Perturbation Theory Reloaded

Toward a precision modeling of the galaxy power spectrum from high-z galaxy surveys

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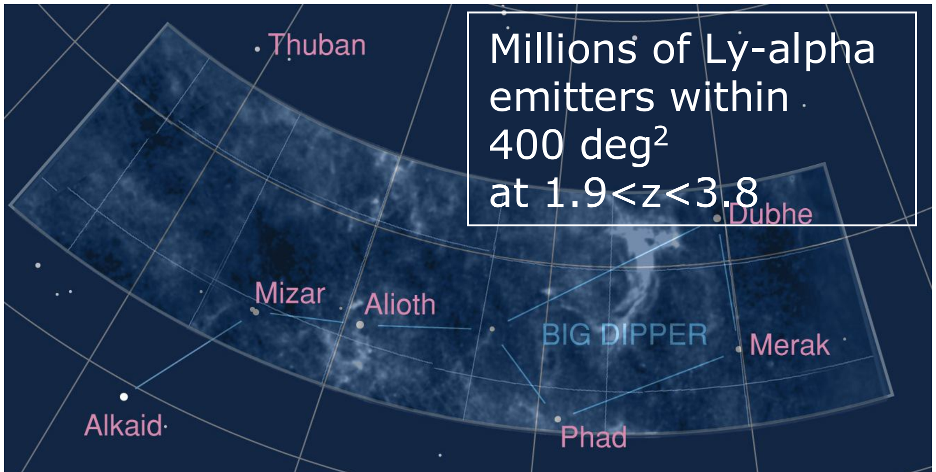
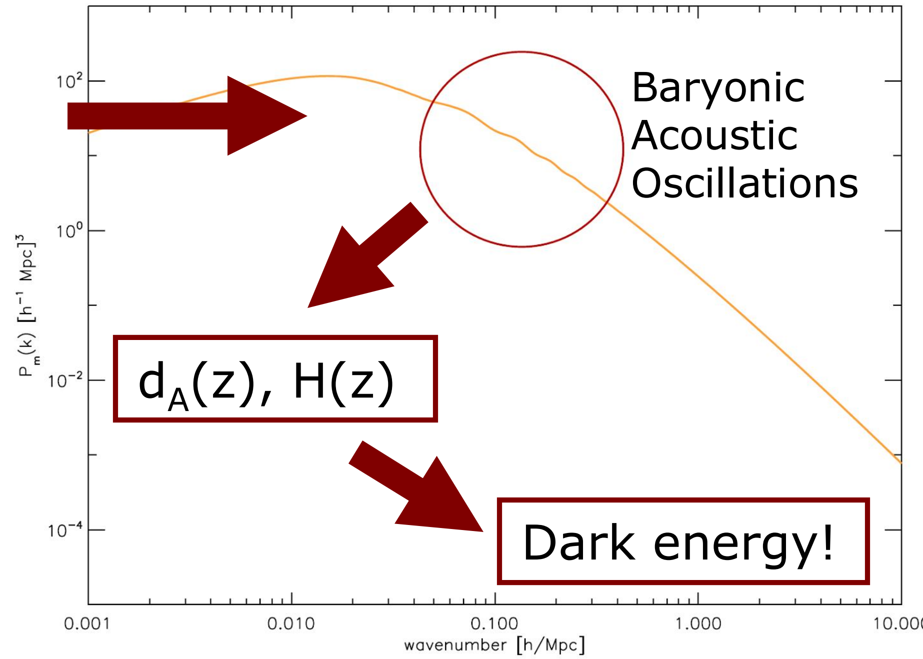
Papers To Talk About

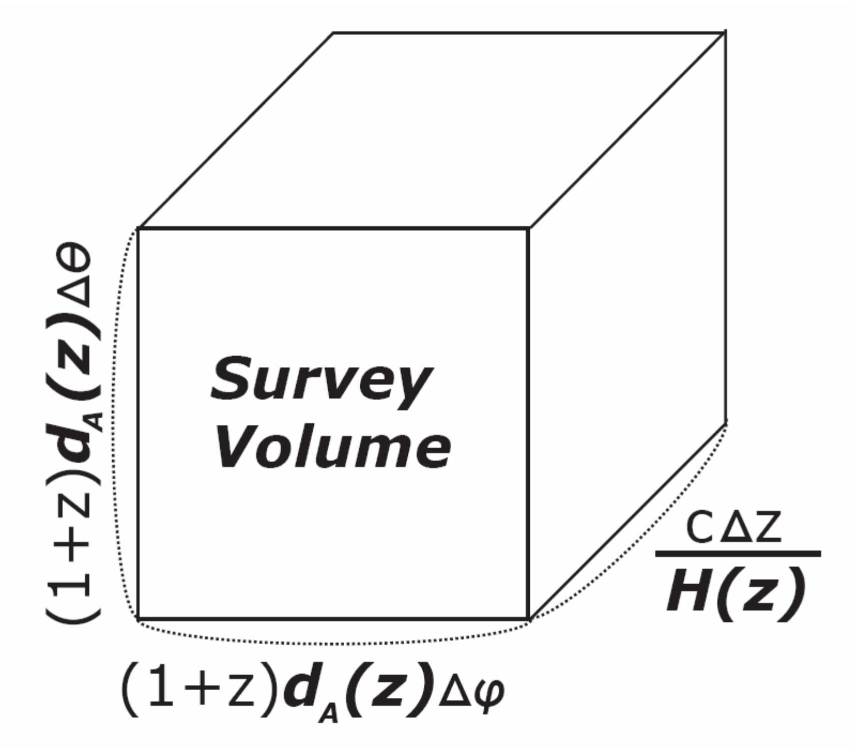
- DJ & E. Komatsu, ApJ, 651, 619 (2006)
- DJ & E. Komatsu, arXiv:0805.2632
- M. Shoji, DJ & E. Komatsu, arXiv:0805.4238
- DJ, E. Sefusatti & E. Komatsu (in preparation)





www.hetdex.org

From P(k) to $d_A(z)$ and H(z)

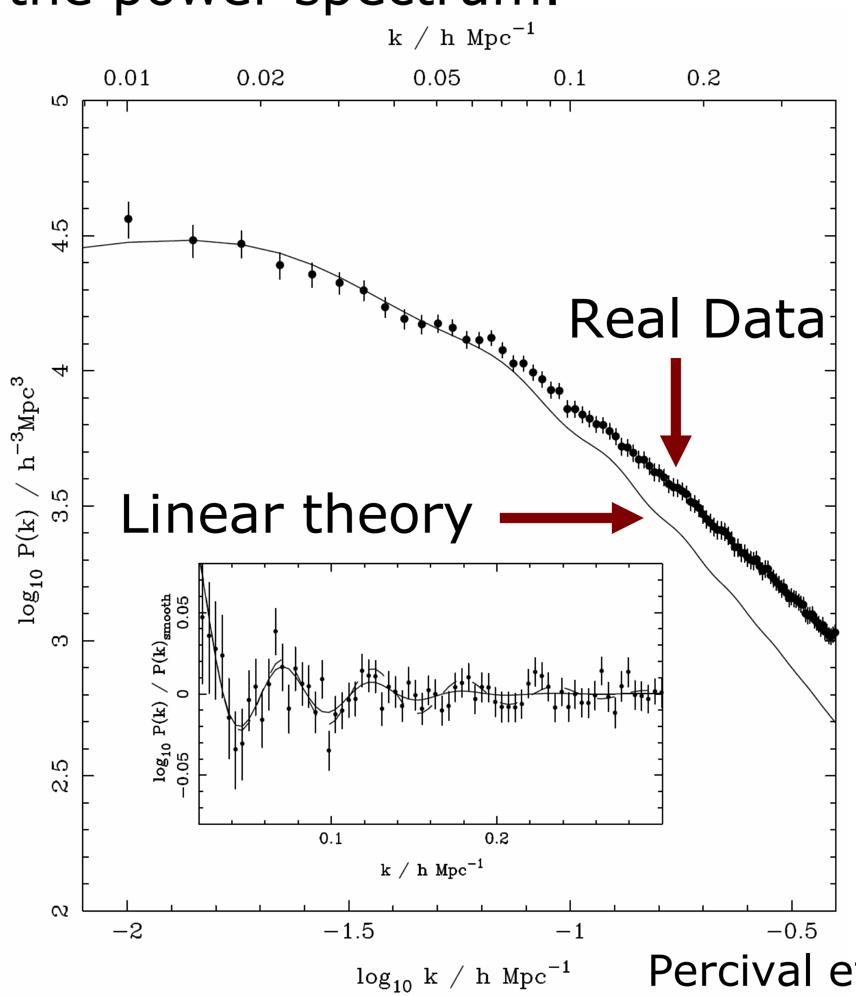


- In galaxy surveys, we chart galaxies by (Θ,ϕ,z).
- In order to convert them to *physical coordinate*, we have to know the expansion rate, H(z), and the angular diameter distance, $d_A(z)$.
- Distance scales shift power spectrum, P(k), in log-scale as

$$P_{obs}(k_\parallel, k_\perp, z) = \frac{d_A^2(z) H_{\rm true}(z)}{d_{A,{\rm true}}^2(z) H(z)} P_{\rm true}\left(\frac{d_{A,{\rm true}}(z)}{d_A(z)} k_\perp, \frac{H(z)}{H_{\rm true}(z)} k_\parallel, z\right)$$

To get d_A and H from P(k),

- We have to understand/model the non-linearities which distort the power spectrum.



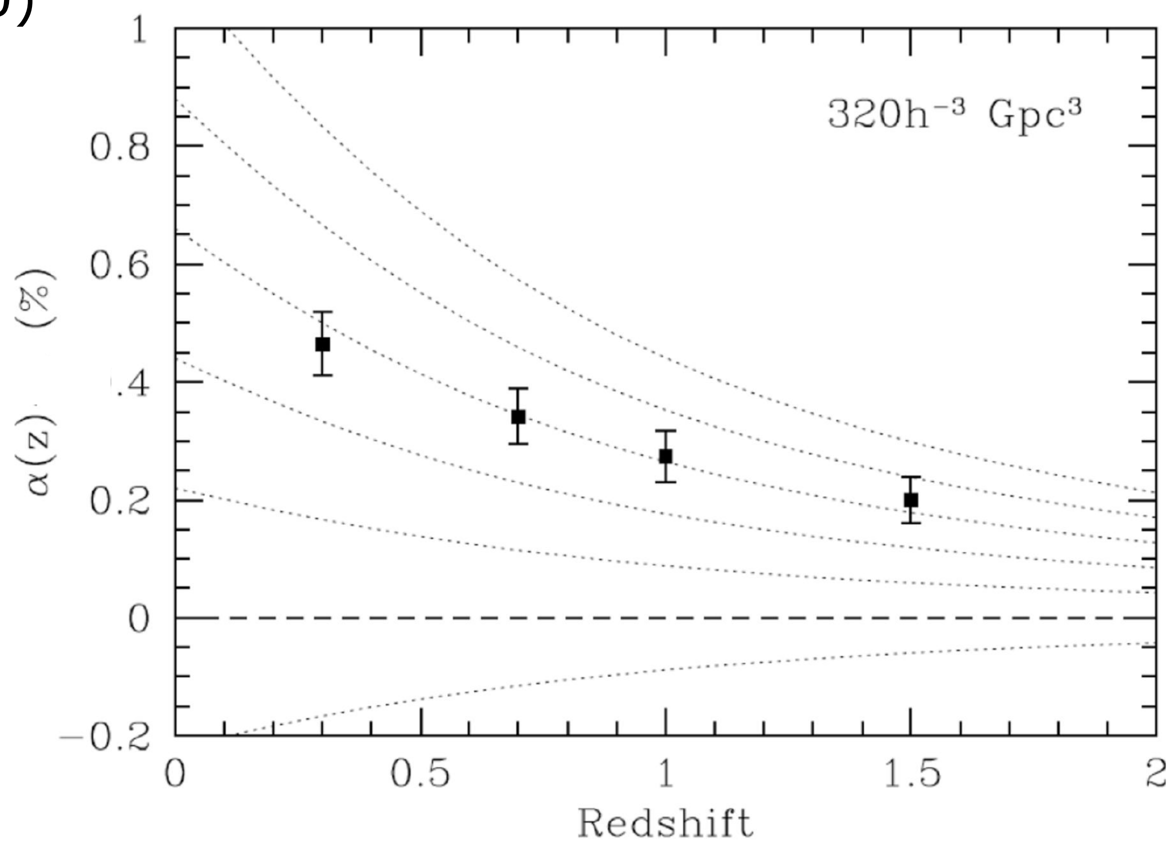
Percival et al. (2006)

- Three non-linearities
  1. Non-linear matter clustering
  2. Non-linear galaxy bias
  3. Non-linear peculiar velocity (redshift-space distortion)

BAOs are most popular,

• because their phases are NOT affected by the non-linear evolution very much.

• Therefore, it is favored when non-linearities are too strong. (e.g. z~0)



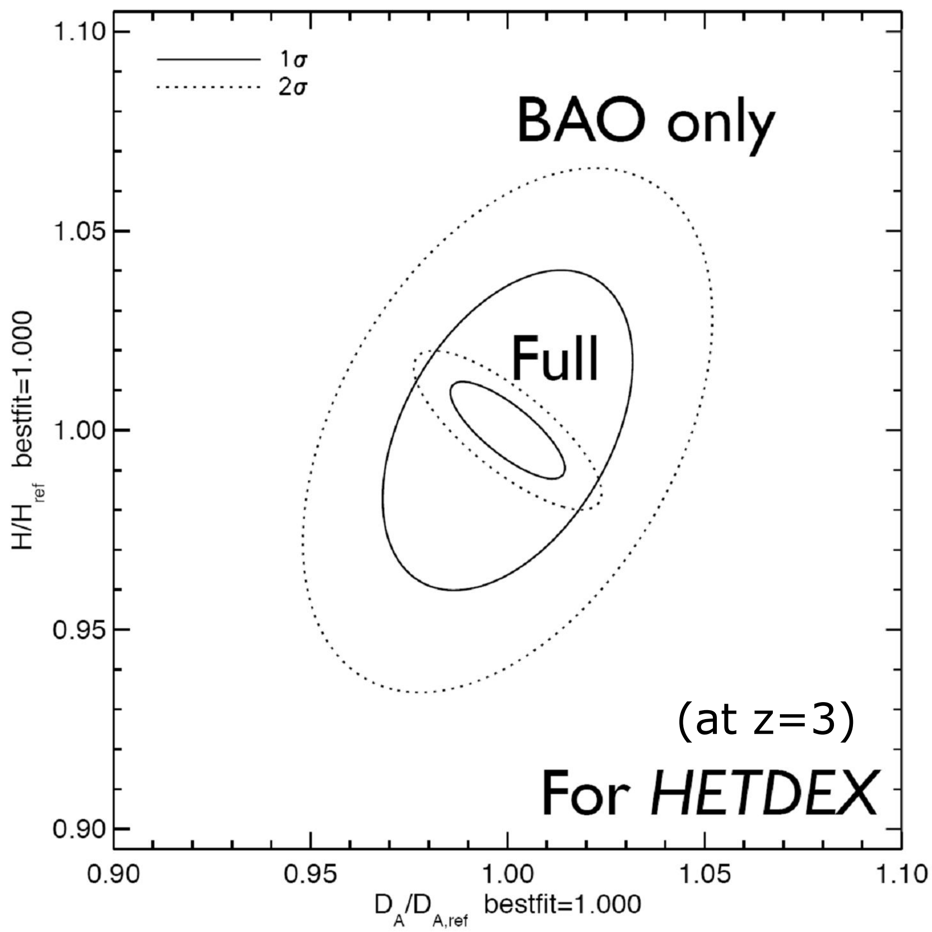
Seo, Seigel, Eisenstein & White (2008)

BAO vs Full Modeling

• Full modeling improves upon the determination of d_A & H by more than a factor of two.

•On the d_A-H plane, the size of the ellipse shrinks by **more than a factor of four**!

•Therefore, using the full information is **equivalent to having <u>four times as much volume</u> as one would have with BAO-only.**



Shoji, DJ & Komatsu (2008)

How to model the nonlinerties?

• Solid theoretical frame work : **Perturbation Theory (PT)**

- It is necessary in order to avoid any empirical, calibration factors.

- Validity of the cosmological **linear** perturbation theory has been verified *observationally*. (Remember WMAP!)

- So, we just go beyond the linear theory, and calculate higher order terms in perturbations.

- 3^{rd}-order perturbation theory (3PT)

Is 3PT New?

- Not at all. It is more than 25 years old.
- However, it has never been applied to the real data so far, because non-linearity is too strong to model PT at $z\sim0$.
- High-z ($z>1$) galaxy redshift surveys are now possible.
- **Non-linearities are weaker at $z>1$, making it possible to use the cosmological perturbation theory!!**

Solving Just Three Equations

- Setting up
  - Consider large scales, where the baryonic pressure is negligible, but smaller than the Hubble horizon. (i.e. $a_0 H << k << k_J$, where k_J is the Jeans scale.)
  - Ignore the shell-crossing, so that the rotational velocity is zero : curl(v)=0

- Matter field is described by Newtonian fluid equations.

$$\dot{\delta} + \nabla \cdot \left[(1+\delta) \boldsymbol{v} \right] = 0$$

$$\dot{\boldsymbol{v}} + \left(\boldsymbol{v} \cdot \nabla \right) \boldsymbol{v} = -\frac{\dot{a}}{a} \boldsymbol{v} - \nabla \phi$$

$$\nabla^2 \phi = 4\pi G a^2 \bar{\rho} \delta$$

3PT Matter power spectrum

Vishiniac (1983);Fry (1984);Goroff et al. (1986);Suto&Sasaki (1991);Makino et al. (1992);Jain&Bertschinger (1994);Scoccimarro&Frieman (1996)

$$P_{\delta\delta}(k,\tau) = D^2(\tau)P_L(k) + D^4(\tau)\left[2P_{13}(k) + P_{22}(k)\right]$$

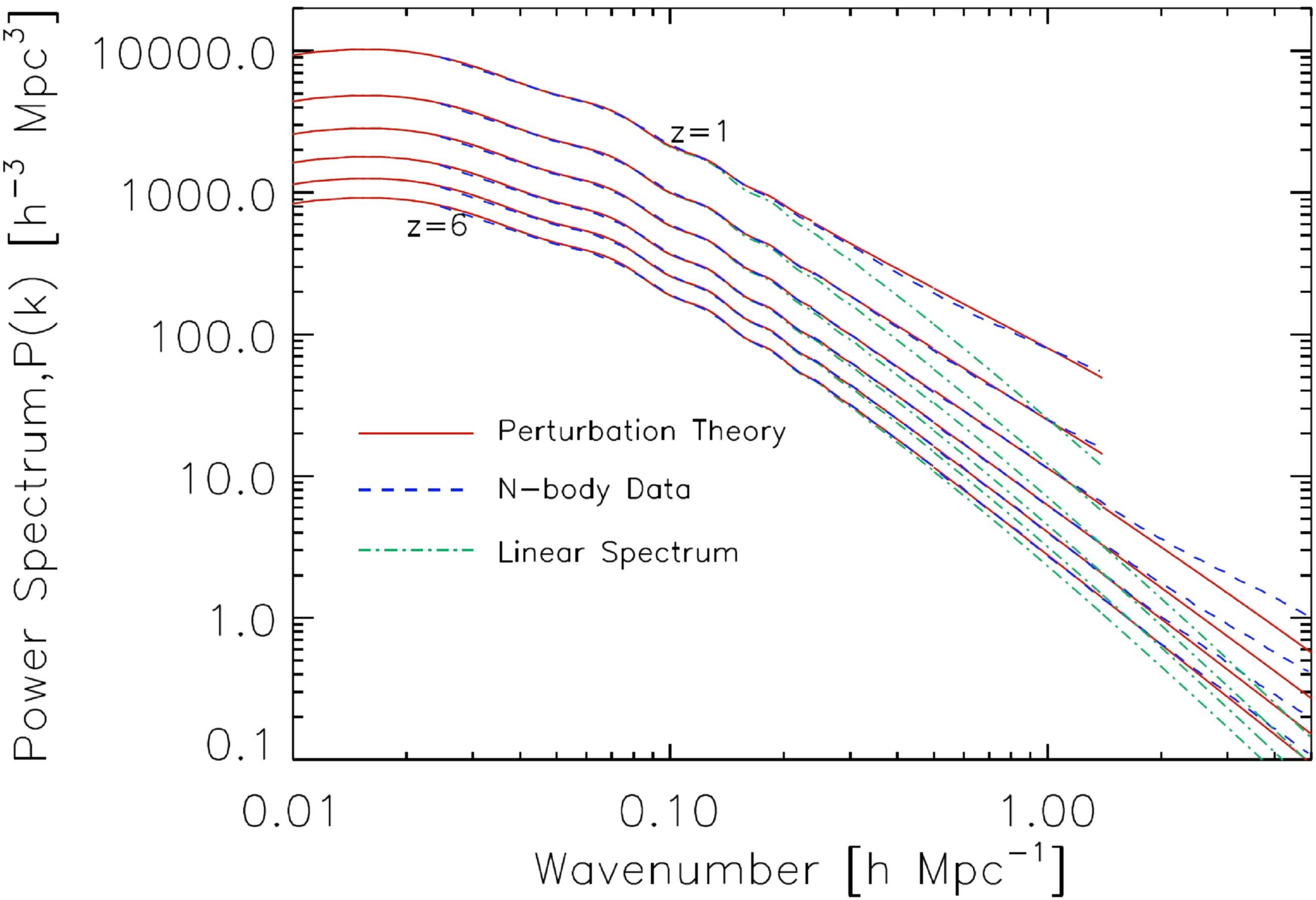
$$P_{22}(k) = 2\int \frac{d^3q}{(2\pi)^3} P_L(q) P_L(|\boldsymbol{k}-\boldsymbol{q}|) \left[F_2^{(s)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})\right]^2$$

$$\begin{aligned} 2P_{13}(k) &= \frac{2\pi k^2}{252} P_L(k) \int_0^\infty \frac{dq}{(2\pi)^3} P_L(q) \\ &\times \left[100\frac{q^2}{k^2} - 158 + 12\frac{k^2}{q^2} - 42\frac{q^4}{k^4}\right. \\ &+ \left.\frac{3}{k^5 q^3}(q^2-k^2)^3(2k^2+7q^2)\ln\left(\frac{k+q}{|k-q|}\right)\right] \end{aligned}$$

$$F_2^{(s)}(\boldsymbol{q}_1,\boldsymbol{q}_2) = \frac{17}{21} + \frac{1}{2}\hat{\boldsymbol{q}}_1\cdot\hat{\boldsymbol{q}}_2\left(\frac{q_1}{q_2}+\frac{q_2}{q_1}\right) + \frac{2}{7}\left[(\hat{\boldsymbol{q}}_1\cdot\hat{\boldsymbol{q}}_2)^2 - \frac{1}{3}\right]$$

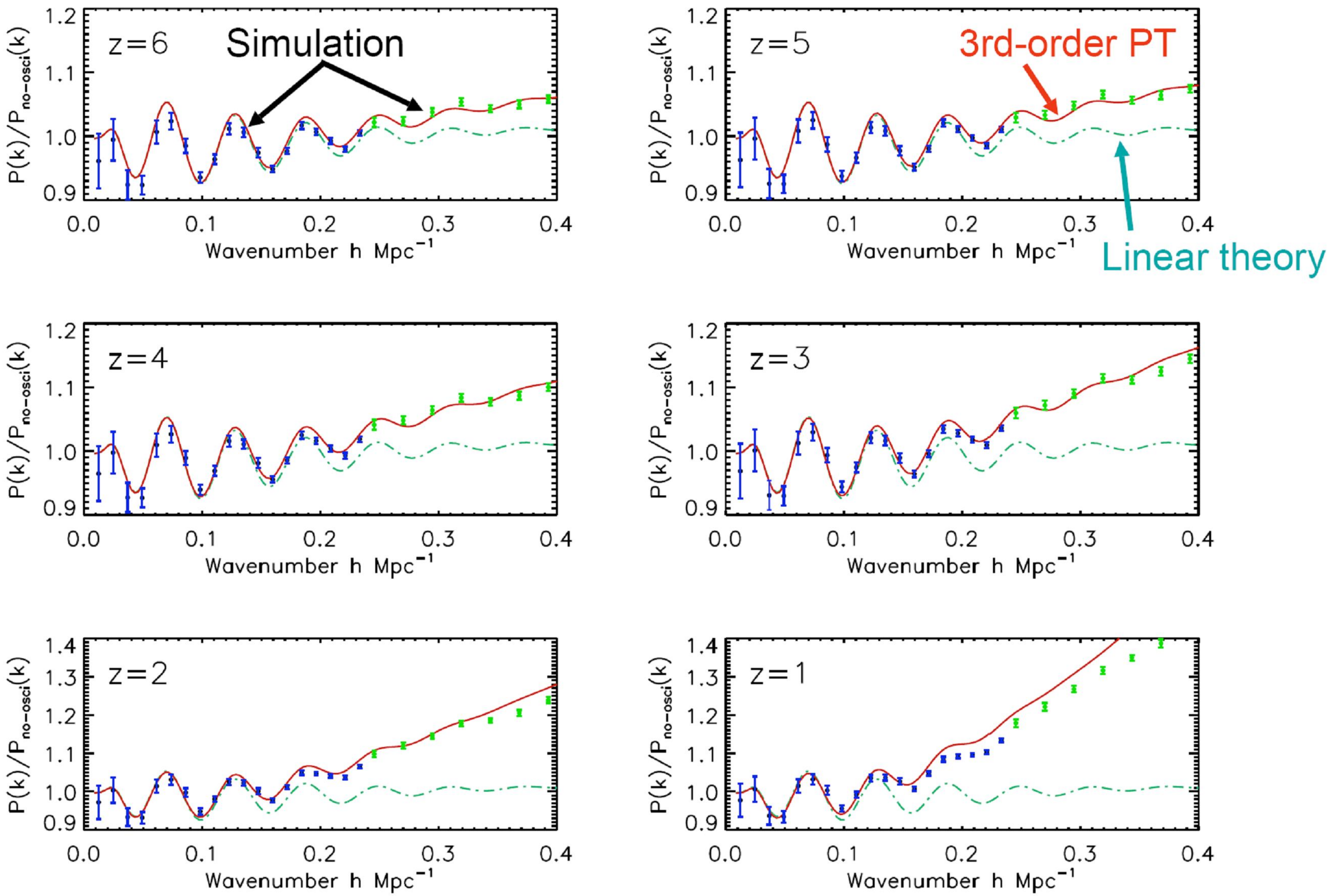
Models Nonlinear matter P(k)

DJ & Komatsu (2006)



BAO : Matter Non-linearity

DJ & Komatsu (2006)



3PT Galaxy power spectrum

- Facts
  - The distribution of galaxies is not the same as that of matter fluctuations.
- Assumption
  - Galaxy formation is a local process, at least on the scales that cosmologists care about.

$$\delta_t(\boldsymbol{x}) = \epsilon + b_1\delta(\boldsymbol{x}) + \frac{1}{2}b_2\delta^2(\boldsymbol{x}) + \frac{1}{6}b_3\delta^3(\boldsymbol{x}) + \mathcal{O}(\delta_1^4)$$

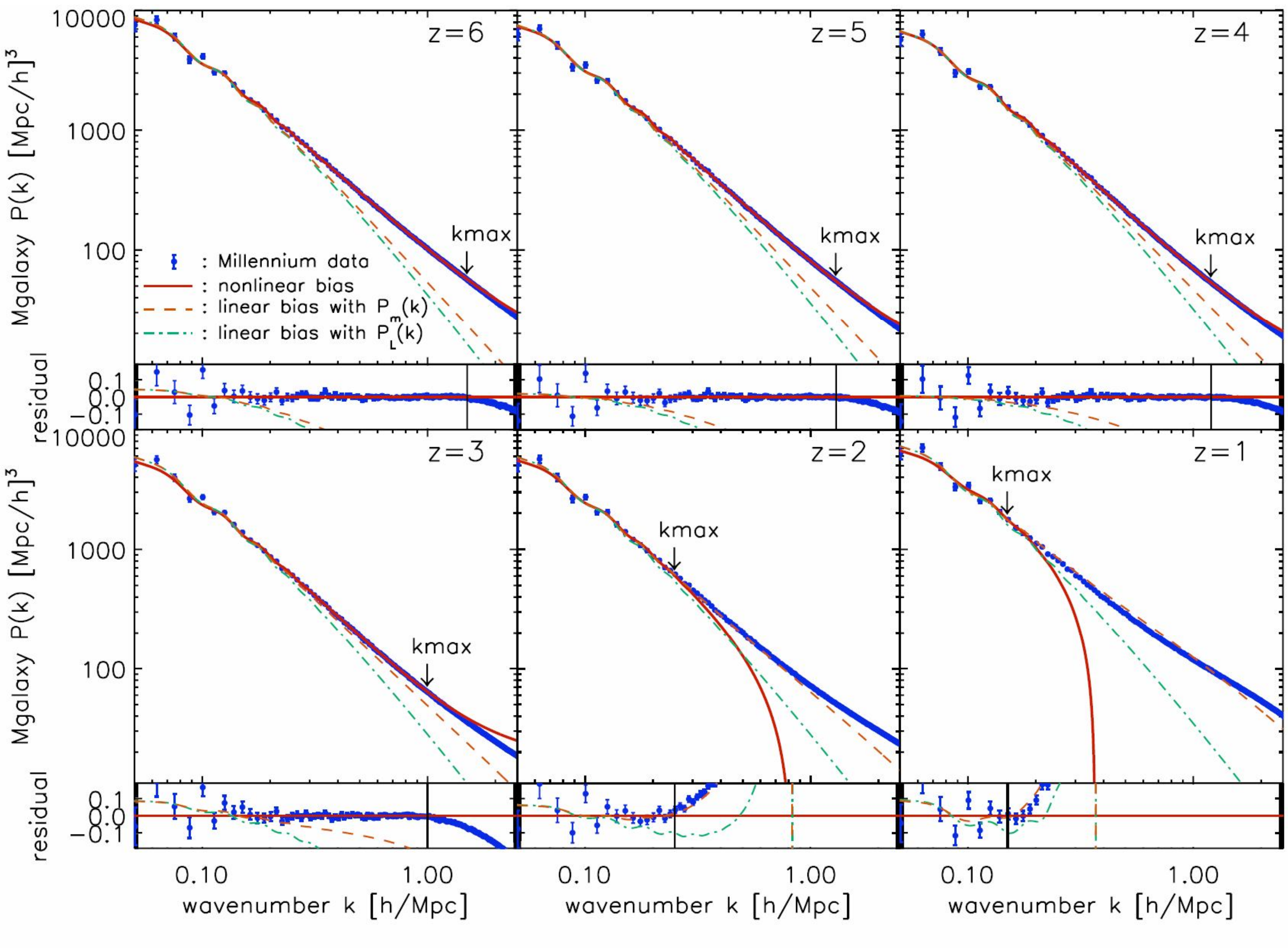
- Result (McDonald, 2006)

$$P_{tt}(k) = P_0 + \tilde{b}_1^2\left[P(k) + \frac{\tilde{b}_2^2}{2}\int\frac{d^3\boldsymbol{q}}{(2\pi)^3}P(q)\left[P(|\boldsymbol{k}-\boldsymbol{q}|) - P(q)\right]\right.$$
$$\left. + 2\tilde{b}_2\int\frac{d^3\boldsymbol{q}}{(2\pi)^3}P(q)P(|\boldsymbol{k}-\boldsymbol{q}|)F_2^{(s)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})\right]$$

  - b1,b2,P0 are free parameters that captures detail information of galaxy formation!

DJ & Komatsu (2008)

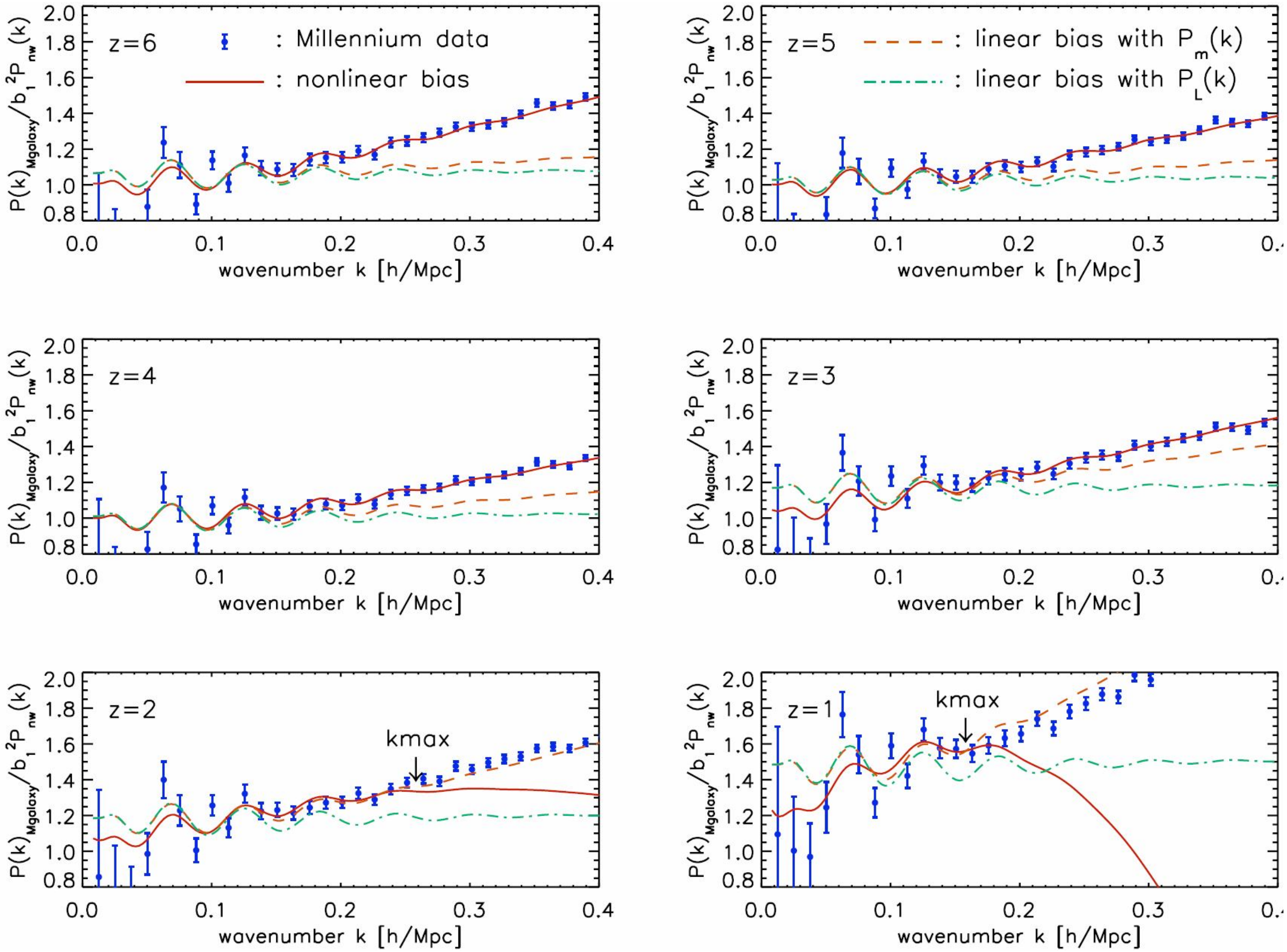
MPA Galaxy power spectrum



- Galaxy power spectrum from the "Millennium Simulation".
- k_{max} is where 3PT deviate from matter P(k).

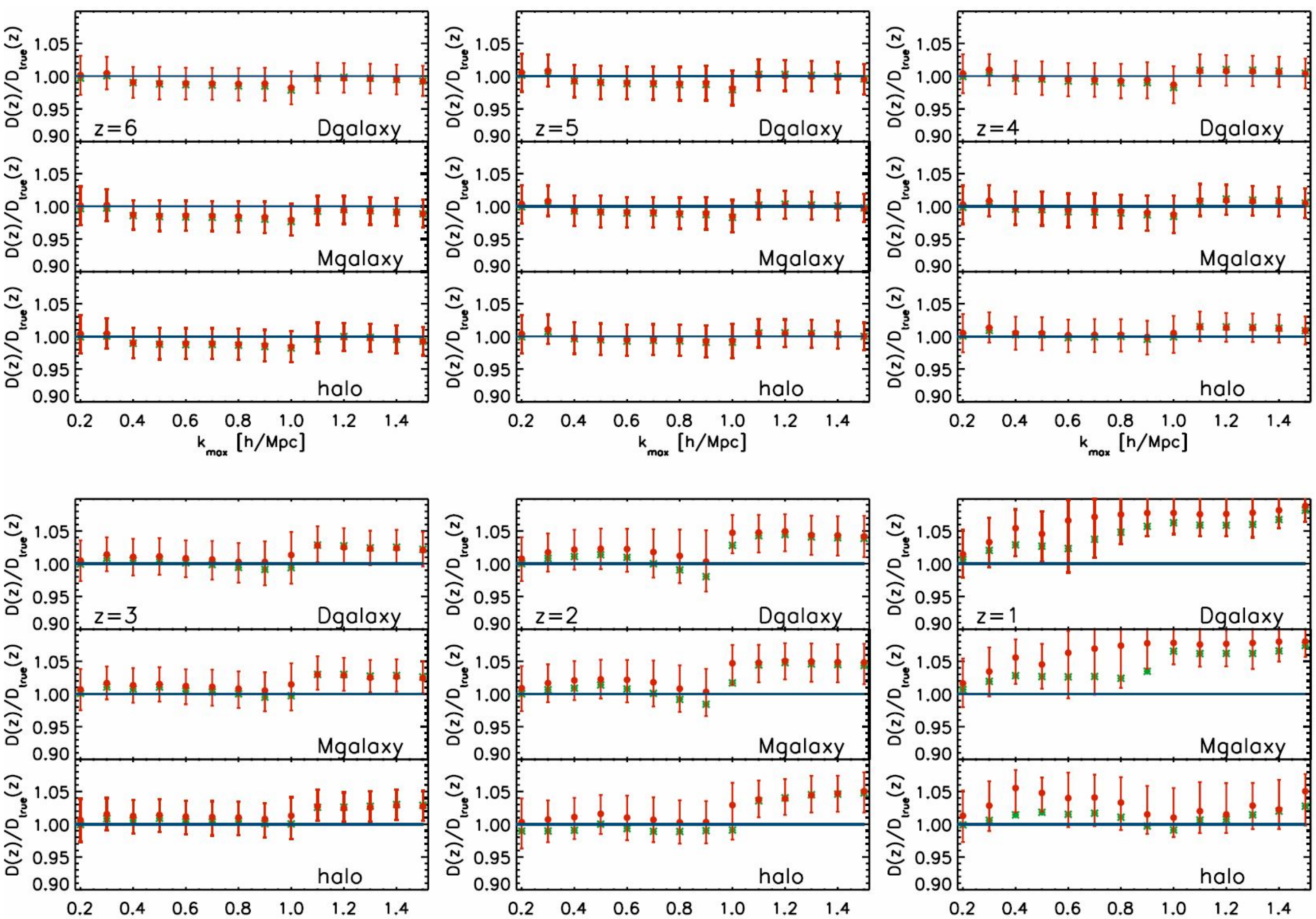
DJ & Komatsu (2008)

BAO : Non-linear bias



DJ & Komatsu (2008)

$d_A(z)$ from $P_g(k)$



- With 3PT, we succeeded in measuring dA(z) from the "observed" power spectra in the Millennium Simulation at z>2.
- Still seems challenging at z=1. Better PT is needed! e.g. Renormalized PT

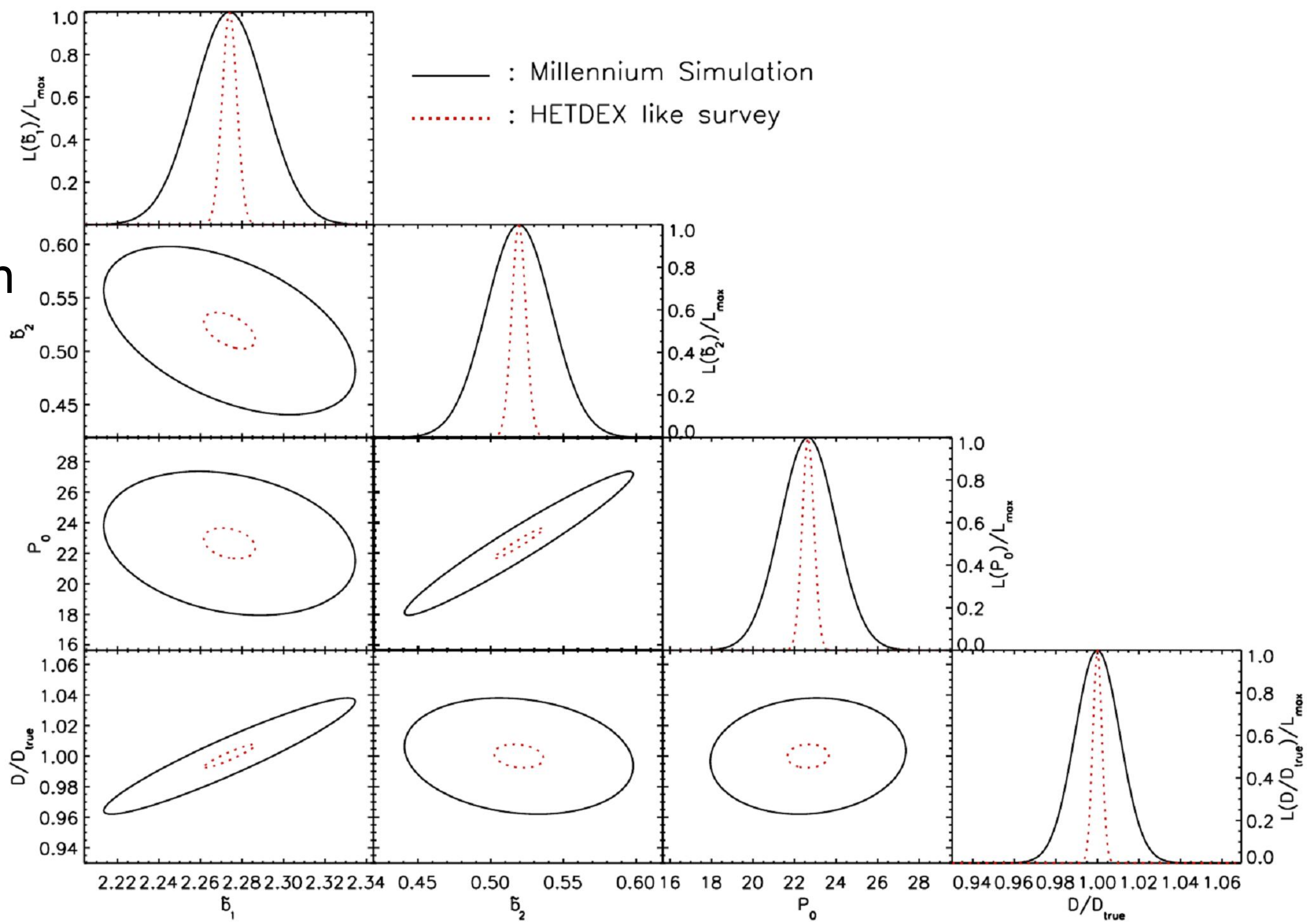
DJ & Komatsu (2008)

So Much Degeneracies

- Bias parameters and the distance are strongly degenerate, if we use the power spectrum information only.

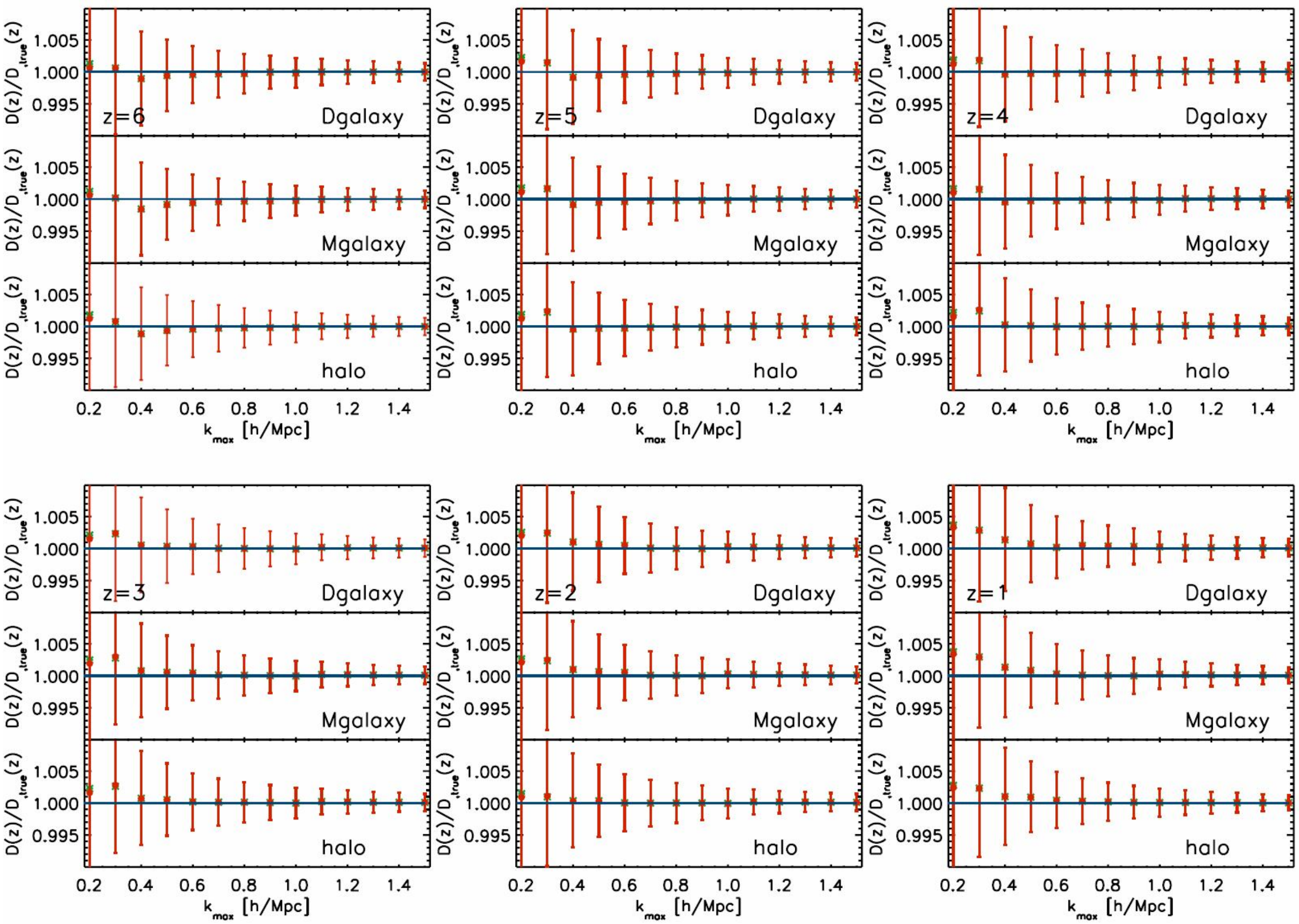
- Solution?

Use the bispectrum!



DJ & Komatsu (2008)

What if we know b_1 and b_2…



- **Result**

The errors in the distance determinations are reduced substantially.

WE MUST USE THE BISPECTRUM!

Galaxy Bispectrum

• Galaxy bispectrum (3-point correlation) depends on b_1 and b_2 as

$$B_t(k_1, k_2, k_3) = \tilde{b}_1^3 \left[B_m(k_1, k_2, k_3) + \tilde{b}_2 \left\{ P(k_1)P(k_2) + (\text{cyclic}) \right\} \right]$$

where B_m is the matter bispectrum given by PT.

• This method has been applied to real data (2dFGRS) :

$$b_1 = 1.04 \pm 0.11, \; b_2 = -0.054 \pm 0.08$$

at z=0.17. (Verde et al. 2002)

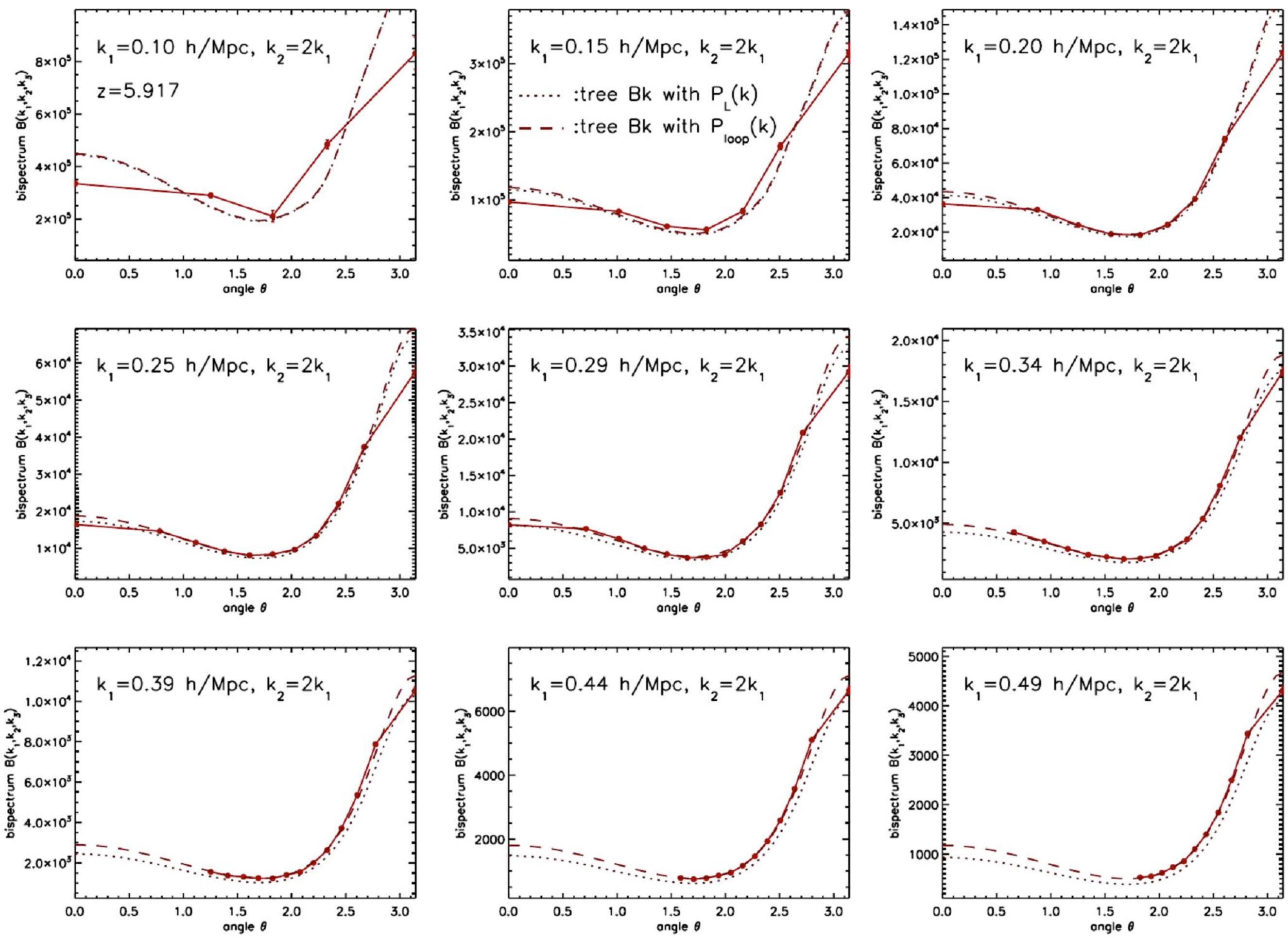
• At higher redshifts, we expect x10 better results.
(Sefusatti & Komatsu 2007)

• The bispectrum is an indispensable tool for measuring the bias parameters.

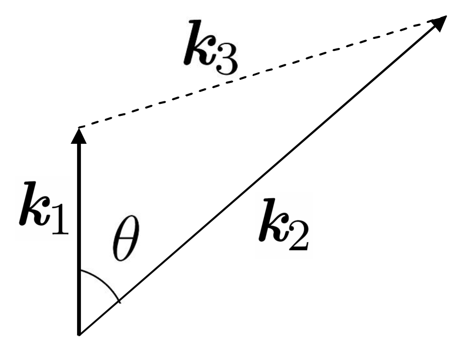
DJ, Sefusatti & Komatsu (In preparation)

3PT vs $B_m(k_1, k_2, \Theta)$ at z=6

$$B_m(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3) = 2P_m(k_1)P_m(k_2)F_2^{(s)}(\boldsymbol{k}_1, \boldsymbol{k}_2) + (\text{cycl.})$$



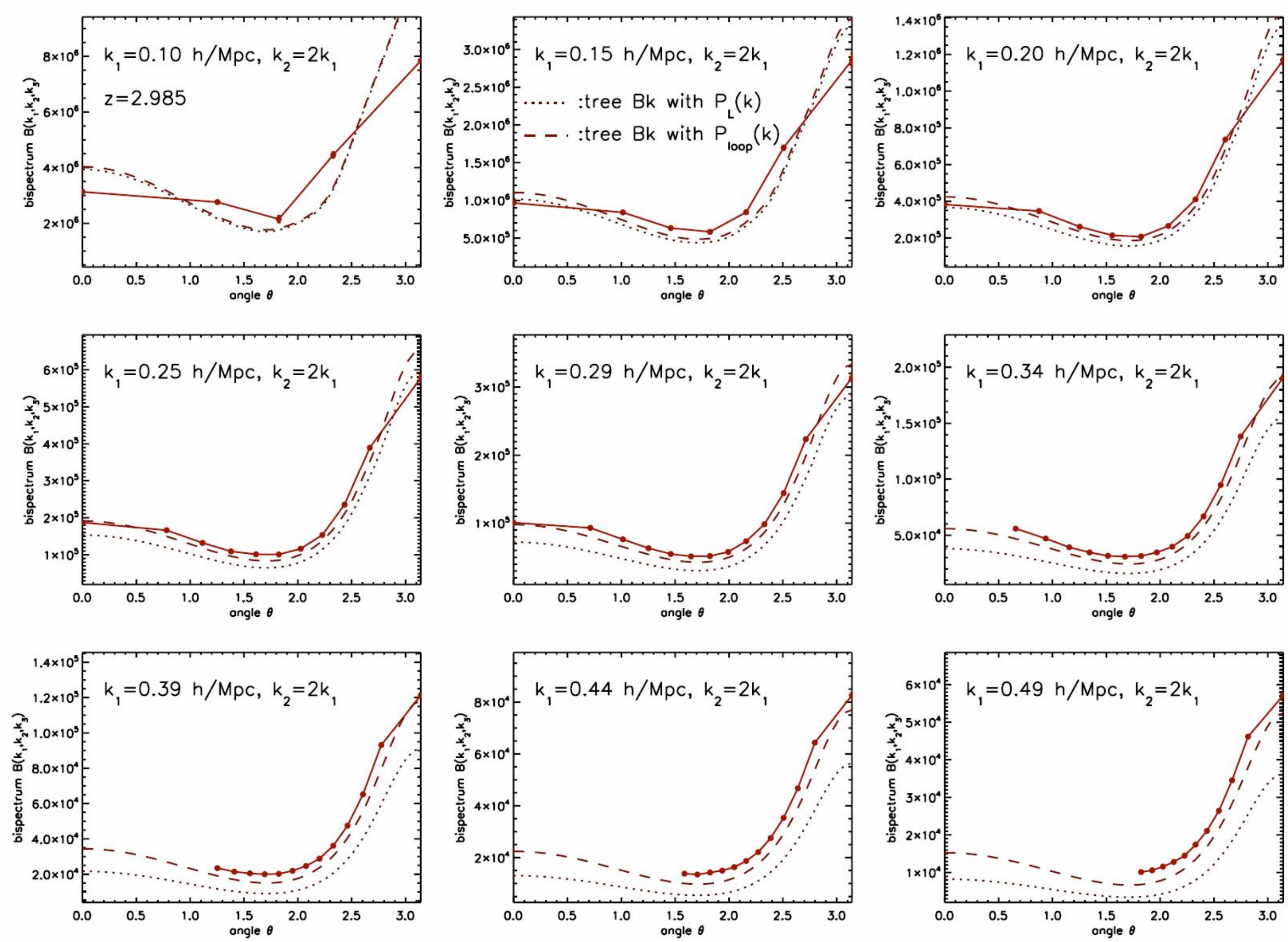
- Tree level matter bispectrum with 3PT power spectrum provides a good agreement at z=6!



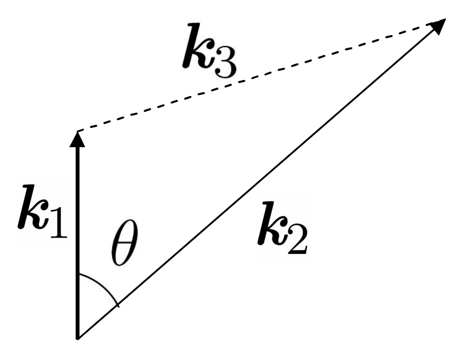
DJ, Sefusatti & Komatsu (In preparation)

3PT vs $B_m(k_1,k_2,\Theta)$ at z=3

$$B_m(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = 2P_m(k_1)P_m(k_2)F_2^{(s)}(\boldsymbol{k}_1,\boldsymbol{k}_2) + (\text{cycl.})$$



- However, the agreement is not satisfactory, even at z=3.
- 4th-order (next to leading order) PT is necessary?
- Preliminary!!



Conclusion

• Modeling the full power spectrum will lead us about 4 times better constraint on the cosmological distance determination than BAO only.

• We understood the effect of matter nonlinearity on P(k) at high redshifts (z>2), using cosmological perturbation theory.

• Nonlinear galaxy bias is also understood, at least on large scales where 3PT is valid.

• Bispectrum must be used: we are now developing a joint analysis pipeline using the power spectrum and bispectrum.

• Biggest limitation

These results are all in real space. We still need to go to redshift space. (DJ & Komatsu (200?), Work in progress)