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4th KIAS workshop

Baryon Acoustic Oscillations in 2D

Theoretical Issues and Observational Prospects

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Plan of talk

- Introduction: BAOs as dual cosmological probe
- Modeling BAOs from perturbation theory
- Anisotropic BAOs from SDSS DR7 LRG samples
- Summary

Introduction

Baryon Acoustic Oscillations (BAOs)

- Acoustic signature of primeval baryon-photon fluid imprinted on galaxy clustering

- Characteristic scale: r~100 Mpc/h, k~0.06 Mpc/h

$\longrightarrow$ *standard ruler*

unique tool to trace *cosmic expansion history*

Detection : SDSS, 2dF

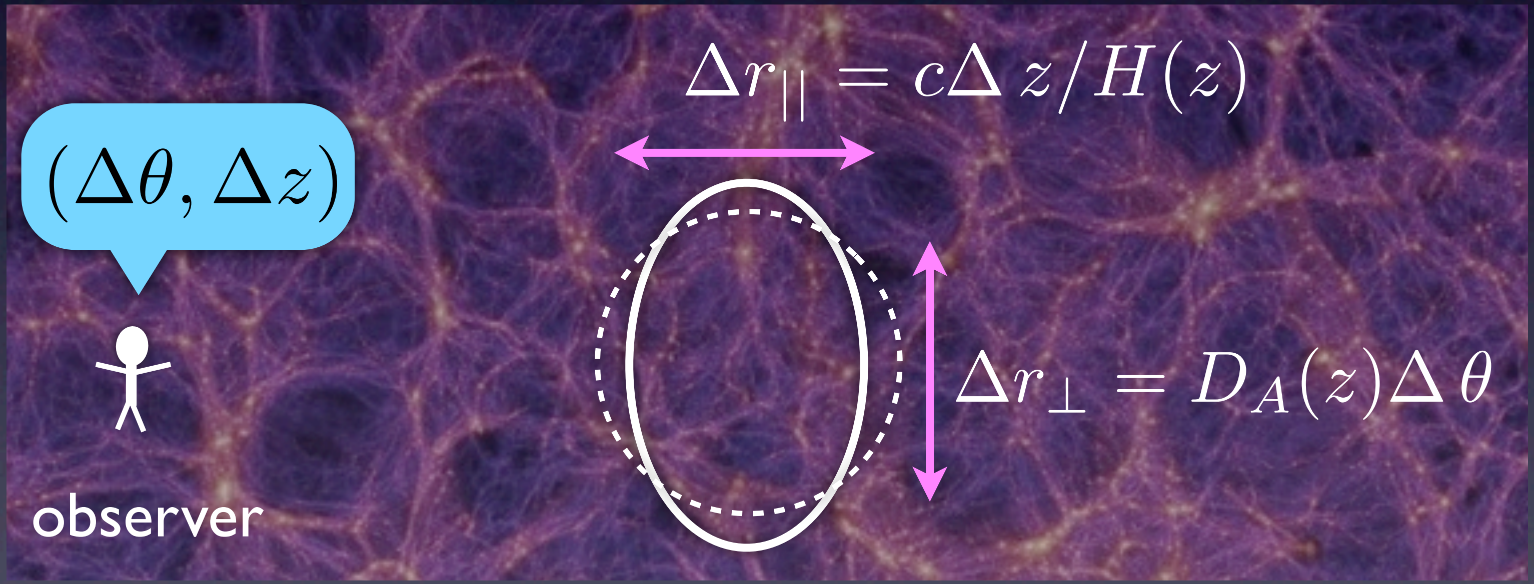
On-going / up-coming :

BOSS, Wiggle-z, HETDEX, SuMIRe-PFS, Euclid, WFIRST, ...etc.

BAOs as dual cosmological probe

Observed galaxy clustering pattern is apparently distorted in two ways:

✓ **Alcock & Paczynski effect**



Using BAO as standard ruler,

H(z) & **DA(z)** can be measured simultaneously

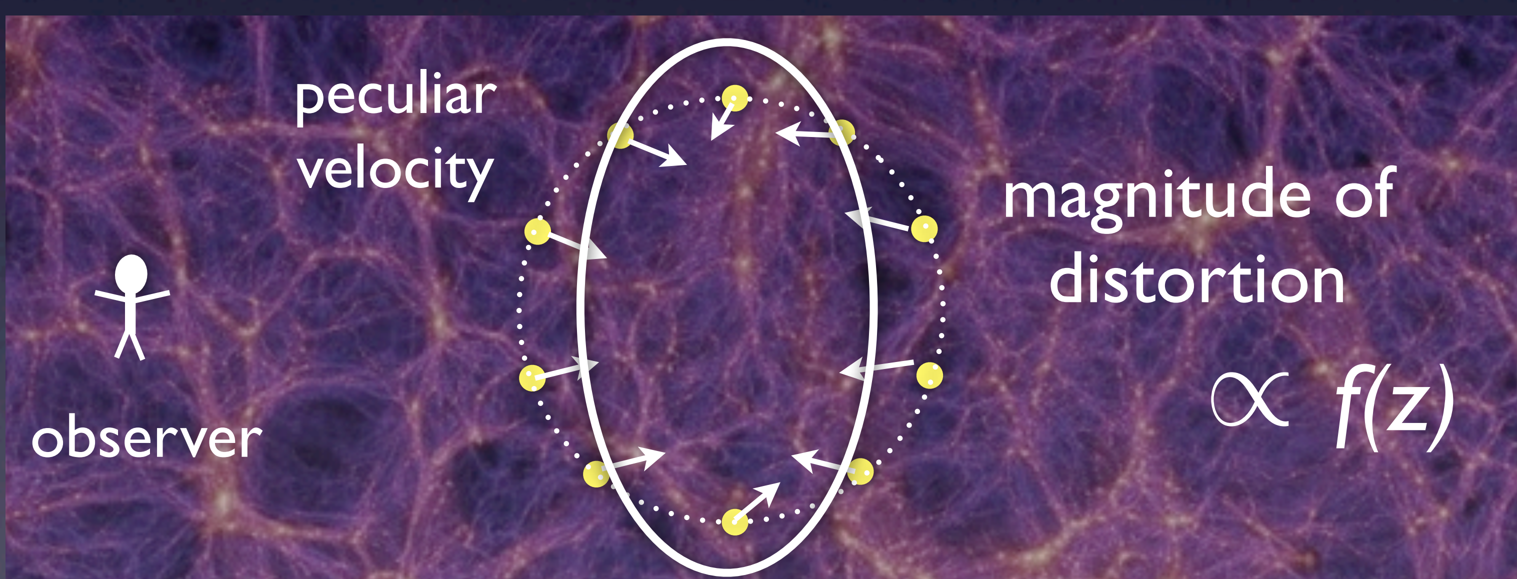
[e.g., Seo & Eisenstein ('03); Hu & Haiman ('03); Blake & Glazebrook ('03); Shoji et al.('09)]

BAOs as dual cosmological probe

Observed galaxy clustering pattern is
apparently distorted in two ways:

✓ **Alcock & Paczynski effect**

✓ **Redshift distortion effect**



growth-rate parameter

$$f(z) \equiv \frac{d\ln D_+}{d\ln a} \simeq \{\Omega_m(z)\}^{\gamma}$$

$$\gamma \approx 0.55 \text{ (GR)}, \quad 0.68 \text{ (DGP)}$$

Linder ('05)

Measurement of **f(z)** offers a test of gravity on cosmological scales.

Linder ('08); Guzzo et al. ('08); Yamamoto et al. ('08); Song & Dore ('09);
Percival & White ('09); White, Song & Percival ('09); Song & Percival ('09)

Practical issues

Precision BAO measurement at a percent level

Accurate theoretical template
to determine acoustic scale and/or redshift distortion

Reducing (known) systematics:

- Non-linear gravitational evolution
- Non-linear redsfhit distortion
- Galaxy biasing

Small, but non-negligible at a percent level precision

Methodology

... still on-going subjects

Fitting

Sophisticated parametric formula and/or hybrid fitting

Seo et al. ('08, '09); Padmanabhan & White ('09)

Reconstructing

Degradation of acoustic features by Zel'dovich approx.

Eisenstein et al. ('07); Huff et al. ('07); Padmanabhan et al. ('09)

Forward modeling

Perturbation theory (PT) based modeling of BAOs

Crocce & Scoccimarro ('06ab,'08); Jeong & Komatsu ('06,'09); Matsubara ('08ab);
AT & Hiramatsu ('08); AT et al. ('09, '10); etc. ...

Perturbation theory: Reloaded

CDM+baryon = pressureless & irrotational fluid

Juszkiewicz ('81), Vishniac ('83), Goroff et al. ('86), Suto & Sasaki ('91), Jain & Bertschinger ('94), ...

Basic eqs.

$$\frac{\partial\delta}{\partial t}+\frac{1}{a}\vec{\nabla}\cdot\left[(1+\delta)\vec{v}\right]=0$$

$$\frac{\partial\vec{v}}{\partial t}+\frac{\dot{a}}{a}\vec{v}+\frac{1}{a}(\vec{v}\cdot\vec{\nabla})\vec{v}=-\frac{1}{a}\vec{\nabla}\Phi$$

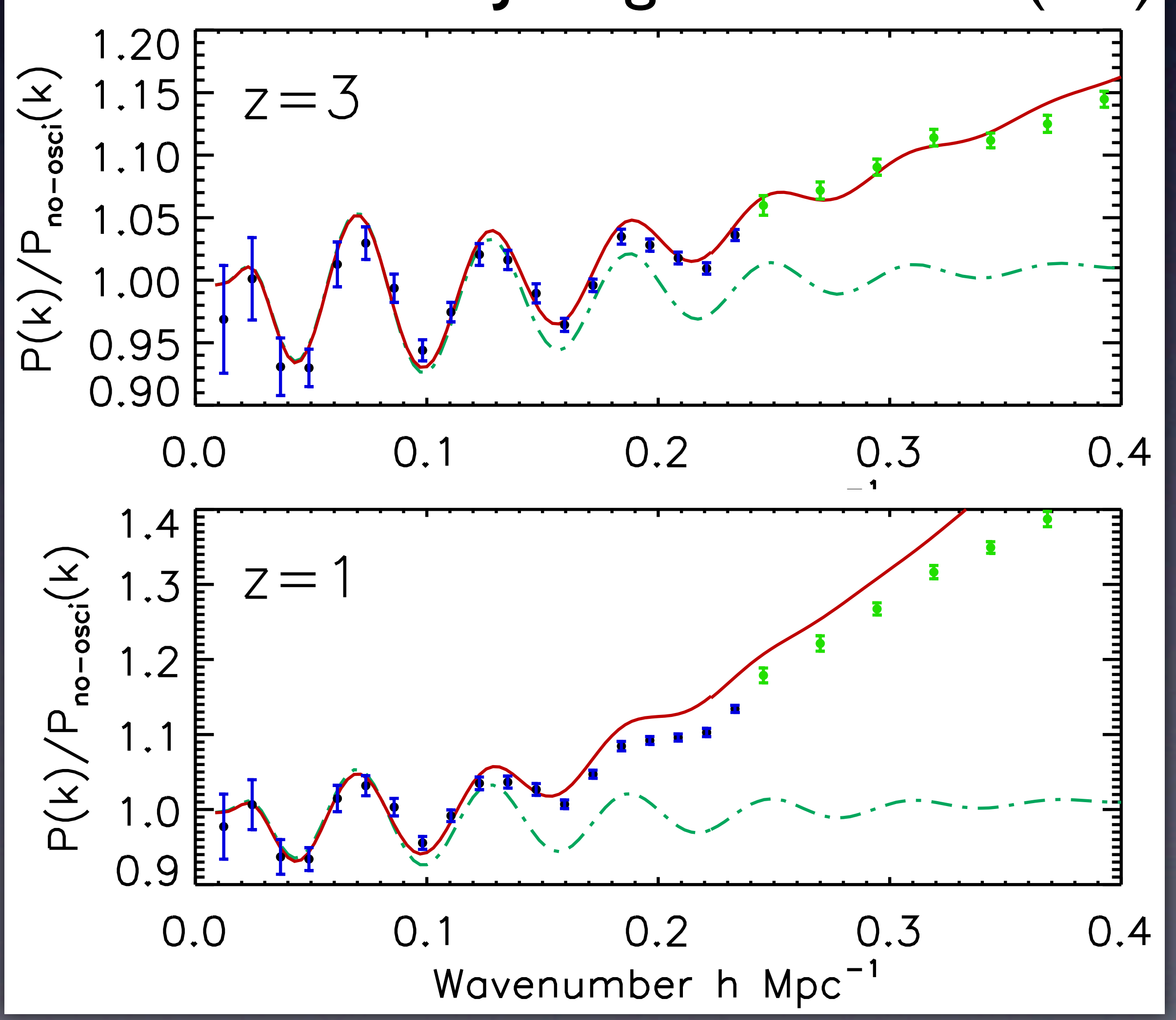
$$\frac{1}{a^2}\nabla^2\Phi=4\pi G\bar{\rho}_m\,\delta$$

Perturbative expansion

$$\delta=\delta^{(1)}+\delta^{(2)}+\delta^{(3)}+\cdots$$

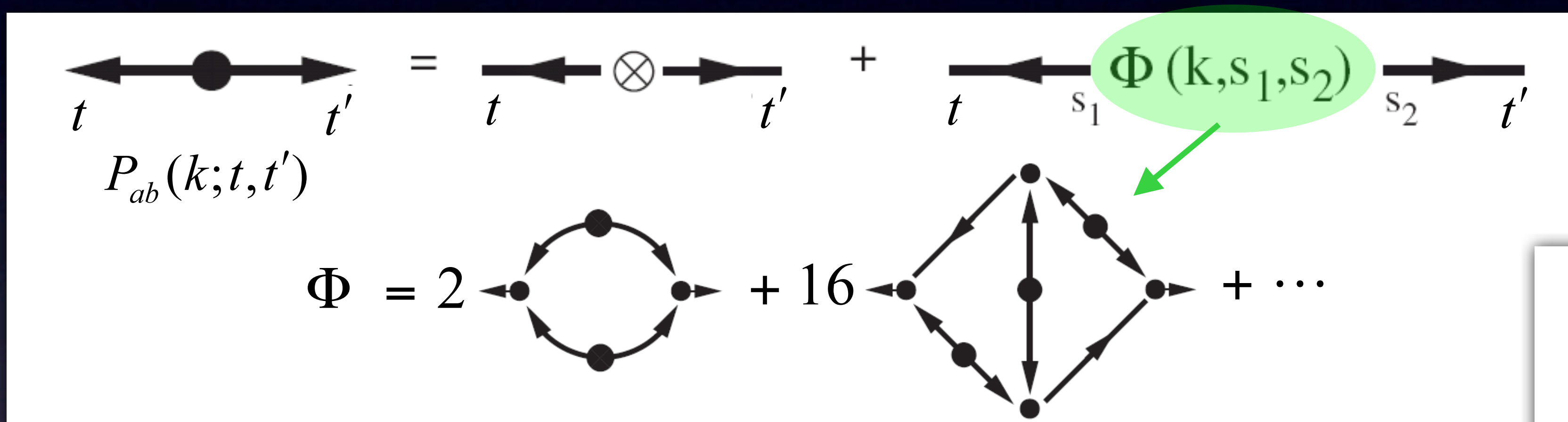
$$\Rightarrow\ \langle\delta(\mathbf{k};z)\delta(\mathbf{k}';z)\rangle=(2\pi)^3\delta_D(\mathbf{k}+\mathbf{k}')\,P(k;z)$$

Jeong & Komatsu ('06)

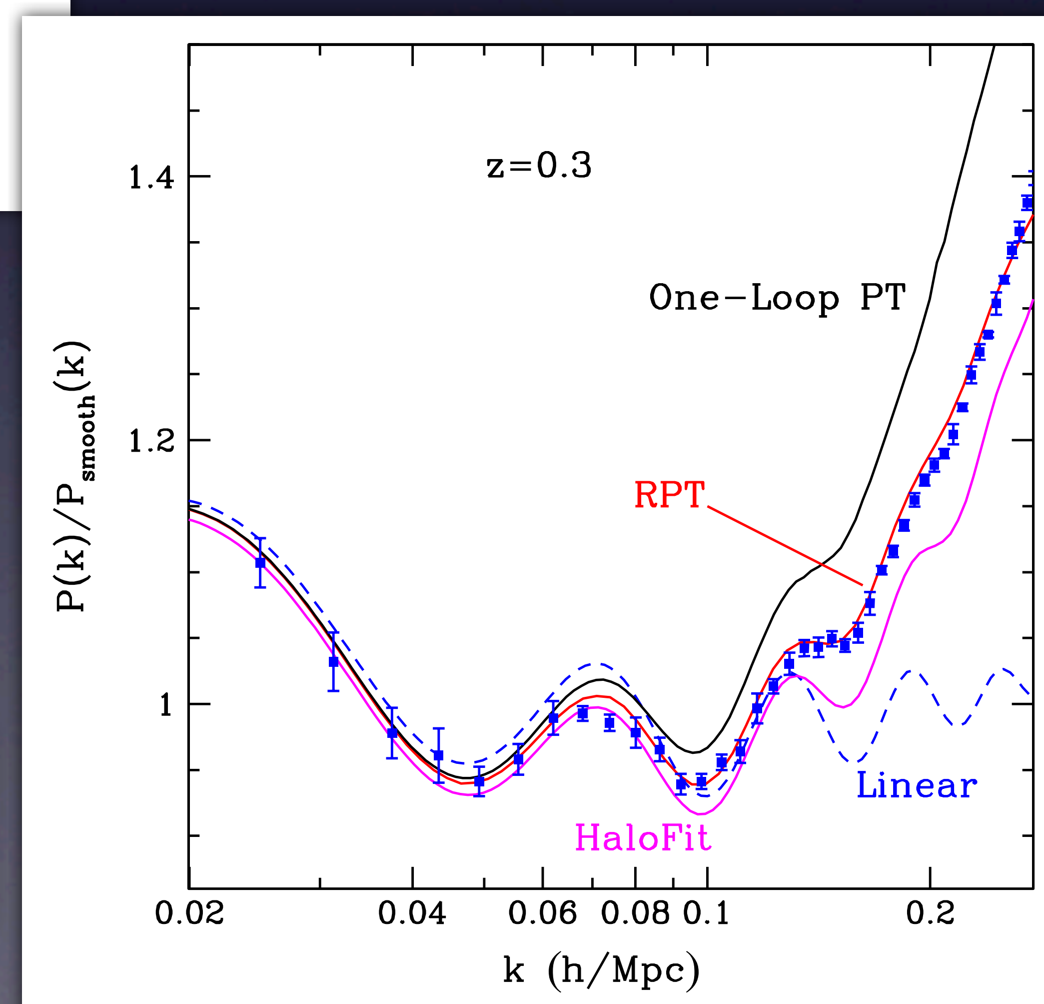


Perturbation theory: Revolution

Reorganizing standard PT expansions in terms of non-perturbative quantities (renomalized PT)



Crocce & Scoccimarro ('06ab, '08)



Development of improved PT

- Lagrangian PT — Matsubara ('08ab)
- Time-RG — Pietroni ('08)
- Closure approx. — AT & Hiramatsu ('08); AT et al. ('09)
- Gamma expansion — Bernardeau et al. ('09)

Standard PT vs. Improved PT

Standard PT

$$P(k) = \underline{P^{(11)}(k)} + \underline{\left(P^{(22)}(k) + P^{(13)}(k)\right)} + \underline{\left(P^{(33)}(k) + P^{(24)}(k) + P^{(15)}(k)\right)} + \cdots$$

Linear (tree) $\propto D^2(t)$

1-loop $\propto D^4(t)$

2-loop $\propto D^6(t)$

Naive expansion scheme regarding δ as a small expansion parameter

Improved PT (closure approx.)

$$P(k;t) = \underline{G^2(k|t,t_0)}P(k;t_0) + \underline{\int dt_1 \int dt_2\, G(k|t_1,t_0)G(k|t_2,t_0)\,\Phi_{1-\mathrm{loop}}[P(k);t_1,t_2]}$$

propagator

initial P(k)

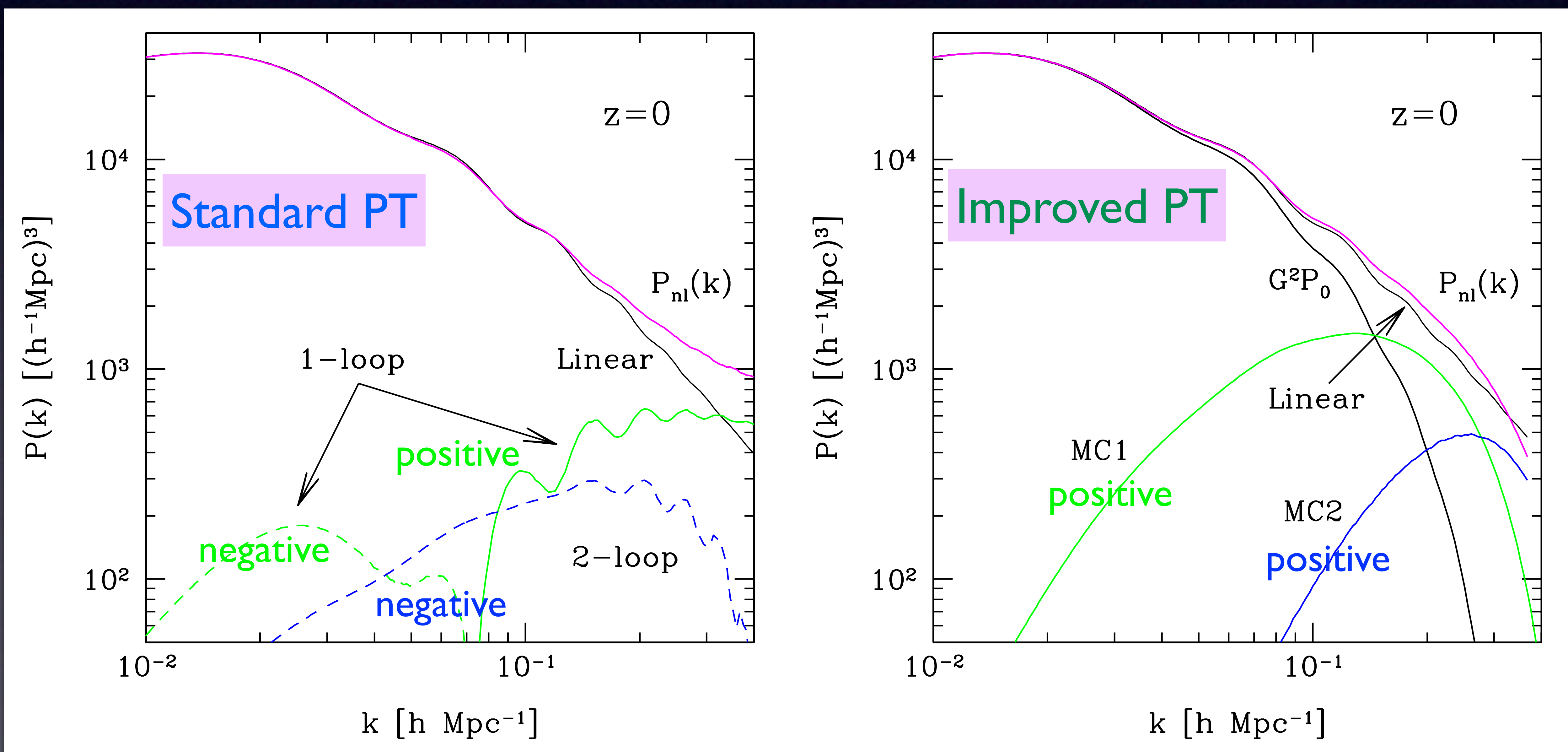
Mode-coupling (MC) term

- Non-perturbative effect is incorporated through propagator
- Iteratively evaluate MC term (irreducible loop diagrams) by Born approx.

Convergence properties

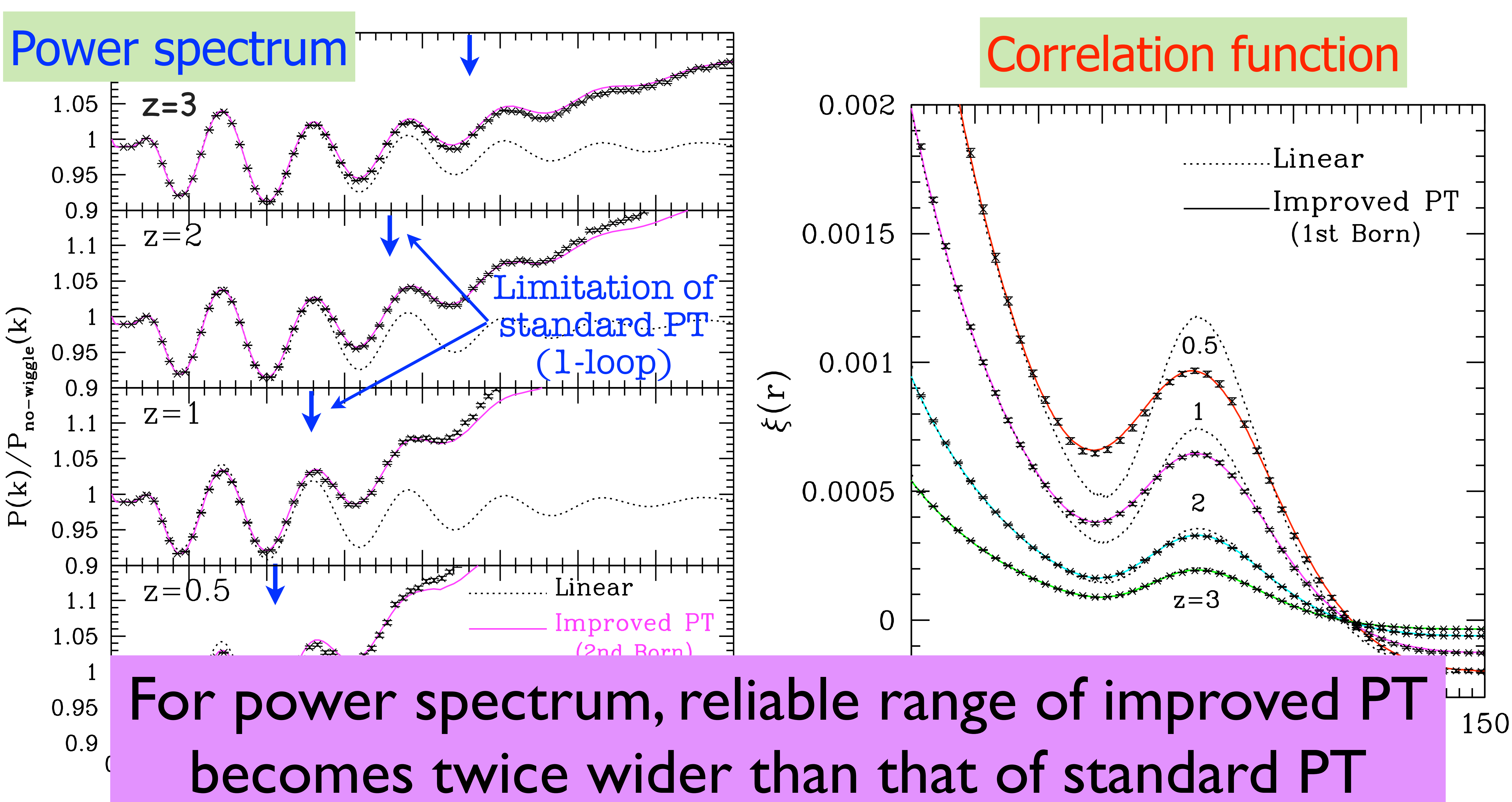
- All corrections become comparable at low-z.
- Positivity is not guaranteed.

Corrections from MC terms are positive and localized, and shifted to higher-k as increasing the order of Born approx.



Improved PT in real space

AT, Nishimichi, Saito & Hiramatsu ('09)



For power spectrum, reliable range of improved PT becomes twice wider than that of standard PT

Modeling redshift distortion

Definition

redshift space real space

$$\vec{\mathbf{s}} = \vec{\mathbf{r}} + \frac{(\vec{\mathbf{v}}\cdot\hat{\mathbf{z}})}{a\,H(z)}\,\hat{\mathbf{z}}\,; \qquad \begin{cases} \mathbf{v} & : \text{peculiar velocity} \\ \hat{\mathbf{z}} & : \text{observer's line-of-sight direction} \end{cases}$$

Observed clustering pattern is apparently distorted.

- Anisotropy (2D power spectrum)

$$P(k) \longrightarrow P^{(\mathrm{S})}(k,\,\mu)\,; \qquad \mu \equiv (\vec{\mathbf{k}}\cdot\hat{\mathbf{z}})/|\vec{\mathbf{k}}|$$

- Power spectrum amplitude

Enhancement	Kaiser effect	(small-k)
Suppression	Finger-of-God effect	(large-k)

Redshift-space power spectrum

Exact expression

$$\mathbf{x} = \mathbf{r} - \mathbf{r}'$$

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

$$u_z = (\vec{\mathbf{v}}\cdot\hat{\mathbf{z}})/(a\,H)$$

$$\Delta u_z = u_z(\mathbf{r}) - u_z(\mathbf{r}')$$

(Popular) analytic model

e.g., Scoccimarro (2004)

$$P^{(\mathrm{S})}(k,\mu) = \underbrace{e^{-(k\mu\,\sigma_{\mathrm{v}})^2}}_{\text{Finger of God}} \underbrace{\left[P_{\delta\delta}(k) - 2\,\mu^2\,P_{\delta\theta}(k) + \mu^4\,P_{\theta\theta}(k)\right]}_{\text{(non-linear) Kaiser}}$$

fitting parameter

(1D velocity dispersion)

... physical, but still empirical formula

Missing terms, found

From low-k expansion of the exact formula,

$$P^{(\mathrm{S})}(k,\mu)=e^{-(k\mu f\sigma_{\rm v})^2}\Big[P_{\delta\delta}(k)-2f\mu^2P_{\delta\theta}(k)+f^2\mu^4P_{\theta\theta}(k)+A(k,\mu)+B(k,\mu)\Big]$$

Leading-order corrections to the mode-coupling btw velocity & density

Non-Gaussian correction

$$A(k,\mu)=-2\,k\,\mu\int\frac{d^3\mathbf{p}}{(2\pi)^3}\,\frac{p_z}{p^2}B_\sigma(\mathbf{p},\mathbf{k}-\mathbf{p},-\mathbf{k})$$

anti-phase oscillation

$$\Big\langle\theta(\mathbf{k}_1)\left\{\delta(\mathbf{k}_2)-\mu_2^2\,\theta(\mathbf{k}_2)\right\}\left\{\delta(\mathbf{k}_3)-\mu_3^2\,\theta(\mathbf{k}_3)\right\}\Big\rangle=(2\pi)^3\delta_D(\mathbf{k}_{123})\,B_\sigma(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

Gaussian correction

$$B(k,\mu)=(k\mu)^2\int\frac{d^3\boldsymbol{p}}{(2\pi)^3}F(\boldsymbol{p})F(\boldsymbol{k}-\boldsymbol{p})$$

small in amplitude (<1-2%)

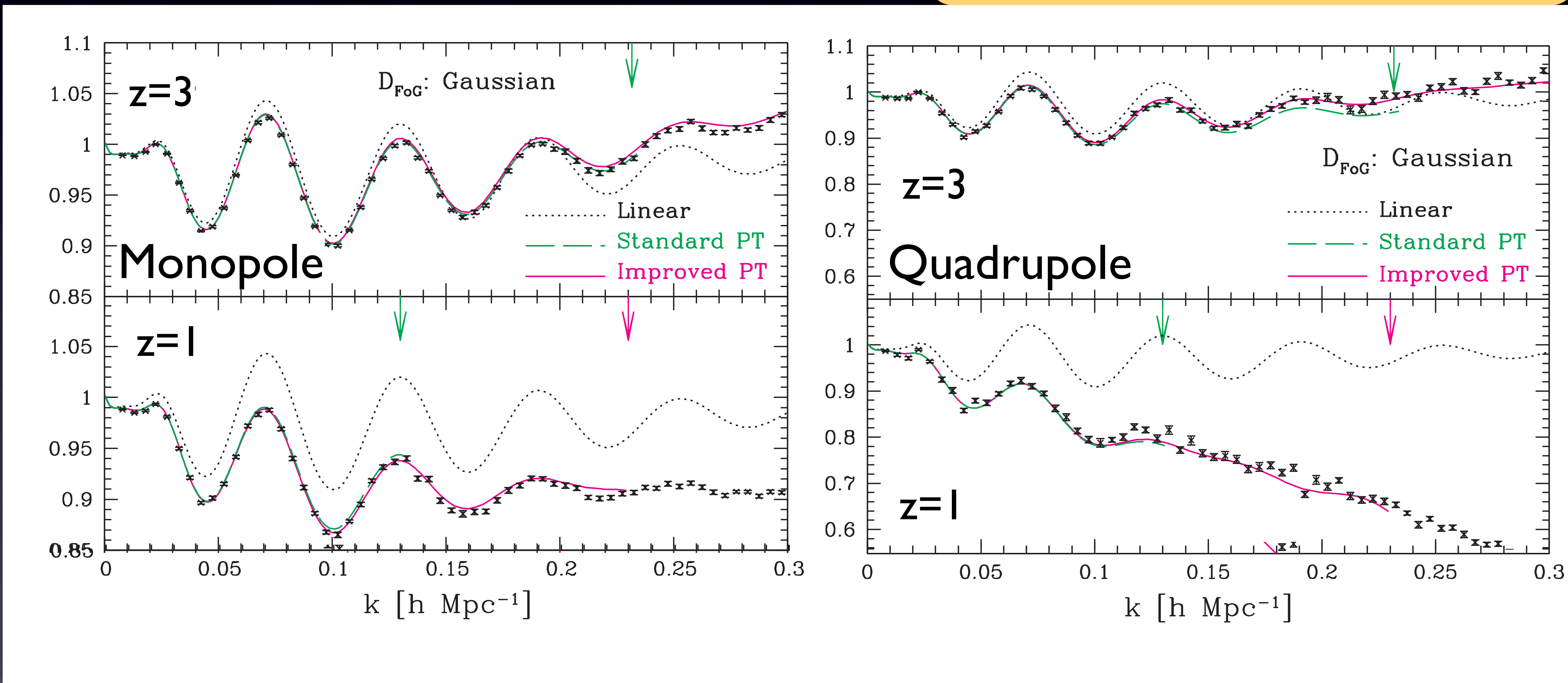
$$F(\boldsymbol{p})\equiv\frac{p_z}{p^2}\left\{P_{\delta\theta}(p)-\frac{p_z^2}{p^2}P_{\theta\theta}(p)\right\}$$

These also depend on ‘f’

Role of corrections

Including corrections

$$P^{(\mathrm{S})}(k,\mu) = \sum_{\ell=\mathrm{even}} P_\ell^{(\mathrm{S})}(k)\,\mathcal{P}_\ell(\mu)$$

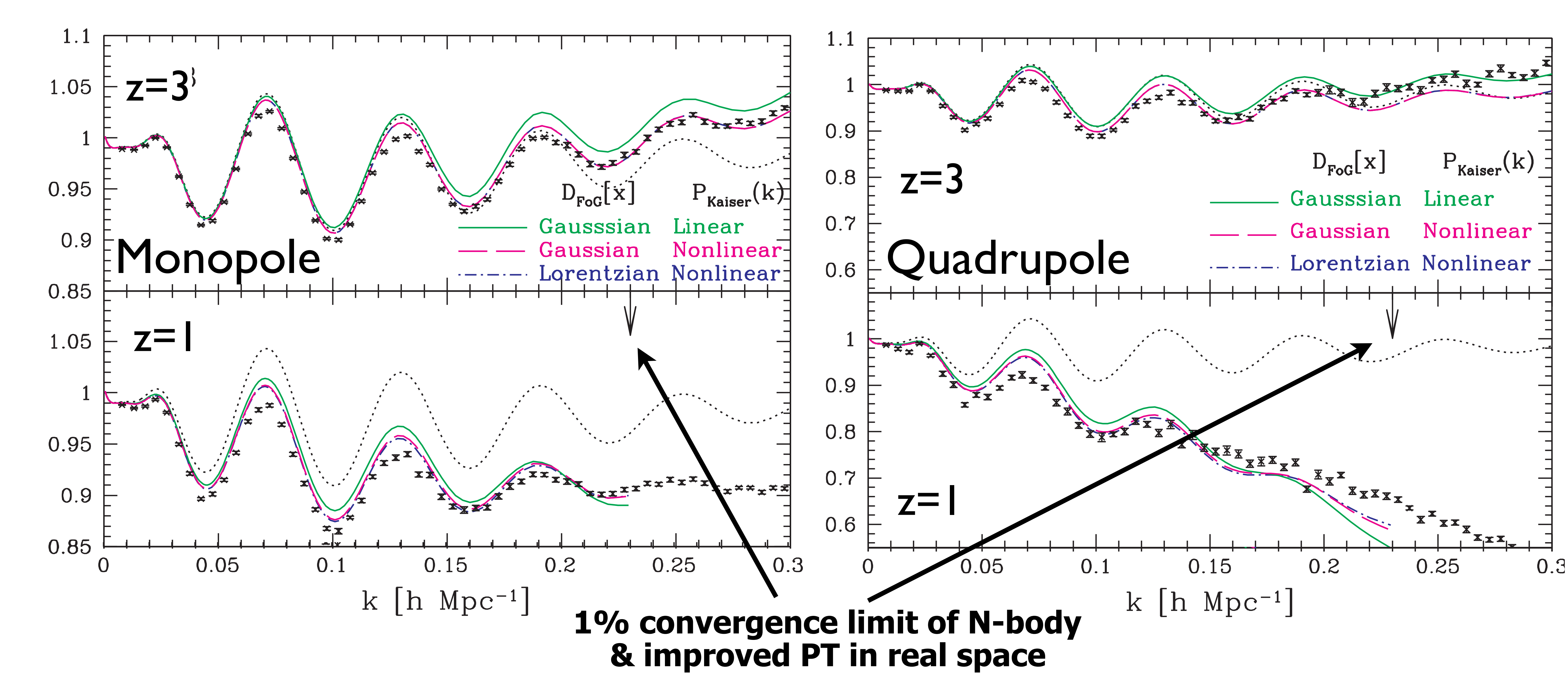


AT, Nishimichi & Saito ('10)

Role of corrections

Neglecting corrections

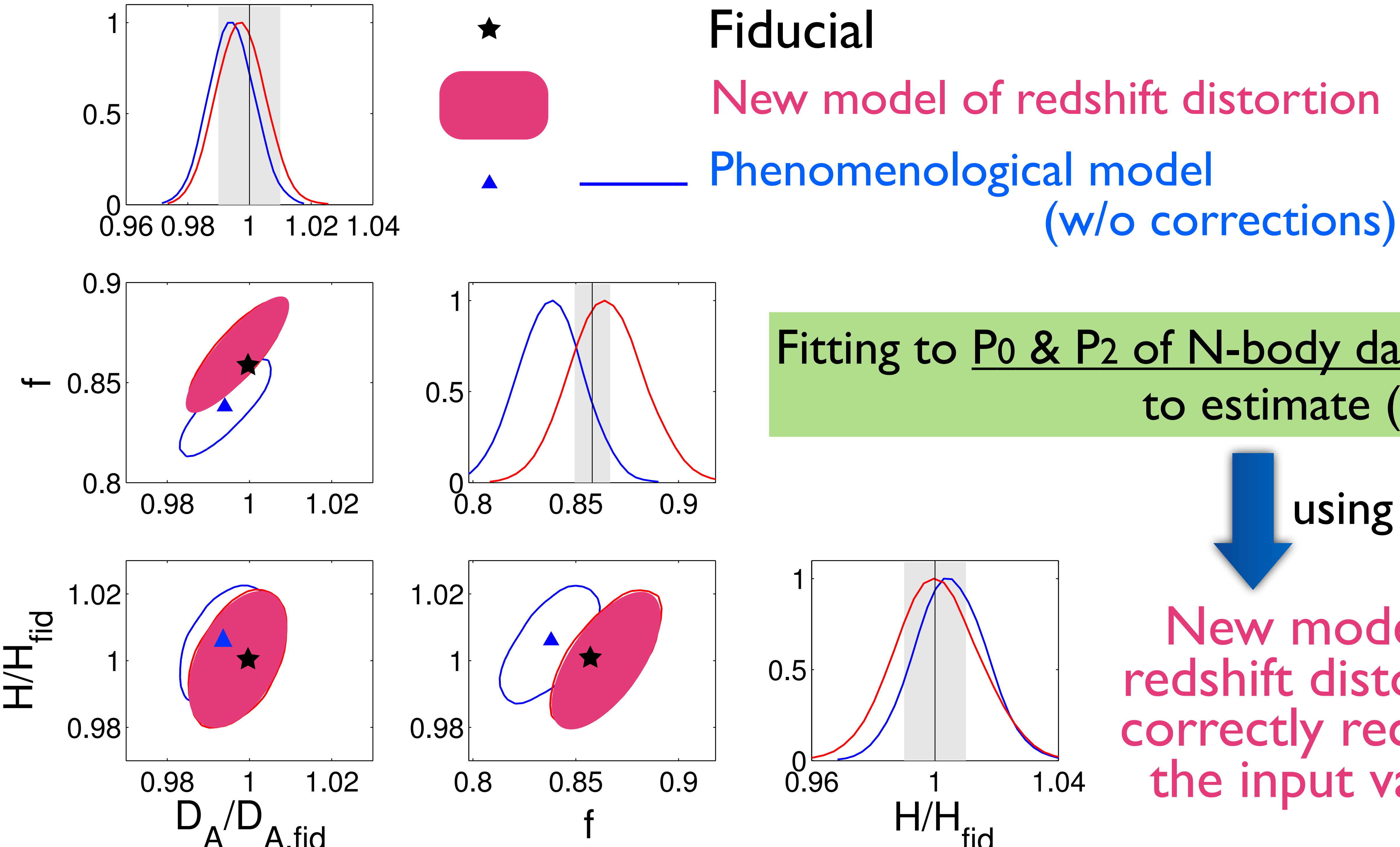
$$P^{(\mathrm{S})}(k,\mu) = \sum_{\ell=\mathrm{even}} P_\ell^{(\mathrm{S})}(k)\,\mathcal{P}_\ell(\mu)$$



Even in 1% convergence limit, discrepancy manifest (few % in P0, >5% in P2)

Check: recovery of D_A, H & f

AT, Nishimichi & Saito ('10)



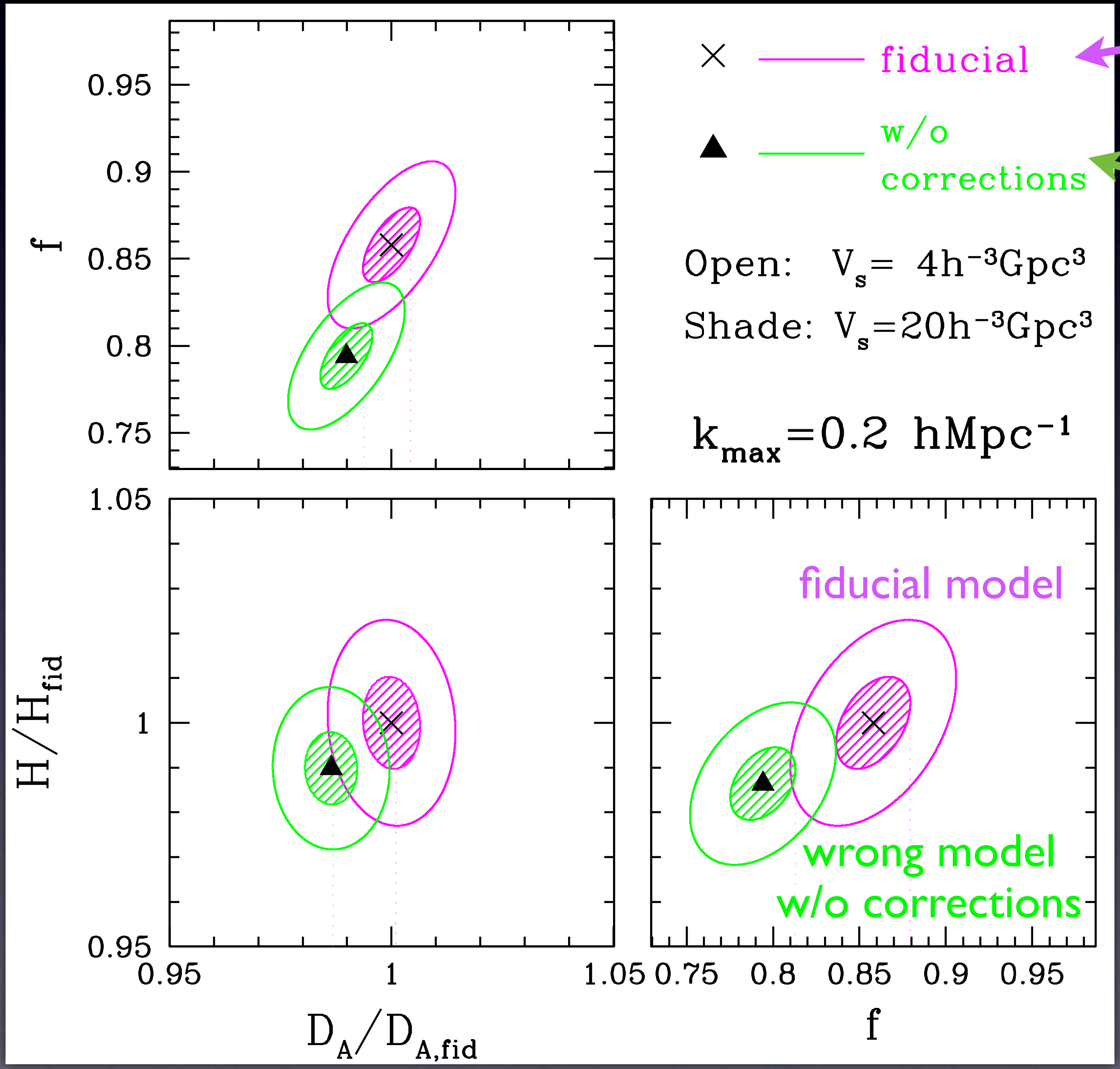
Fitting to P_0 & P_2 of N-body data
to estimate (D_A, H, f)

using MCMC

New model of redshift distortion correctly recovers the input values

Impacts on future surveys

Fisher matrix analysis using full 2D information



New model of redshift distortion

Phenomenological model (w/o corrections)

Assumptions

$z = 1,$ linear bias $(b = 2)$,
$n_g = 5 \times 10^{-4} h^3 \mathrm{Mpc}^{-3}$

Systematic biases:

- DA, H : 1~2 %
- f : ~5 %

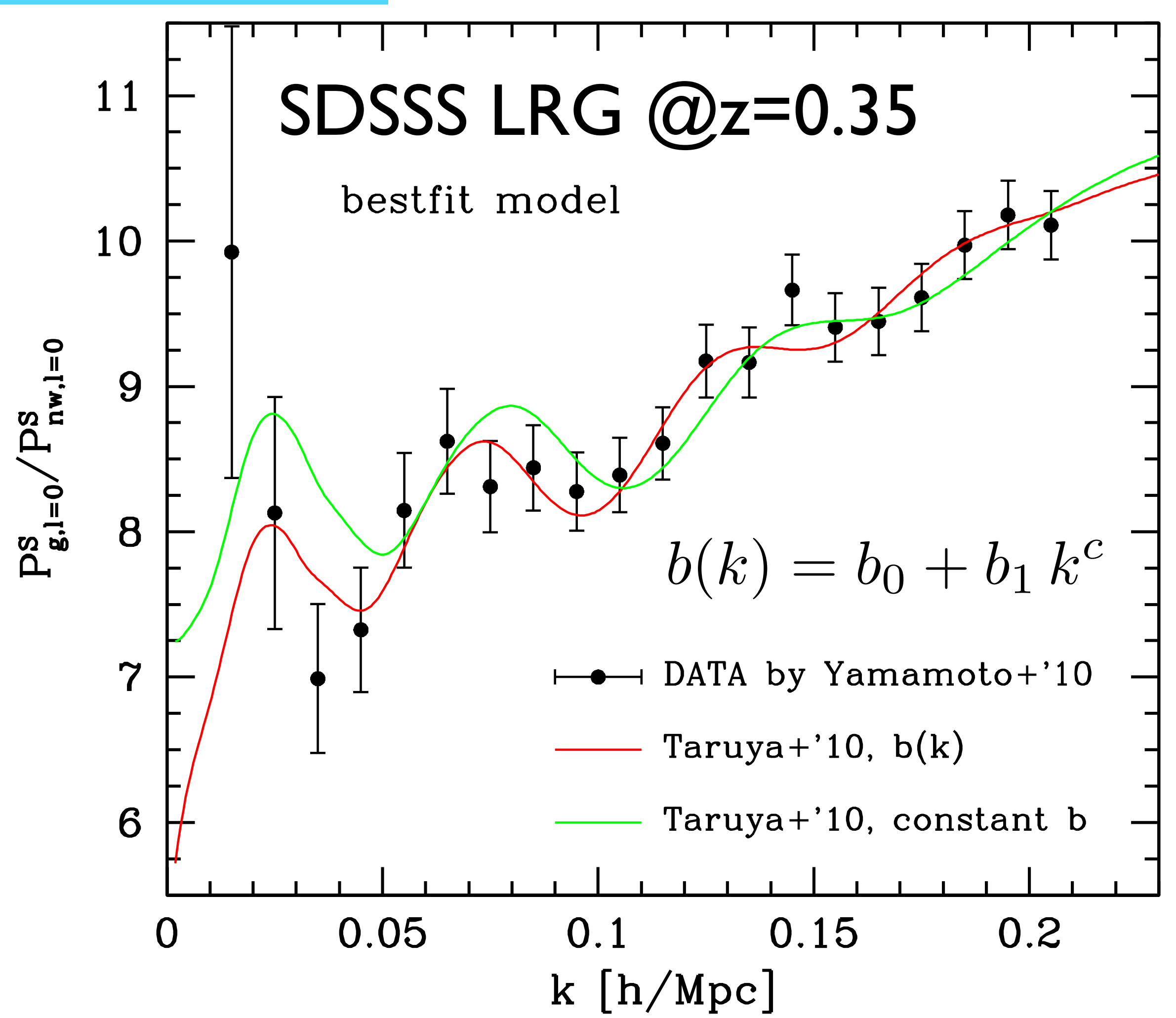
cannot be negligible even for stage III-class surveys

SDSS DR7 LRG samples

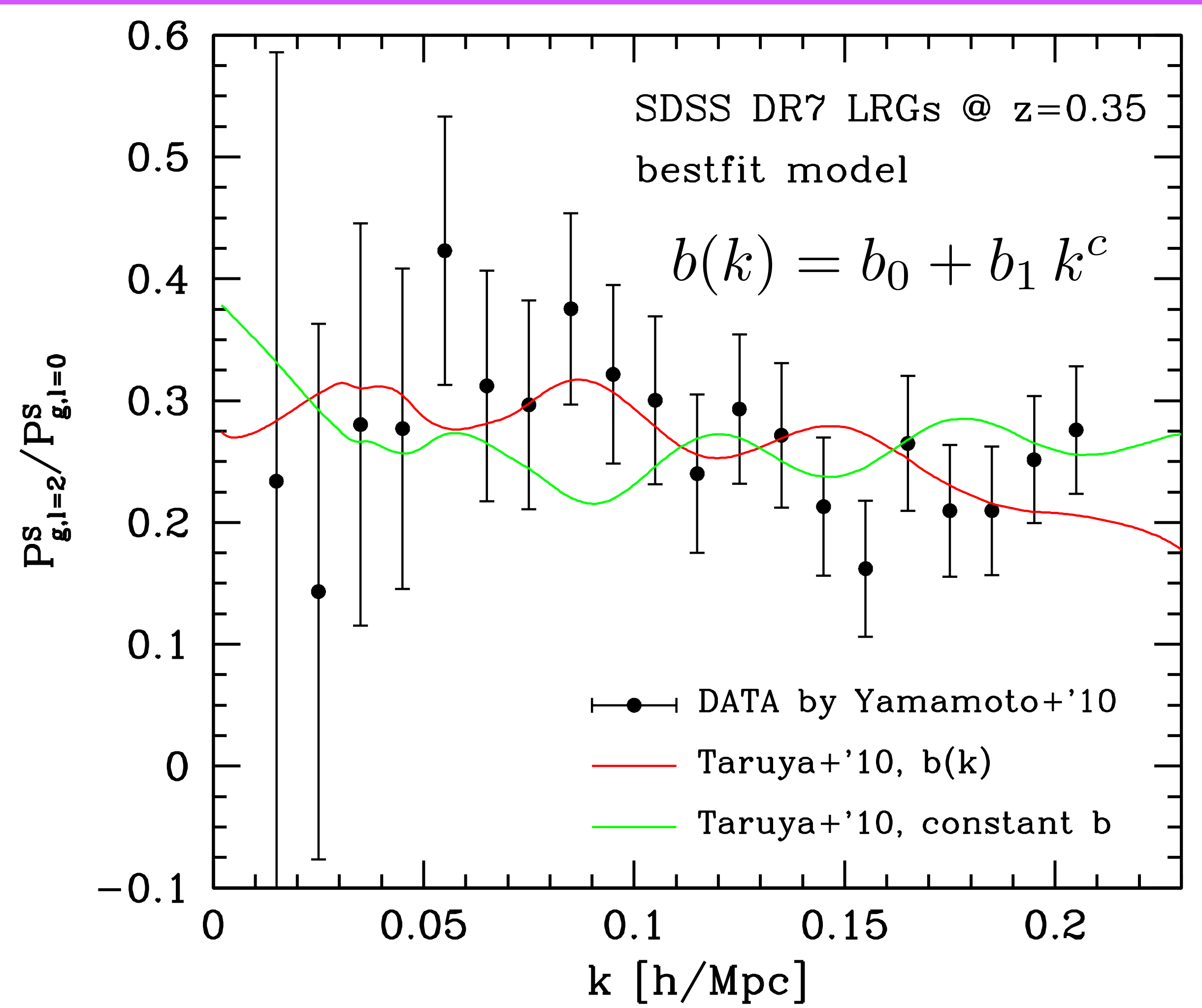
Assuming linear scale-dependent bias,

monopole & quadrupole spectra ⟶ fit to PT model

Monopole



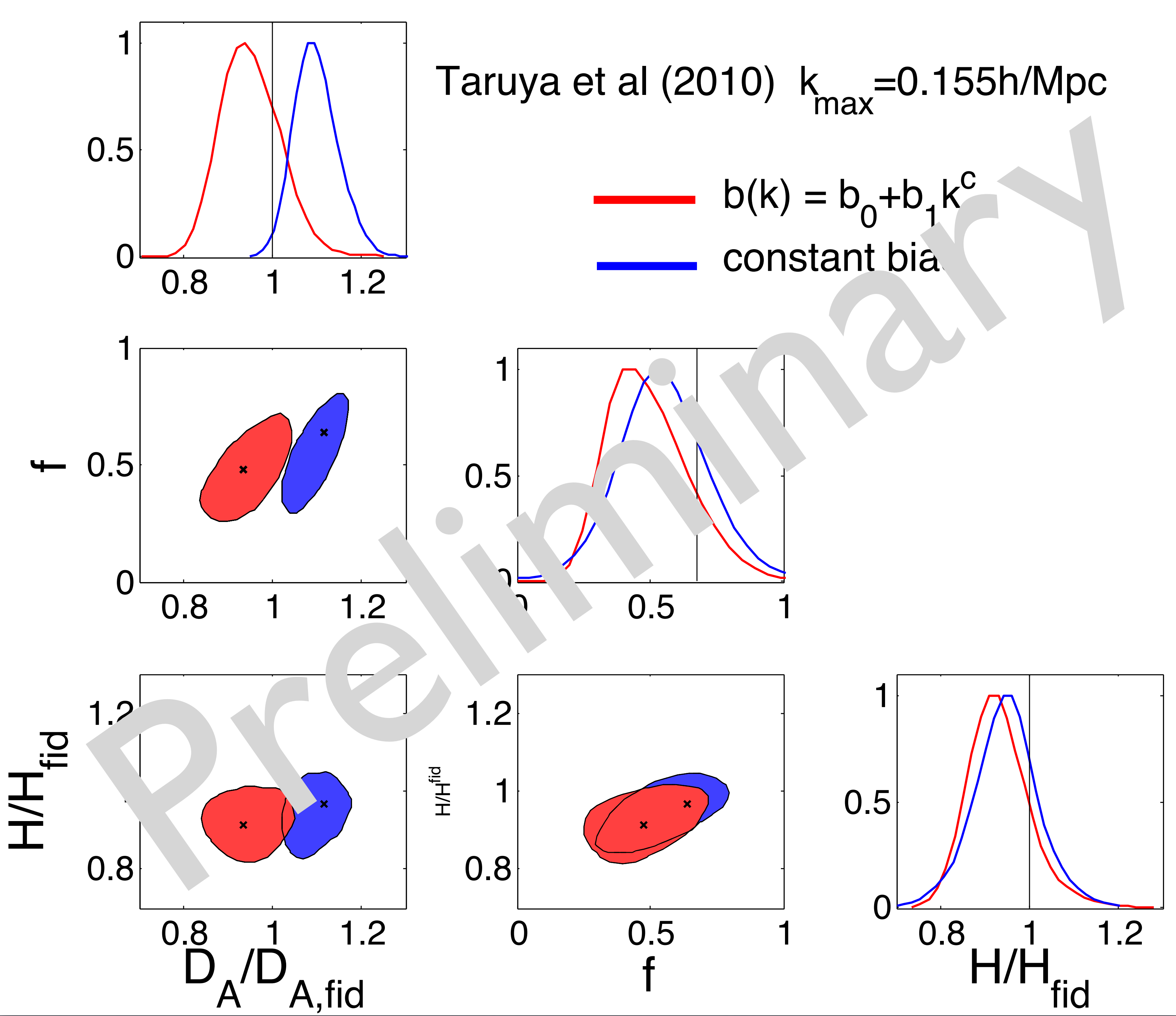
Quadrupole-to-Monopole ratio



Saito, Nishimichi, AT & Yamamoto ('10) in prep.

Constraints on DA, H & f

Saito, Nishimichi, AT & Yamamoto ('10) in prep.



Simultaneously constrain DA, H & f from SDSS DR7 LRGs

However,

Resultant constraint on DA is rather sensitive to property of galaxy bias

Summary

Modeling and predicting BAOs from perturbation theory

gravitational evolution
redshift distortion

PT-based model has been making rapid progress
and accuracy of prediction now reaches a percent level !

- Application to SDSS DR7 LRG

  $\longrightarrow$ simultaneous constraint on D_A, H & f

- Impact of scale-dependent (non-linear) galaxy bias

  ……… remaining final issue