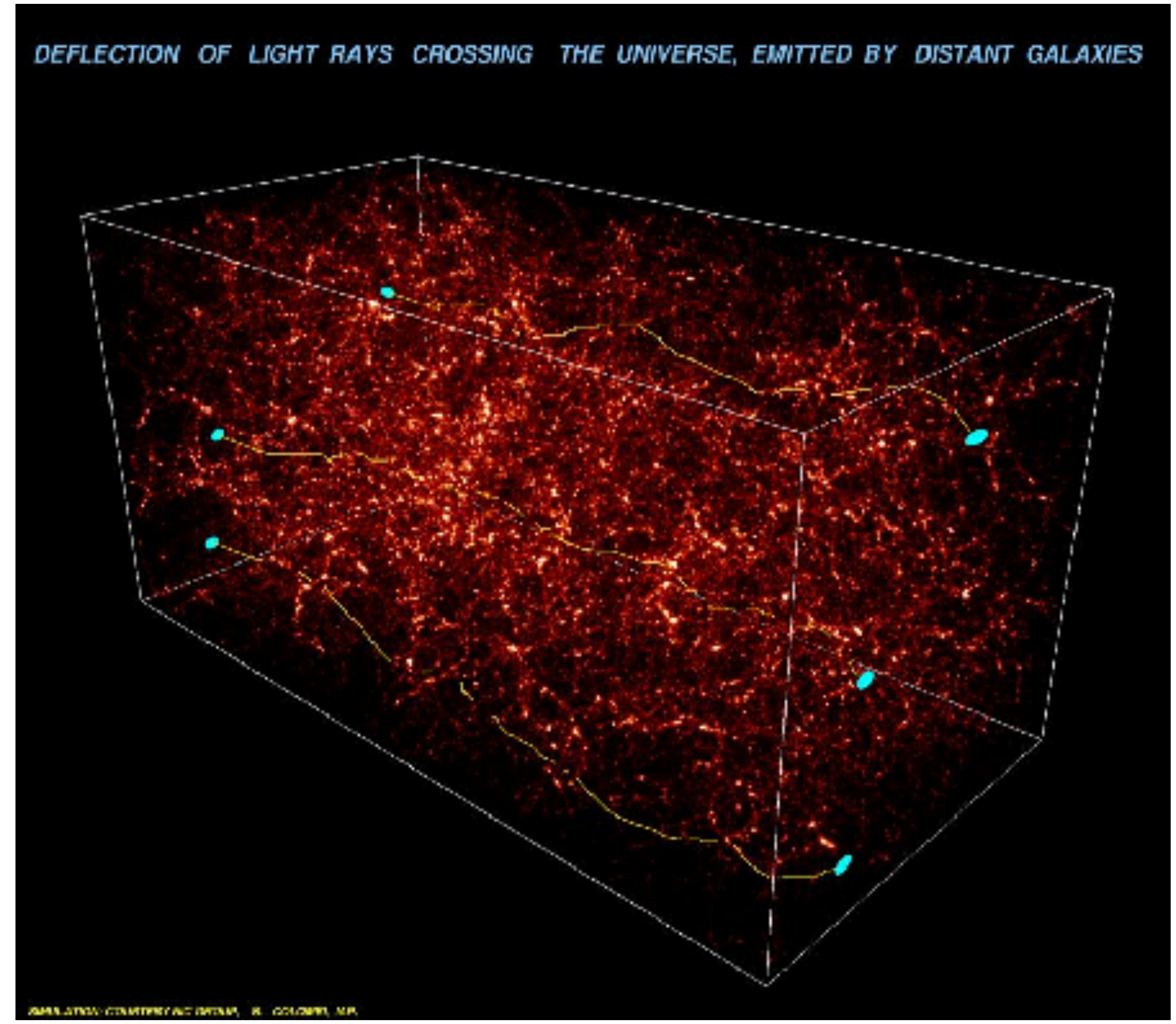
$$\boxed{k^2(\phi - \psi) = \cancel{12\pi G a^2(1+w)\bar{\rho}\sigma,}}$$

Jain,Zhang 0709.2375

Structure growth

- weak lensing (tomography)



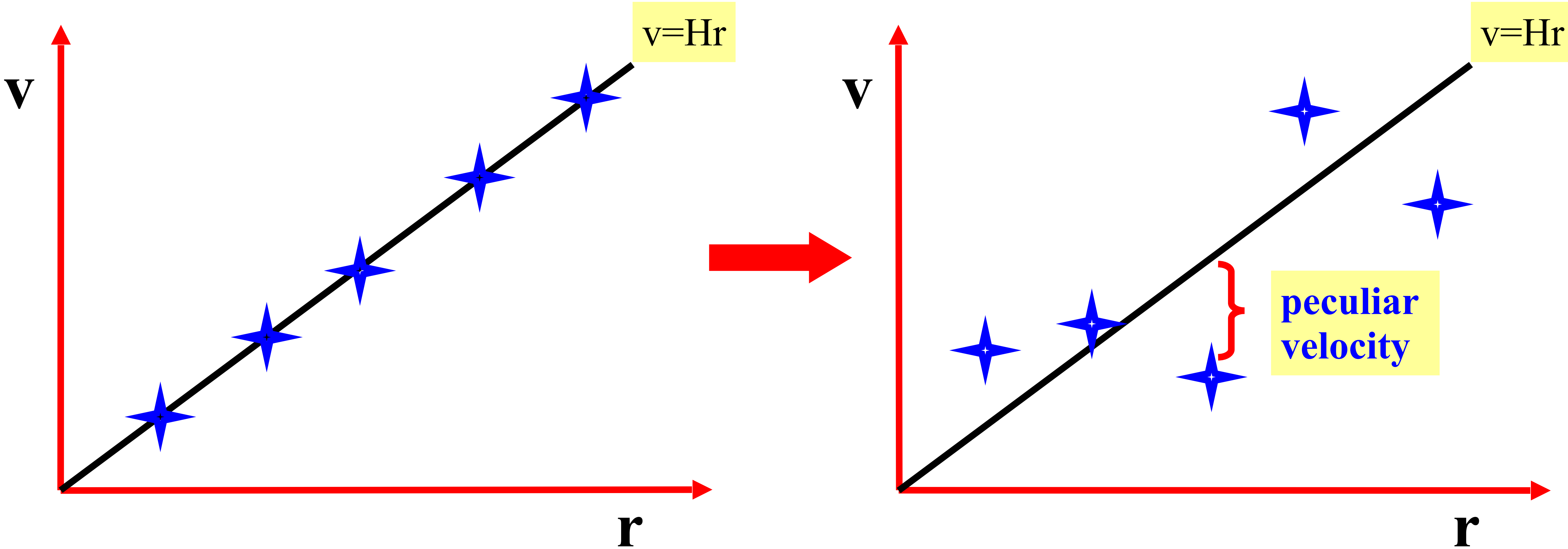


- velocity field

$$\frac{d\delta}{dt} + \frac{1}{a}\nabla \bullet \vec{v} = 0$$

Peculiar velocity: a window to the dark universe

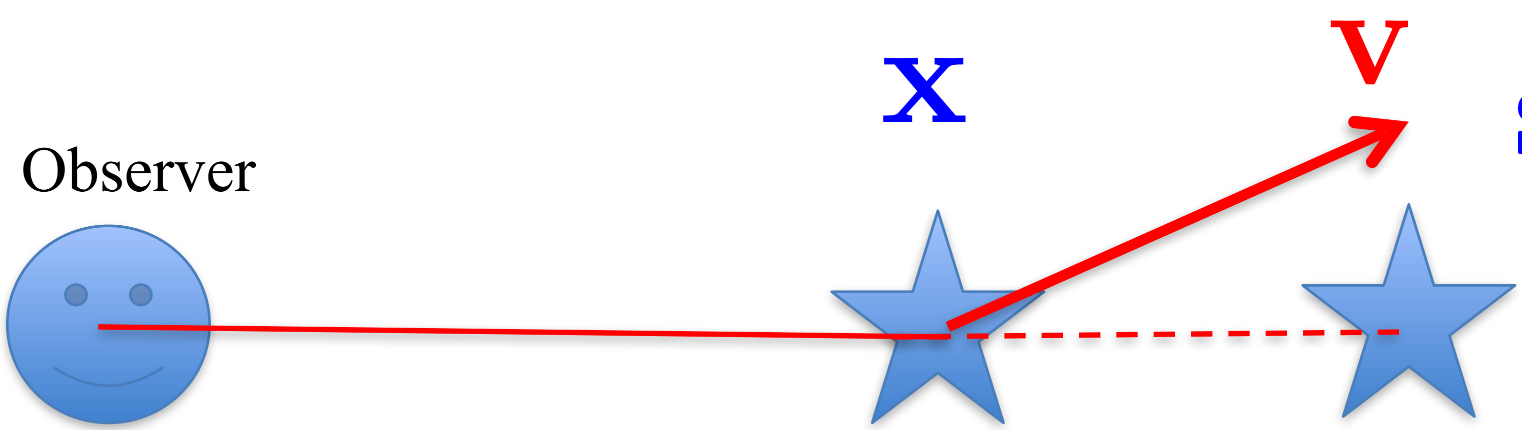
- **Matter distribution in our universe is inhomogeneous**
- **Gravitational attraction arising from inhomogeneity perturbs galaxies and causes deviation from the Hubble flow**



PJZ'PPT

Redshift space distortion

$$z^o = z + v_z$$



$$\mathbf{s} = \mathbf{x} + \frac{v_z}{H}\hat{z}$$

- Peculiar velocity changes the galaxy redshift and hence distorts the galaxy distribution in an anisotropic way
- Galaxy clustering along the line of sight is different to that perpendicular to the line of sight

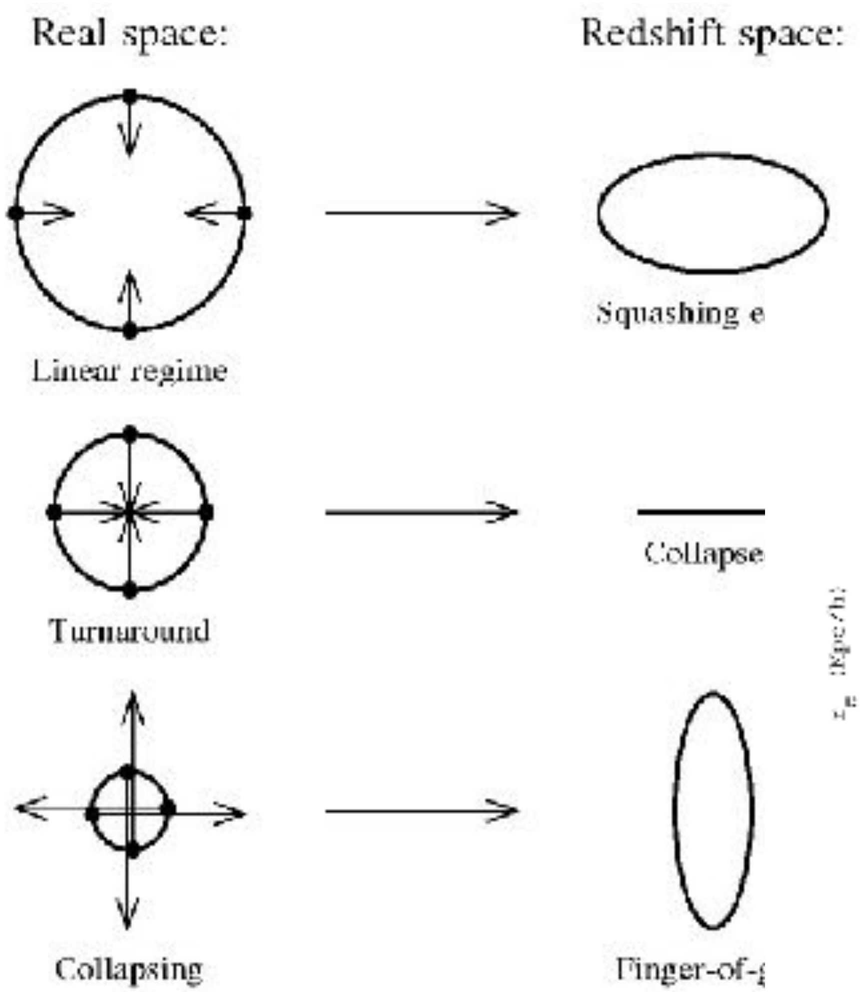
PJZ'PPT

RSD Introduction

Redshift space distortion

In observation, galaxy distance is determined by "redshift"

Peculiar velocity of galaxies cause them to appear displaced along the line of sight in redshift space



A. J. S. Hamilton, astro-ph/9708102

SDSS DR9, CMASS, 2D correlation function

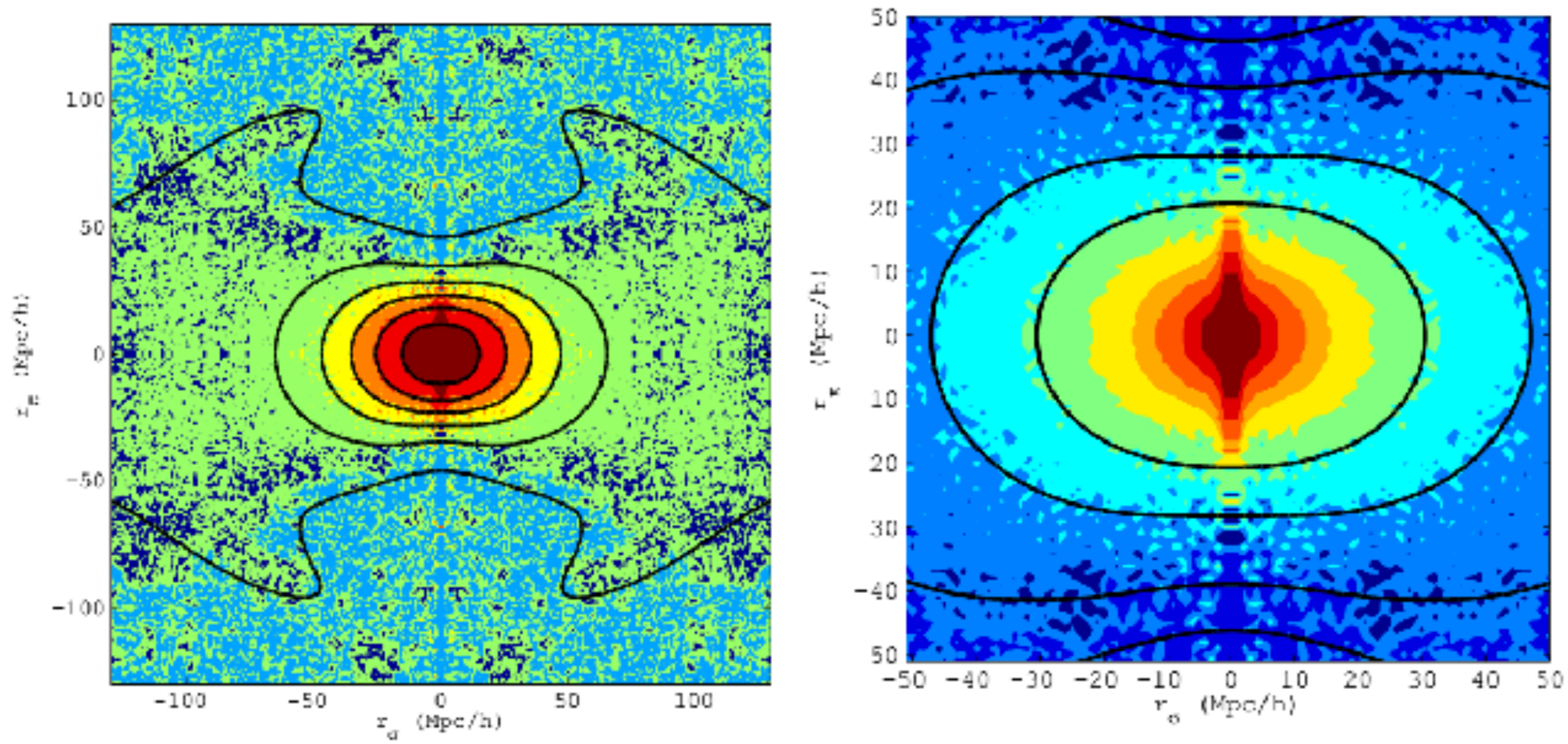
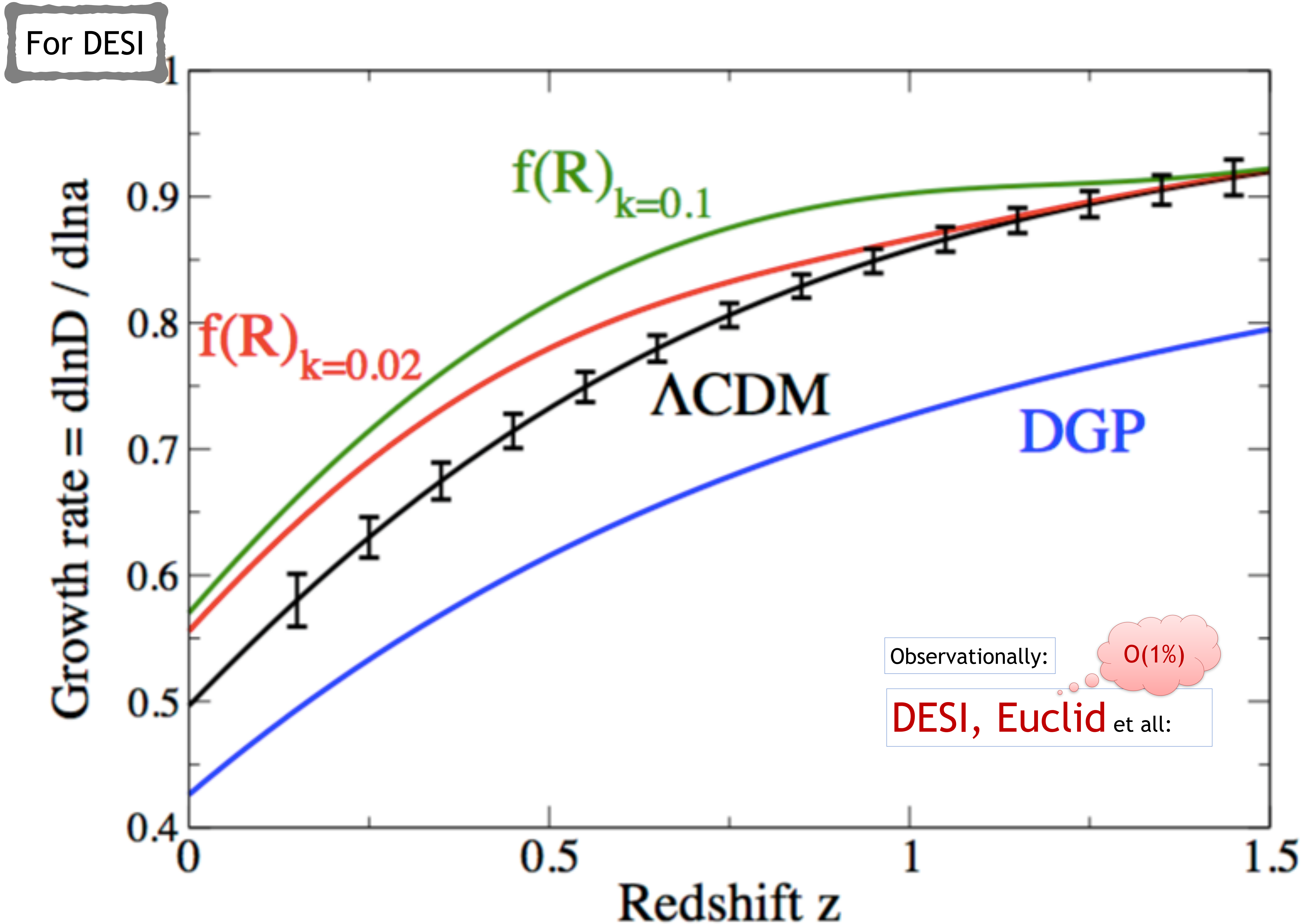


Figure 3. *Left panel*: Two-dimensional correlation function of CMASS galaxies (color) compared with the best fit model described in Section 6.1 (black lines). Contours of equal ξ are shown at [0.6, 0.2, 0.1, 0.05, 0.02, 0]. *Right panel*: Smaller-scale two-dimensional clustering. We show model contours at [0.14, 0.05, 0.01, 0]. The value of ξ_0 at the minimum separation bin in our analysis is shown as the innermost contour. The $\mu \approx 1$ "finger-of-god" effects are small on the scales we use in this analysis.

Reid et al. 1203.6641

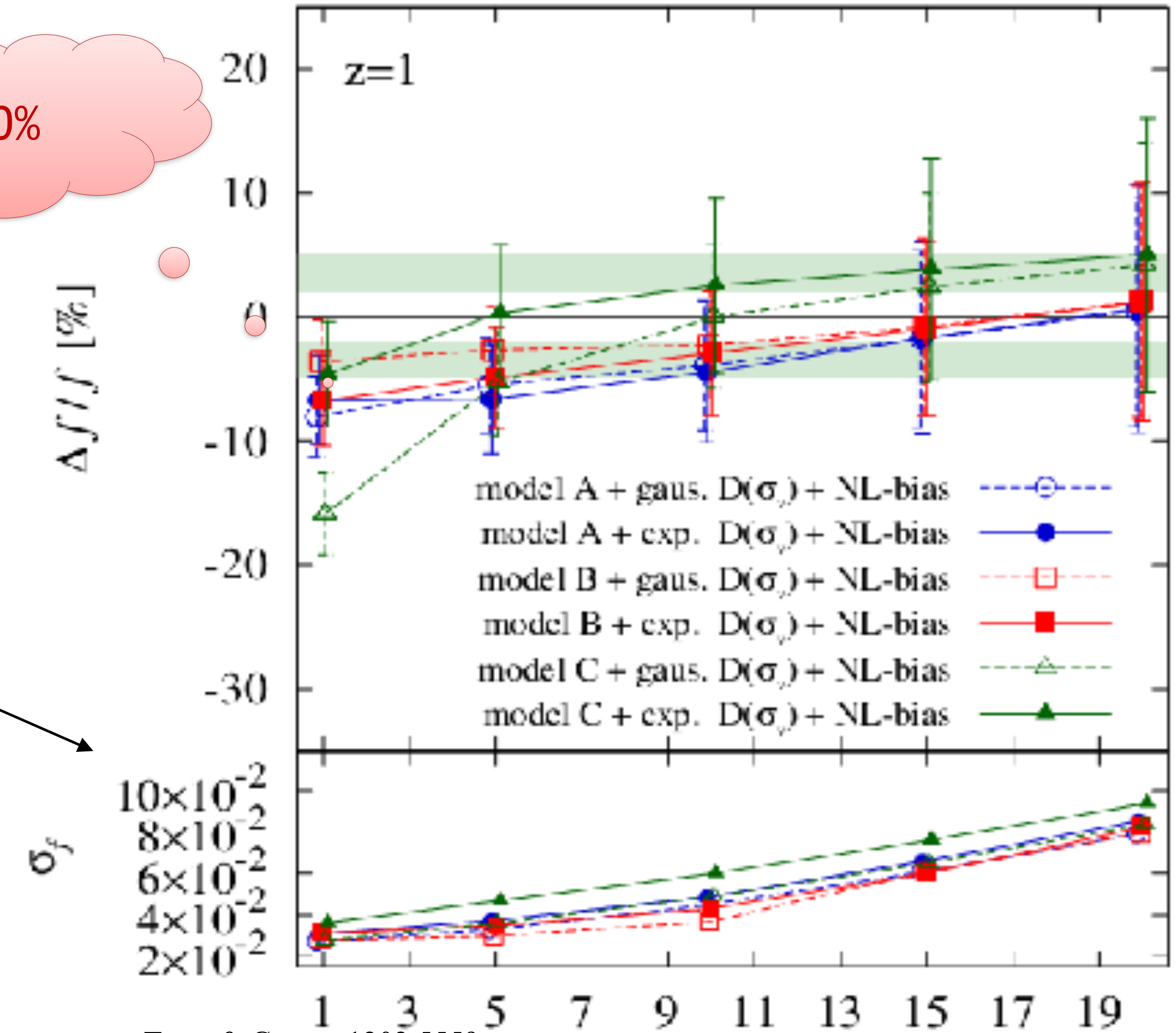


Huterer et al. 1309.5385

Redshift space distortion: small scale modelling and systematic errors

$$\boxed{N_k \propto k^3}$$

5-10%

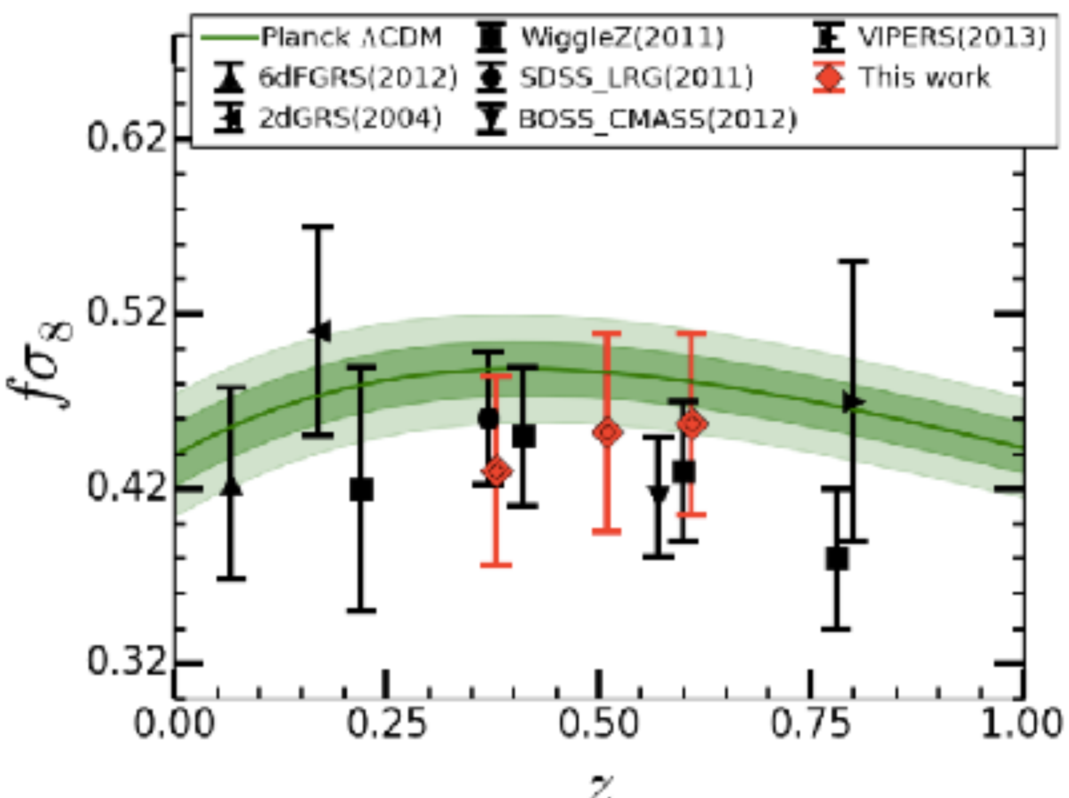


Torre & Guzzo, 1202.5559

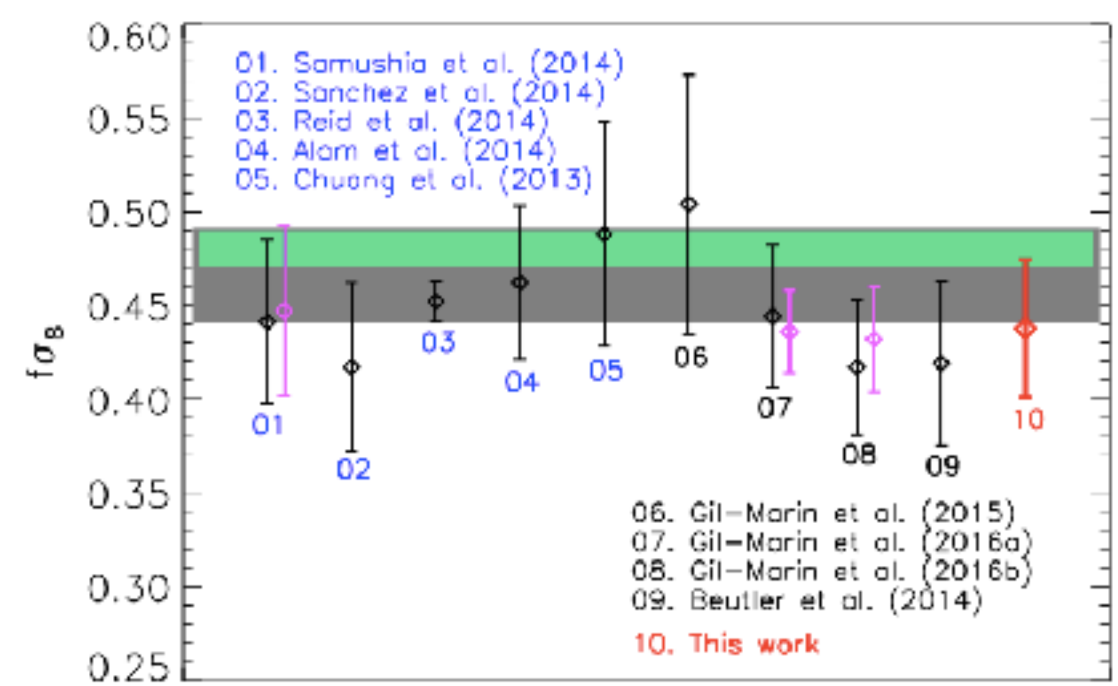
Observationally:

O(1%)

DESI, Euclid et all:



1607.03148



1609.03697

Redshift space distortion modelling: three steps

1. Non-linear mapping of dark matter/halo/galaxy clustering from real space to redshift space

$$P^{(S)}(k,\mu) = \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \langle e^{j_1 A_1} A_2 A_3 \rangle$$

2. Non-linear evolution of density and velocity fields

——— Perturbation theory & High-resolution simulations

$$\delta_n(\mathbf{k}) = \int d^3\mathbf{q}_1 \cdots \int d^3\mathbf{q}_n\, \delta_D(\mathbf{k} - \mathbf{q}_{1\cdots n}) F_n(\mathbf{q}_1, \ldots, \mathbf{q}_n) \delta_1(\mathbf{q}_1) \cdots \delta_1(\mathbf{q}_n)\,,$$

$$\theta_n(\mathbf{k}) = \int d^3\mathbf{q}_1 \cdots \int d^3\mathbf{q}_n\, \delta_D(\mathbf{k} - \mathbf{q}_{1\cdots n}) G_n(\mathbf{q}_1, \ldots, \mathbf{q}_n) \delta_1(\mathbf{q}_1) \cdots \delta_1(\mathbf{q}_n)\,,$$

F. Bernardeau et al, 2002

3. Galaxy/halo density and velocity bias modelling

$$\delta_g(\boldsymbol{x}) = b_1 \delta(\boldsymbol{x}) + \frac{1}{2} b_2 [\delta(\boldsymbol{x})^2 - \sigma_2] + \frac{1}{2} b_{s^2} [s(\boldsymbol{x})^2 - \langle s^2 \rangle] + \text{higher order terms},$$

McDonald&Roy, 0902.0991

1. DM Mapping formula

$$P^{(\mathrm{S})}(k,\mu) = \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \langle e^{j_1 A_1} A_2 A_3 \rangle$$

$$\delta_D(\boldsymbol{k}) + P_s(\boldsymbol{k}) = \int \frac{d^3 r}{(2\pi)^3} e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} \langle e^{ifk_z \Delta u_z}[1+\delta(\boldsymbol{x})] \times [1+\delta(\boldsymbol{x}')]\rangle,$$

e.g. Scoccimarro astro-ph/0407214
Zhang 1207.2722

$$P^{(\mathrm{S})}(k,\mu) = \int \frac{d^3 r}{(2\pi)^3} e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} \langle e^{ifk_z u_z}[1+\delta(\boldsymbol{x})] e^{-ifk_z u'_z}[1+\delta(\boldsymbol{x}')]\rangle$$

Taylor expansion!

$$P^{ss}(\mathbf{k}) = \sum_{L=0}^{\infty} \frac{1}{L!^2}\left(\frac{k\mu}{H}\right)^{2L} P_{LL}(\mathbf{k}) + 2\sum_{L=0}^{\infty}\sum_{L'>L} \frac{(-1)^L}{L!\,L'!}\left(\frac{ik\mu}{H}\right)^{L+L'} P_{LL'}(\mathbf{k})$$

Seljak&McDonald 1109.1888

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

e.g. TNS 1006.0699

$$\langle e^{j_1 A_1} A_2 A_3\rangle = \exp\{\langle e^{j_1 A_1}\rangle_c\}[\langle e^{j_1 A_1} A_2 A_3\rangle_c + \langle e^{j_1 A_1} A_2\rangle_c \langle e^{j_1 A_1} A_3\rangle_c].$$

Cumulant expansion

$$P^{(\mathrm{S})}(k,\mu) = \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \exp\{\langle e^{j_1 A_1}\rangle_c\}[\langle e^{j_1 A_1} A_2 A_3\rangle_c + \langle e^{j_1 A_1} A_2\rangle_c \langle e^{j_1 A_1} A_3\rangle_c].$$

FoG

in terms of j_1

$$\begin{aligned}\langle e^{j_1 A_1} A_2 A_3\rangle_c &+ \langle e^{j_1 A_1} A_2\rangle_c \langle e^{j_1 A_1} A_3\rangle_c \\ &\simeq \langle A_2 A_3\rangle + j_1 \langle A_1 A_2 A_3\rangle_c \\ &\quad + j_1^2\{\tfrac{1}{2}\langle A_1^2 A_2 A_3\rangle_c + \langle A_1 A_2\rangle_c \langle A_1 A_3\rangle_c\} + \mathcal{O}(j_1^3).\end{aligned}$$

TNS 1006.0699
Zheng 1603.00101

The 'extended' TNS model

1006.0699 & 1603.00101

Taylor expansion in terms of $j_1 = -ik\mu$

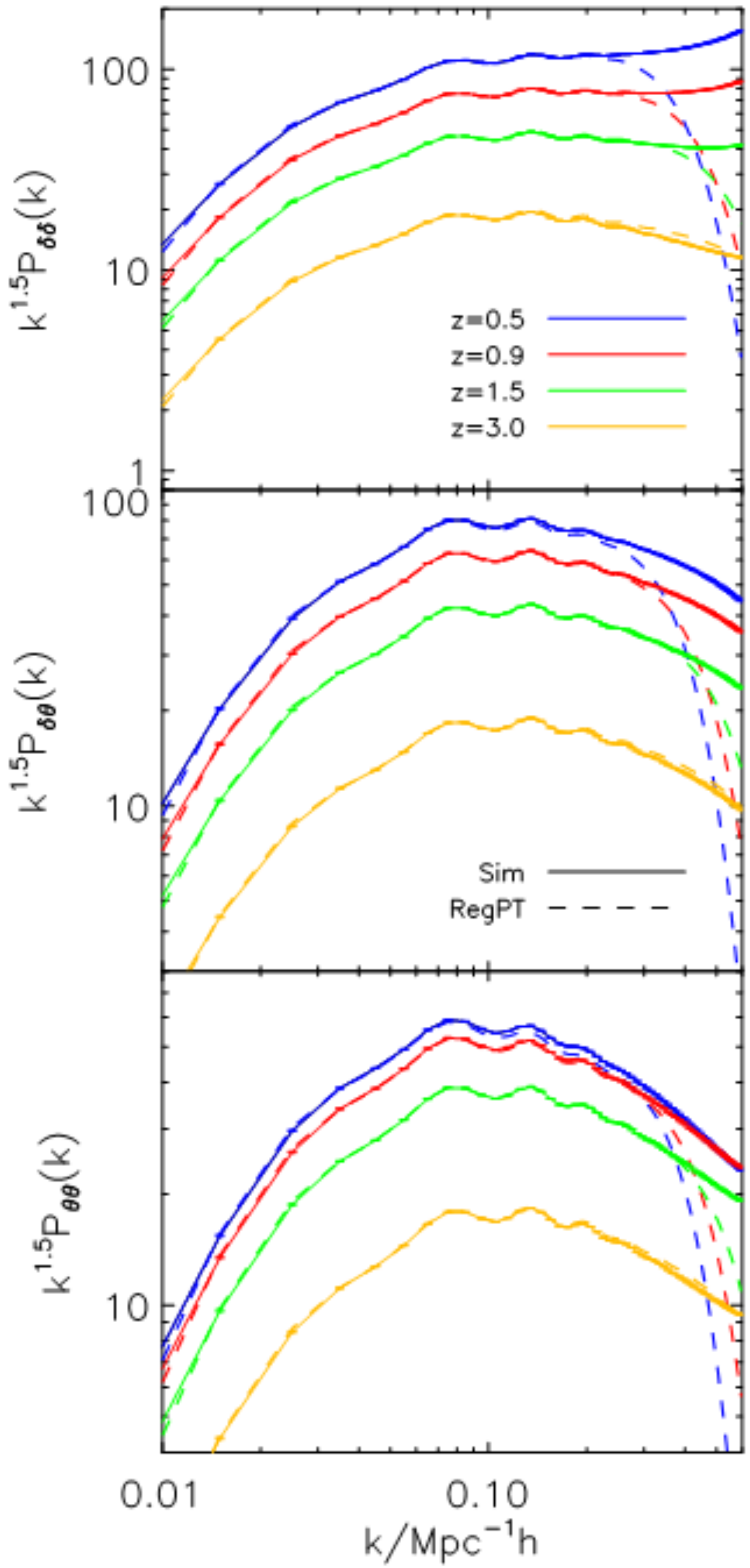
$$
\begin{aligned}
&D^{\rm FoG}_{\rm local}(k\mu, \boldsymbol{x}) \left[\langle e^{j_1 A_1} A_2 A_3 \rangle_c + \langle e^{j_1 A_1} A_2 \rangle_c \langle e^{j_1 A_1} A_3 \rangle_c\right] \\
&\simeq j_1^0 \langle A_2 A_3 \rangle_c + j_1^1 \langle A_1 A_2 A_3 \rangle_c \\
&+ j_1^2 \left\{ \langle A_1 A_2 \rangle_c \langle A_1 A_3 \rangle_c + \frac{1}{2} \langle A_1^2 A_2 A_3 \rangle_c - \langle u_z u_z' \rangle_c \langle A_2 A_3 \rangle_c \right\} \\
&+ \mathcal{O}(j_1^3) , \qquad (14)
\end{aligned}
$$

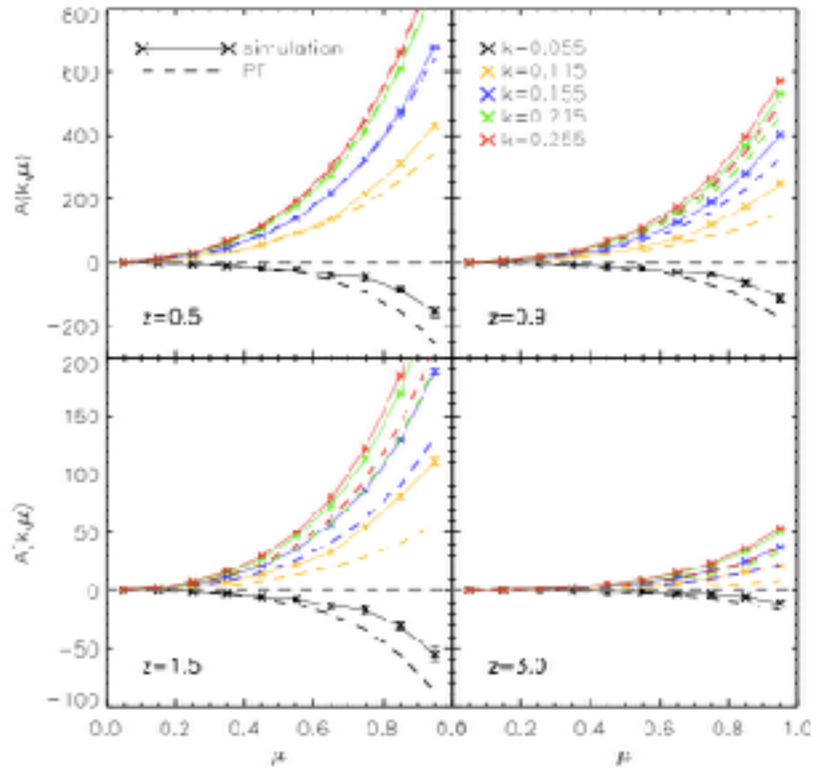
$$
\begin{aligned}
P^{(\rm S)}(k, \mu) &= D^{\rm FoG}(k\mu\sigma_z) P_{\rm perturbed}(k, \mu) \\
&= D^{\rm FoG}(k\mu\sigma_z)[P_{\delta\delta} + 2\mu^2 P_{\delta\Theta} + \mu^4 P_{\Theta\Theta} \qquad (15) \\
&\quad + A(k, \mu) + B(k, \mu) + \underline{T(k, \mu) + F(k, \mu)}].
\end{aligned}
$$

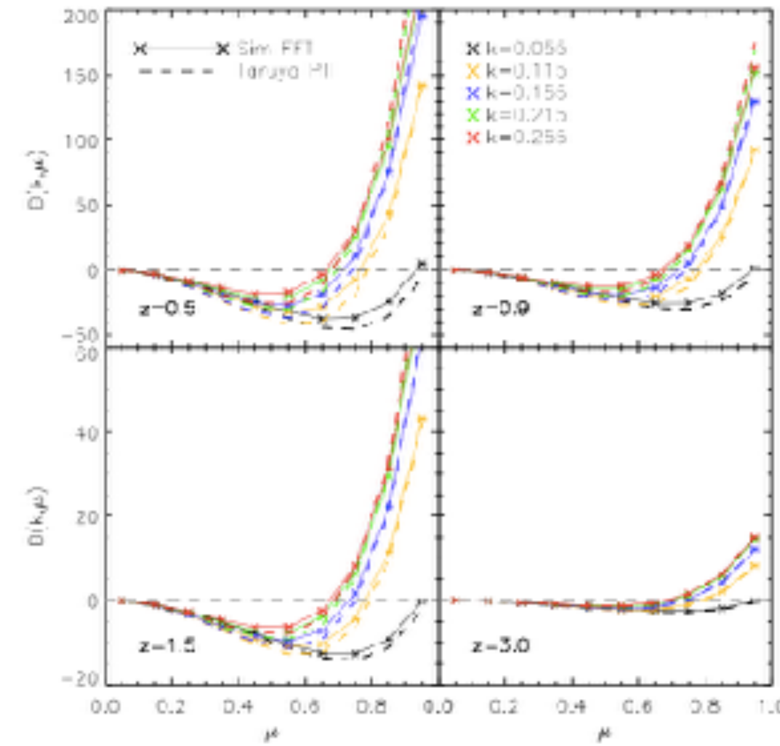
parameter	physical meaning	value
Ω_m	present fractional matter density	0.3132
Ω_Λ	$1 - \Omega_m$	0.6868
Ω_b	present fractional baryon density	0.049
h	$H_0/(100 \text{ km s}^{-1}\text{Mpc}^{-1})$	0.6731
n_s	primordial power spectral index	0.9655
σ_8	r.m.s. linear density fluctuation	0.829
$L_{\rm box}$	simulation box size	$1890\ h^{-1}$Mpc
$N_{\rm p}$	simulation particle number	1024^3
$m_{\rm p}$	simulation particle mass	$5.46 \times 10^{10} h^{-1} M_\odot$

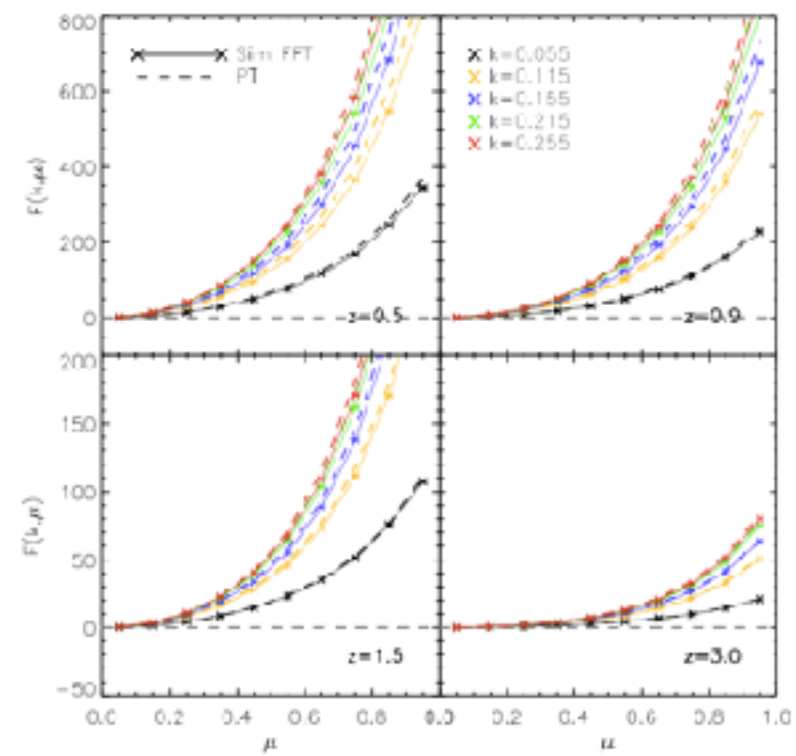
$$
\begin{aligned}
A(k, \mu) &= j_1 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \langle A_1 A_2 A_3 \rangle_c \\
&= j_1 \int d^3\boldsymbol{x}\; e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \langle (u_z - u_z') \\
&\quad \times (\delta + \nabla_z u_z)(\delta' + \nabla_z u_z') \rangle_c
\end{aligned}
$$

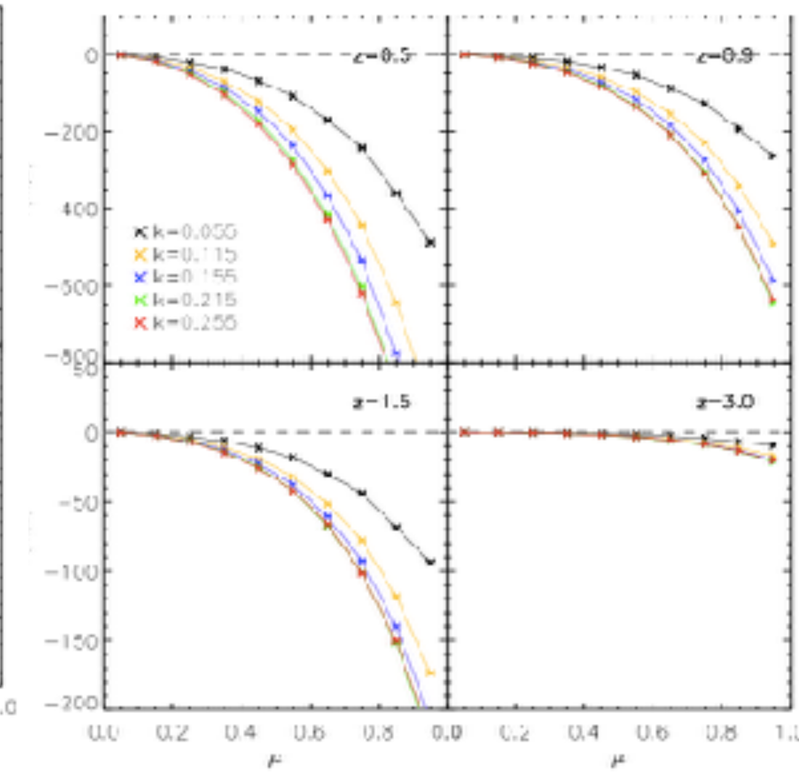
2-point





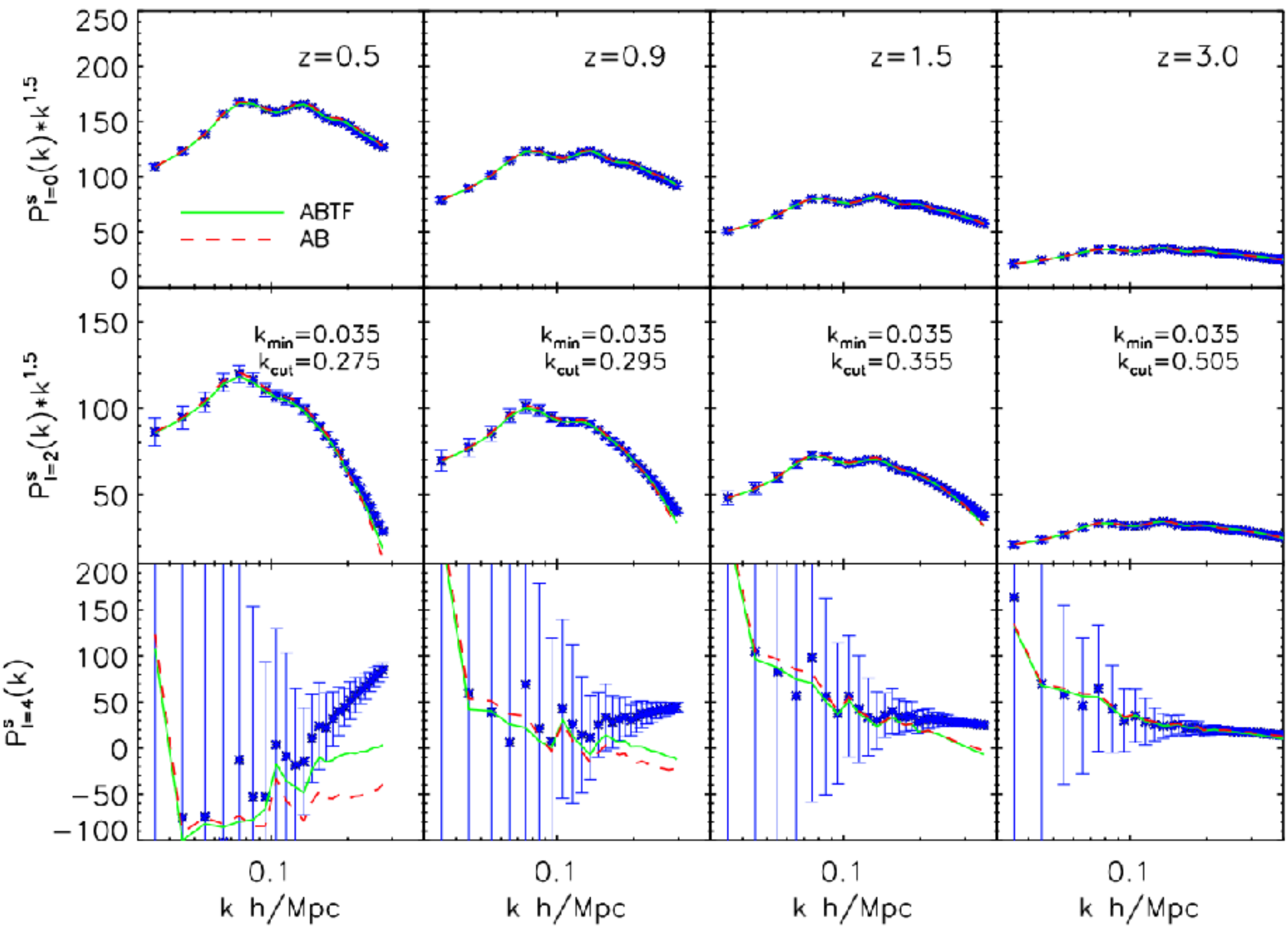






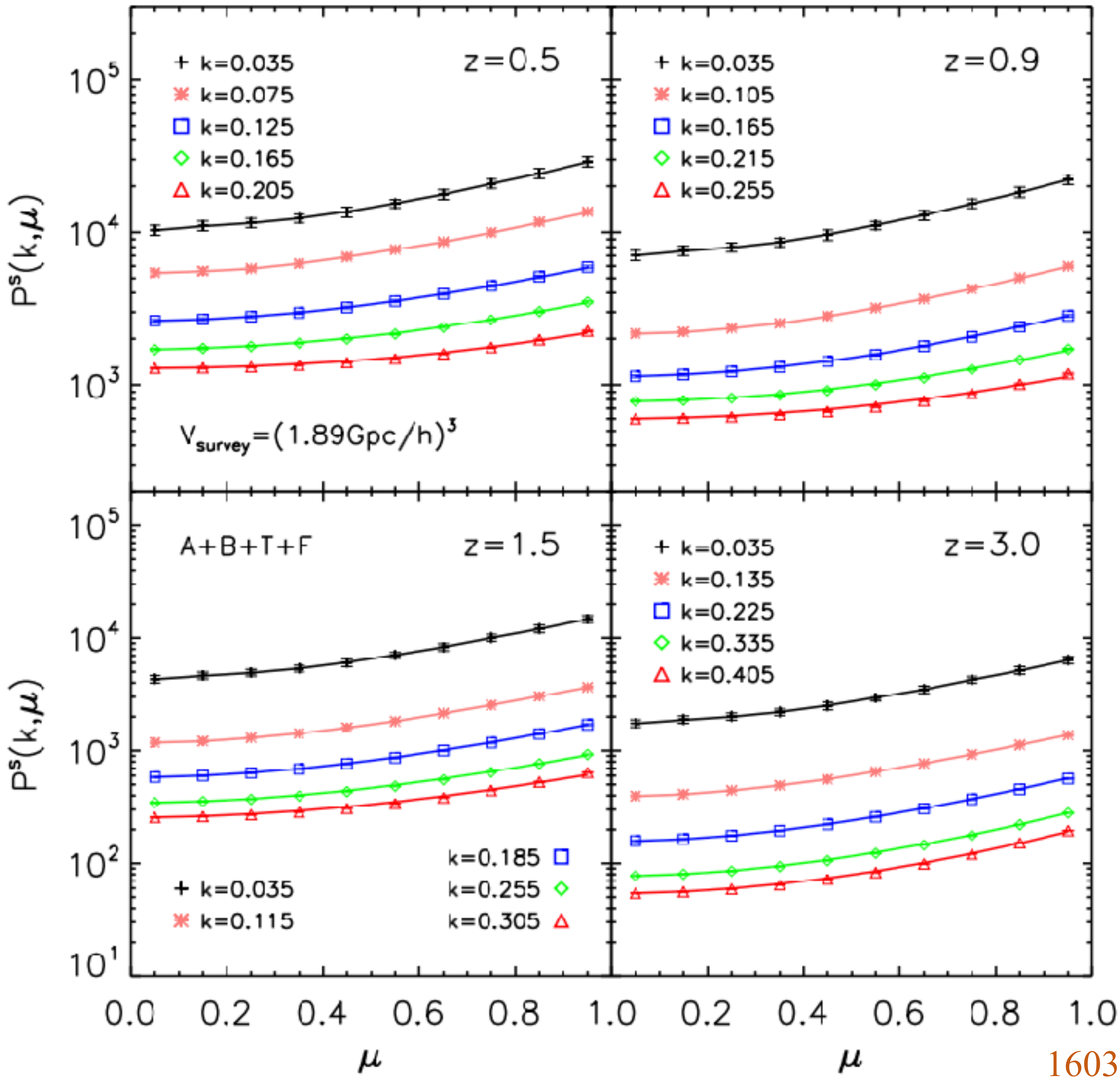
All higher order terms are important

1603.00101



z=0.5
z=0.9
z=1.5
z=3.0
ABTF
AB
k_min=0.035
k_cut=0.275
k_min=0.035
k_cut=0.295
k_min=0.035
k_cut=0.355
k_min=0.035
k_cut=0.505
P^s_l=0(k)*k^1.5
P^s_l=2(k)*k^1.5
P^s_l=4(k)
k h/Mpc

1603.00101



z=0.5
k=0.035
k=0.075
k=0.125
k=0.165
k=0.205
V_survey=(1.89Gpc/h)^3
z=0.9
k=0.035
k=0.105
k=0.165
k=0.215
k=0.255
A+B+T+F
z=1.5
k=0.035
k=0.115
k=0.185
k=0.255
k=0.305
z=3.0
k=0.035
k=0.135
k=0.225
k=0.335
k=0.405
P^s(k,μ)
μ

1603.00101

2. Density bias model

$$\delta_g(\boldsymbol{x}) = b_1\delta(\boldsymbol{x}) + \frac{1}{2}b_2[\delta(\boldsymbol{x})^2 - \sigma_2] + \frac{1}{2}b_{s^2}[s(\boldsymbol{x})^2 - \langle s^2\rangle] + \text{higher order terms},$$

McDonald&Roy, 0902.0991

$$P_{g,\delta\delta}(k) = b_1^2 P_{\delta\delta}(k) + 2b_2 b_1 P_{b2,\delta}(k) + 2b_{s2} b_1 P_{bs2,\delta}(k) + b_2^2 P_{b22}(k) + 2b_2 b_{s2} P_{b2s2}(k) + b_{s2}^2 P_{bs22}(k) + 2b_1 b_{3\mathrm{nl}}\sigma_3^2(k) P^{\mathrm{lin}}(k),$$

$$P_{g\theta}(k) = b_1 P_{\delta\theta}(k) + b_2 P_{b2,\theta}(k) + b_{s2} P_{bs2,\theta}(k) + b_{3\mathrm{nl}}\sigma_3^2(k) P^{\mathrm{lin}}(k),$$

Hector et.al, 1407.5668

Lagrangian local

$$b_{s^2} = -\frac{4}{7}(b_1 - 1)$$ (Baldauf et al. 2012; Chan et al. 2012),

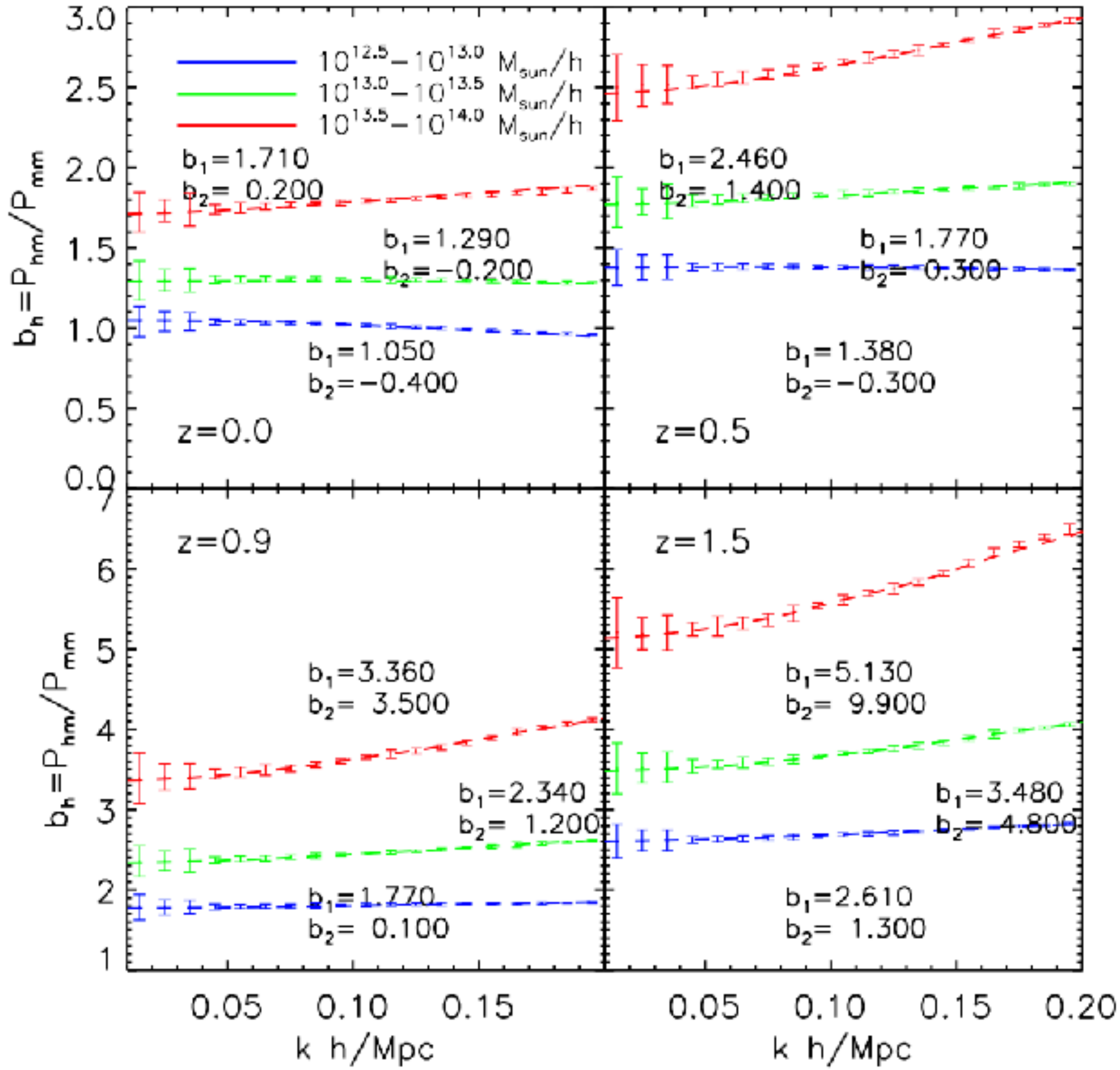
$$b_{3\mathrm{nl}} = \frac{32}{315}(b_1 - 1)$$ (Beutler et al. 2014; Saito et al. 2014).

Halo RSD mapping formula test

$$P_h^{(S)}(k,\mu) = D^{\mathrm{FoG}}(k\mu\sigma_z)[(1 + k^2\mu^2\sigma_{z,\mathrm{sim}}^2/2)(P_{\delta_h\delta_h} + 2\mu^2 P_{\delta_h\Theta} + \mu^4 P_{\Theta\Theta}) + b_1^3 A(k,\mu,f/b_1) + b_1^4\tilde{T}(k,\mu,f/b_1)]$$

No velocity bias, Lagrangian local bias for PS, linear bias for higher order term

$$P_{\delta_h \delta} = b_1 P_{\delta\delta}(k) + b_2 P_{b2,\delta}(k) + b_{s2} P_{bs2,\delta}(k) + b_{3\mathrm{nl}} \sigma_3^2(k) P_{\mathrm{m}}^{\mathrm{L}}(k)$$

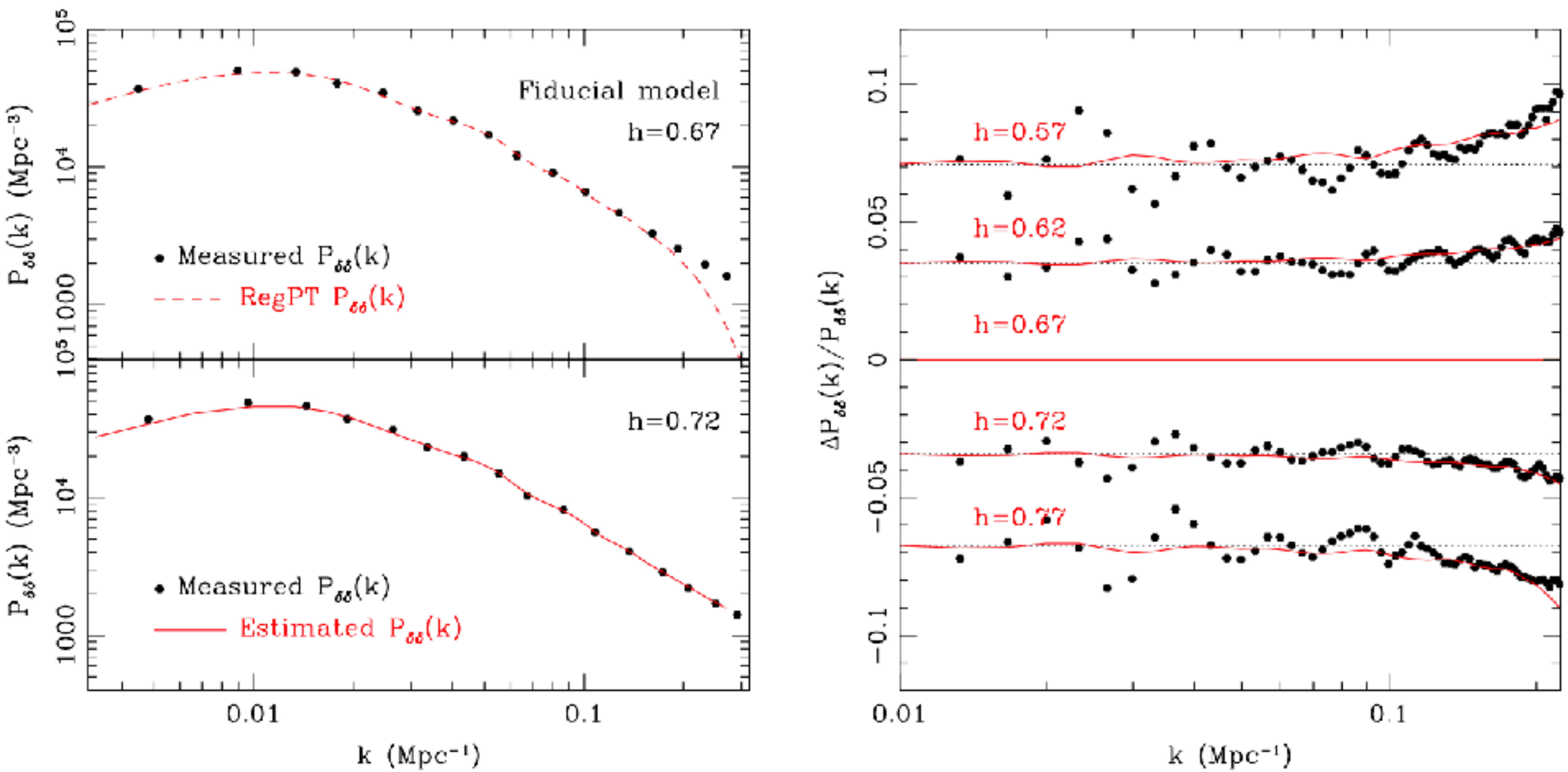


Y. Zheng, Y. Song and M.Oh, in preparation, 2017

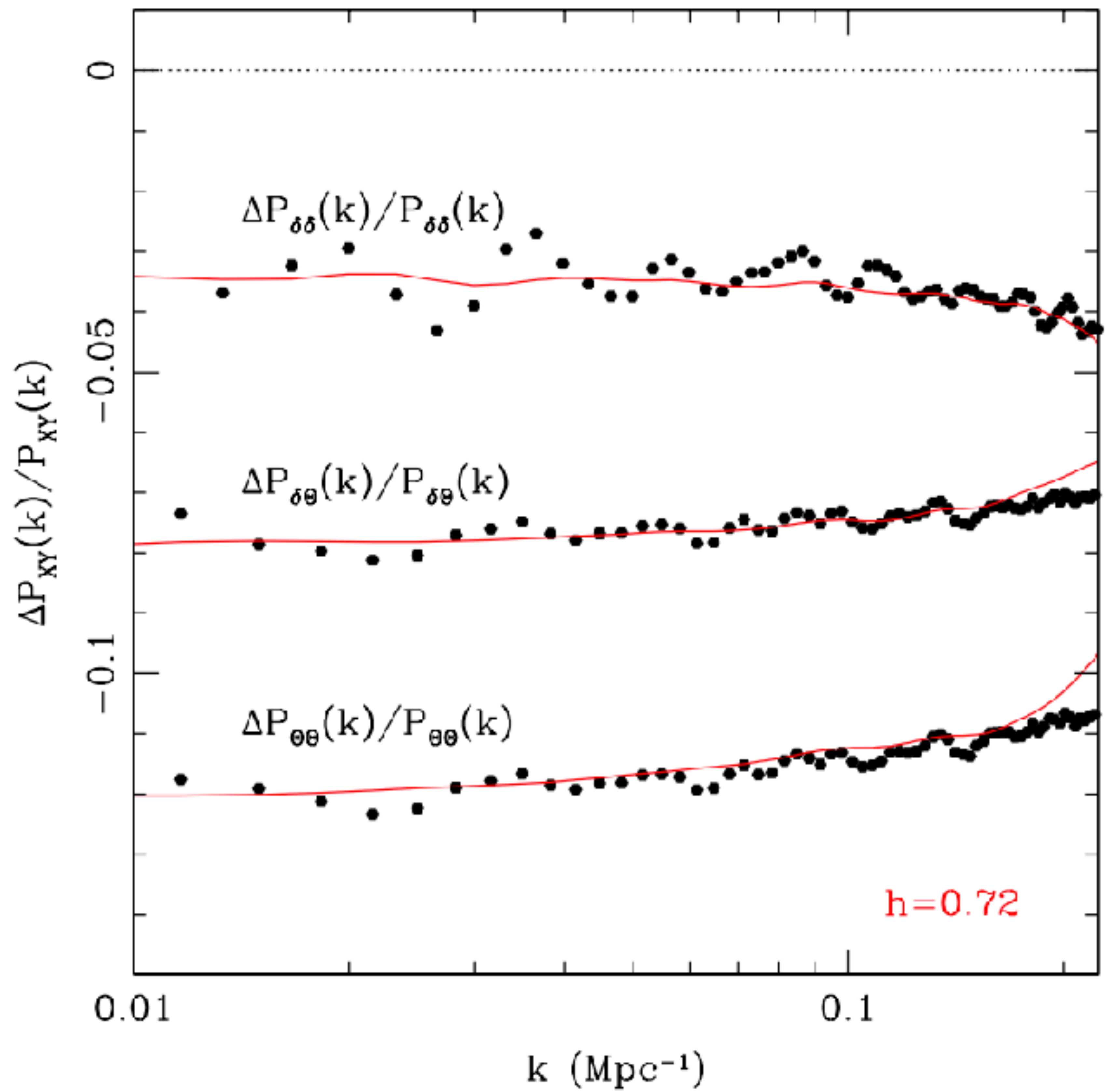
3. Non-linear evolution

Y. Song, Y. Zheng, M. Oh, and A. Taruya, in preparation, 2017

$$P_{XY}(k) = P^{\rm th}_{XY}(k,z) + P^{\rm res}_{XY}(k,z)$$



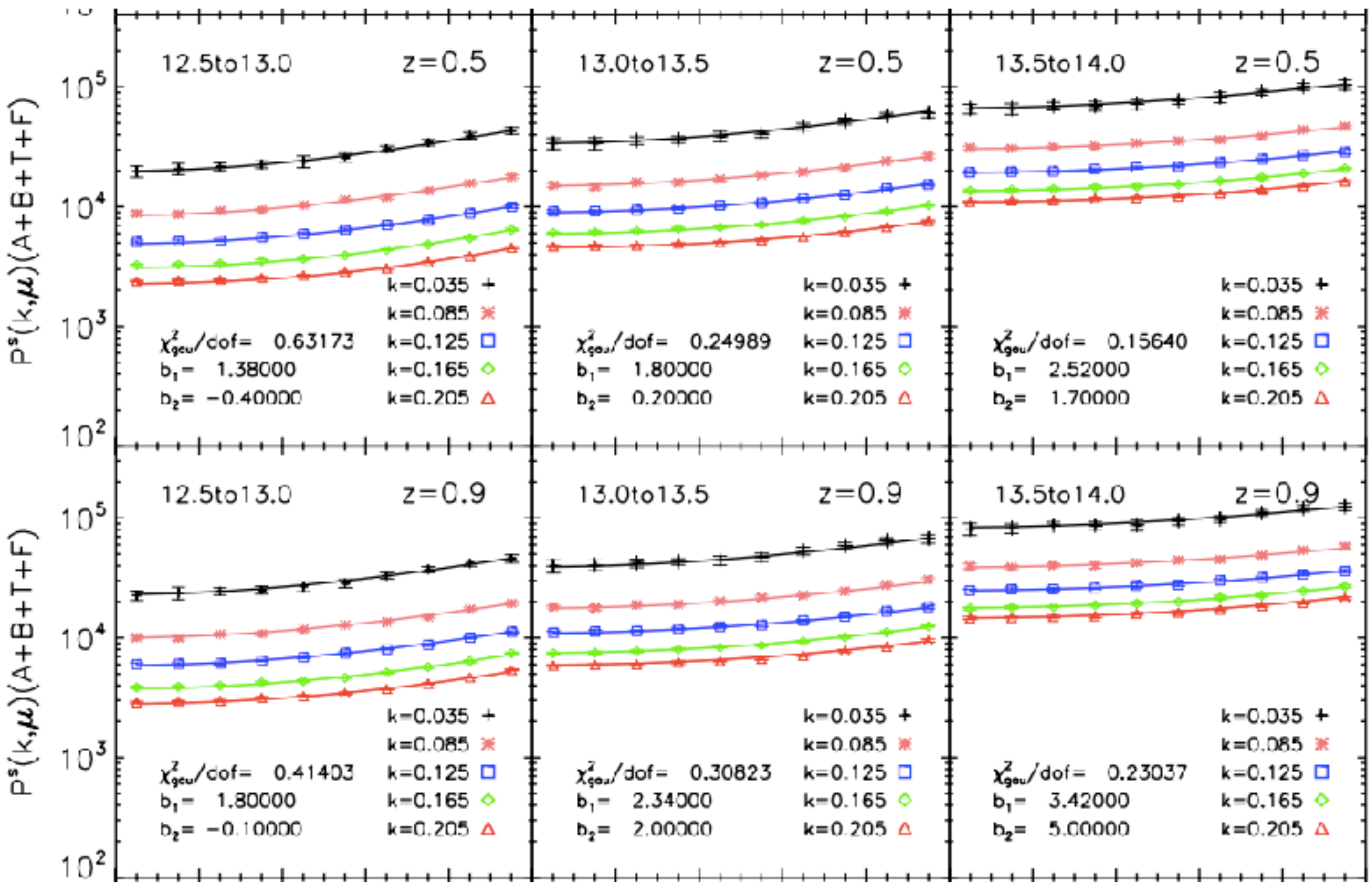
Y. Song, Y. Zheng, M. Oh, and A. Taruya, in preparation, 2017



4.Full halo RSD model

b_1,b_2,\sigma_v

$$P_h^{(\mathrm{S})}(k,\mu) = D^{\mathrm{FoG}}(k\mu\sigma_z)[(1+k^2\mu^2\sigma^2_{z,\mathrm{sim}}/2)(P_{\delta_h\delta_h}+2\mu^2P_{\delta_h\Theta}+\mu^4P_{\Theta\Theta})$$
$$+b_1^3A(k,\mu,f/b_1)+b_1^4\tilde{T}(k,\mu,f/b_1)]\,.$$



Y. Zheng, Y. Song and M.Oh, in preparation, 2017

Discussion

- Better Taylor expansion of the mapping formula? Convergence test?
- Density bias model, velocity bias?
- Blind test for RSD model? GreatRSD?
- FoG calculation? 1611.09075

Perturbative theory: EFTofLSS?

What's in between? Numerator?

Full numerical, LSS analysis like CMB? Quantum computer?