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BAOs in 2D

Modeling redshift-space power spectrum from perturbation theory

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Contents

- Introduction: why 2D ?
- Modeling redshift-space distortion
- Impact on parameter estimations
- Summary

Introduction

Precise measurement of Baryon Acoustic Oscillations (BAOs)

- A major science goal of galaxy redshift surveys
- Characteristic scale of BAO as a standard ruler to trace cosmic expansion history

→ nature of dark energy

Reducing systematics is a big issue :

- non-linear evolution
- redshift distortion
- galaxy bias

Aim of this talk

Methodology

There are several techniques to reduce systematics
(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

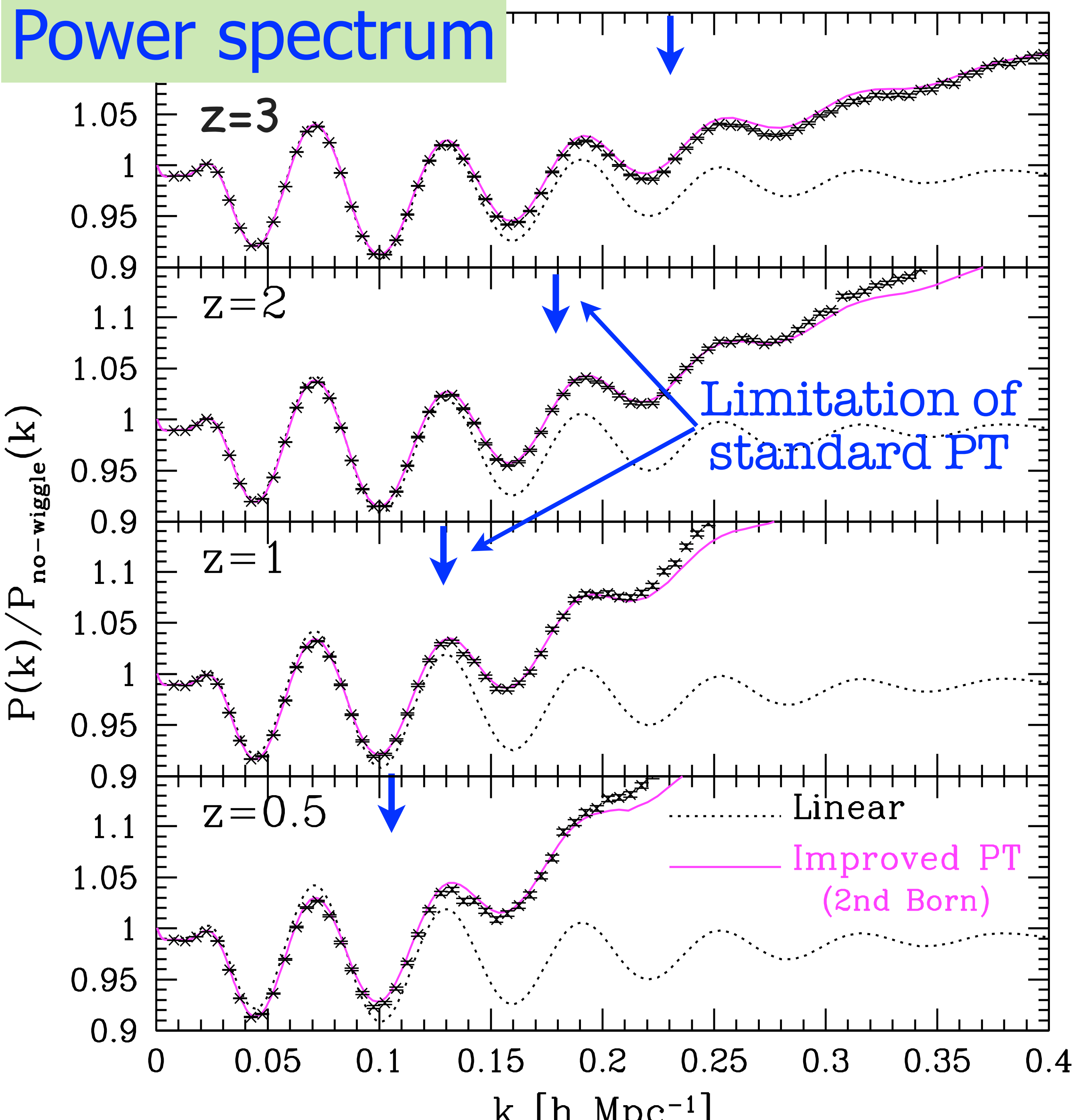
Crocce & Scoccimarro (’08); Jeong & Komatsu (’06,’09);
Matsubara (‘08a,b); AT & Hiramatsu (’08); AT et al. (’09); etc. ...

Development of new analytic method

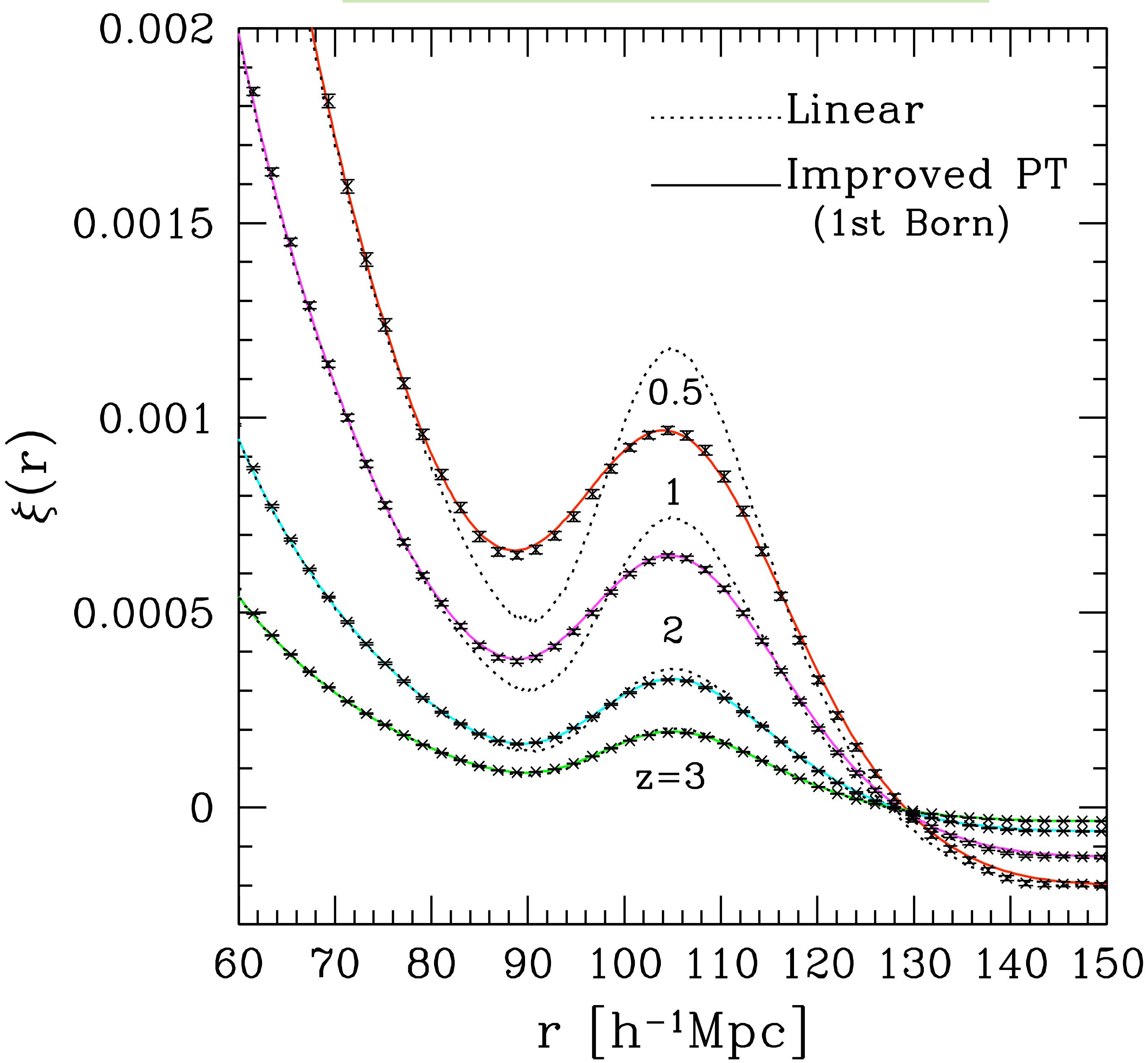
An improved treatment of perturbation theory (PT) to deal with non-linear gravitational evolution

AT & Hiramatsu (2008)
AT, Nishimichi, Saito & Hiramatsu (2009)

Power spectrum



Correlation function



Development of new analytic method

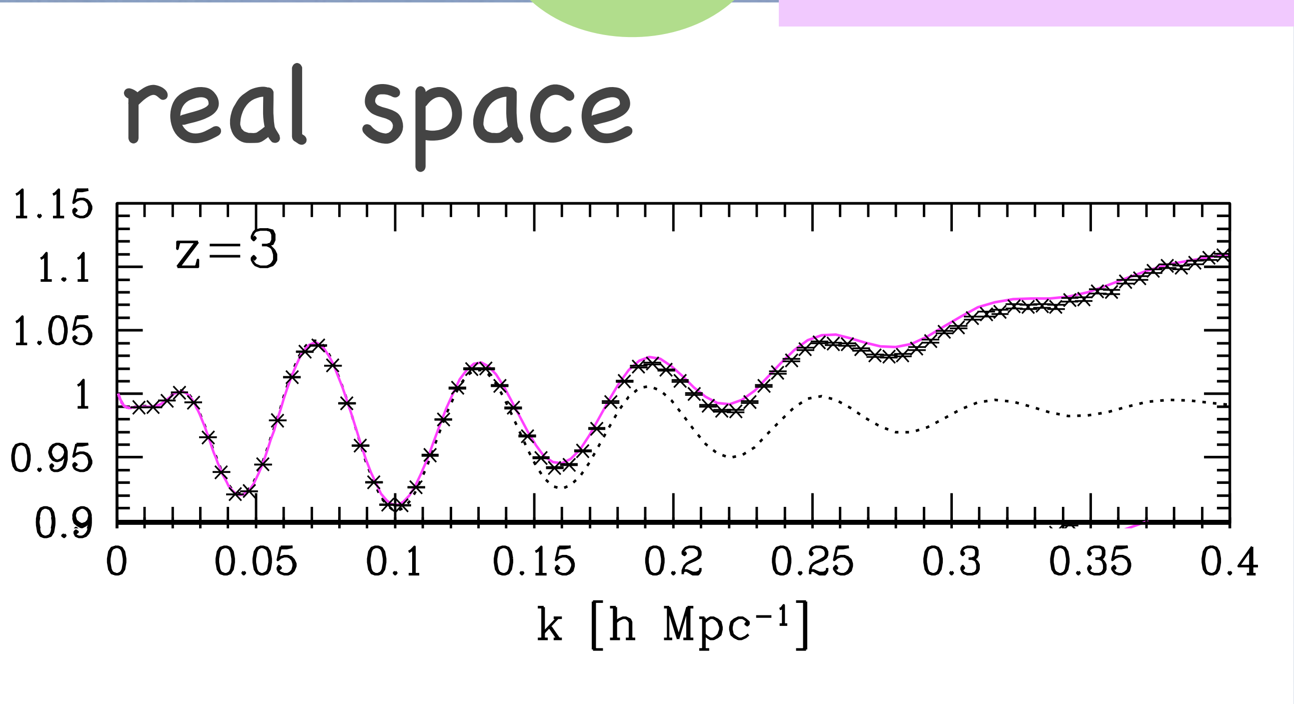
An improved treatment of perturbation theory (PT) to deal with non-linear gravitational evolution

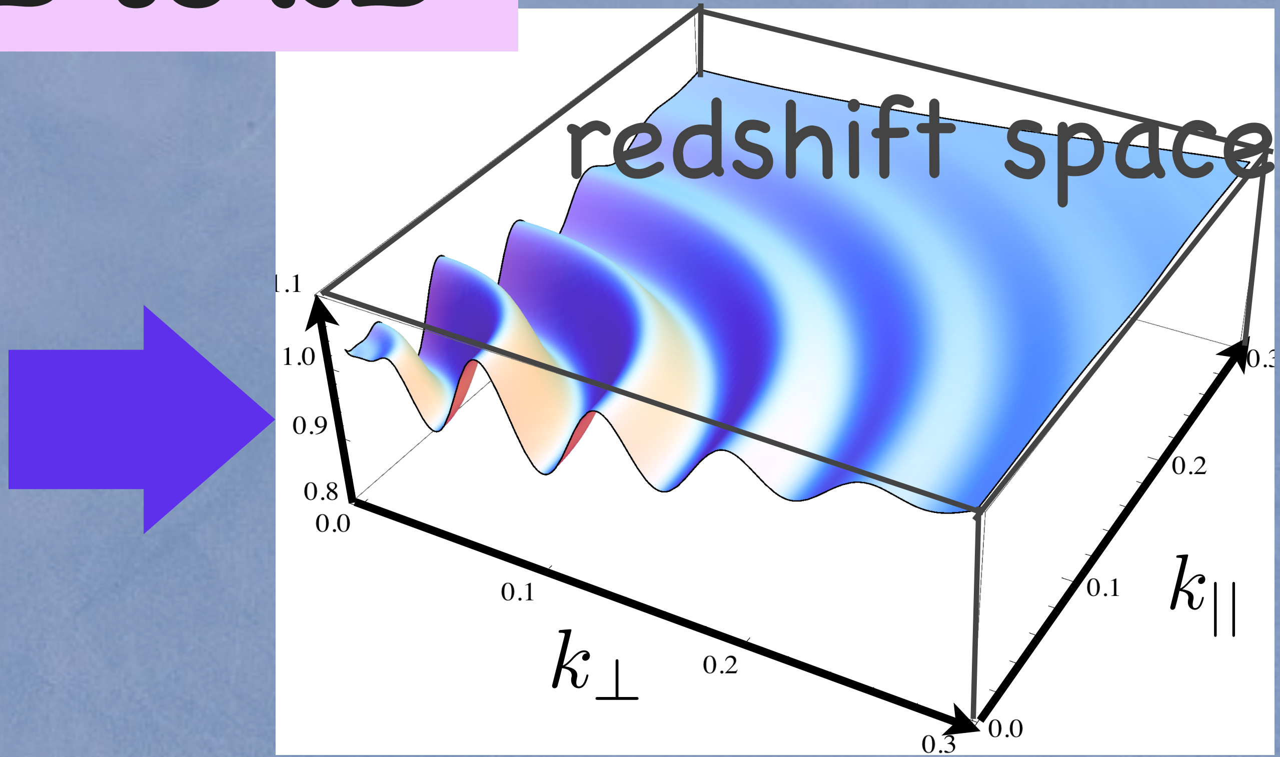
AT & Hiramatsu (2008)
AT, Nishimichi, Saito & Hiramatsu (2009)

This talk

Based on improved PT of non-linear structure growth, further investigation on modeling BAOs

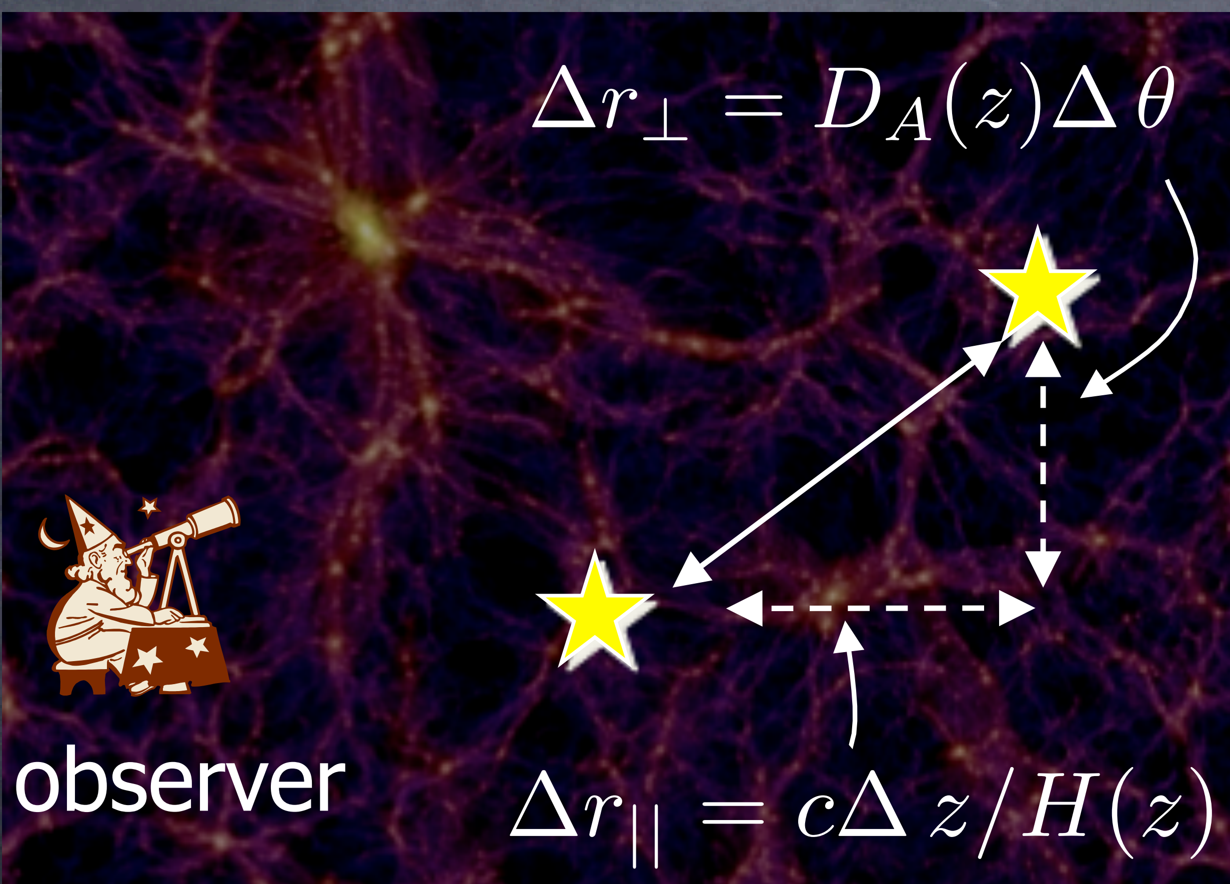
Key word **From 1D to 2D**





Alcock-Paczynski (AP) effect

Different distance measurements between parallel & transverse directions cause apparent anisotropies in P(k)



Using BAO as standard ruler,

H(z) & DA(z)

can be determined simultaneously

→ strong constraints on dark energy E.O.S

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

Note majority of recent works focuses on angle-averaged 1D BAOs

⟶ only constrain the combination, $D_A(z)^2/H(z)$

Gravity test

In modeling 2D, redshift distortion effect is inevitable,

but it provides a way to test gravity on cosmological scales

On linear regime,

Kaiser ('87)

strength of redshift distortion

$\propto$ growth-rate parameter : $f(z) \equiv \dfrac{d\ln D_+}{d\ln a}$

$\left[D_+(z) : \text{linear growth rate} \right]$

In general relativity,

$$f(z) \simeq \{\Omega_{\rm m}(z)\}^{\gamma} \quad ; \quad \gamma = 0.55$$

e.g., Linder ('05)

Deviation of γ from 0.55 implies a breakdown of GR on cosmological scales

Redshift distortion

Definition

redshift space real space

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

Observed clustering pattern is apparently distorted.

- Anisotropy (2D power spectrum)

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

- Power spectrum amplitude

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

Power spectrum in redshift space

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)

1D velocity dispersion

$$P^{(\mathrm{S})}(k,\mu) = e^{-(k\mu\,\sigma_{\mathrm{v}})^2}\left[P_{\delta\delta}(k) - 2\,\mu^2\,P_{\delta\theta}(k) + \mu^4\,P_{\theta\theta}(k)\right]$$

Finger of God — (non-linear) Kaiser

fitting parameter

... physical, but still empirical formula

Missing terms, found

From low-k expansion of the exact formula for $P^{(\mathrm{S})}(k,\mu)$,

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

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

Non-Gaussian correction

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

antiphase 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

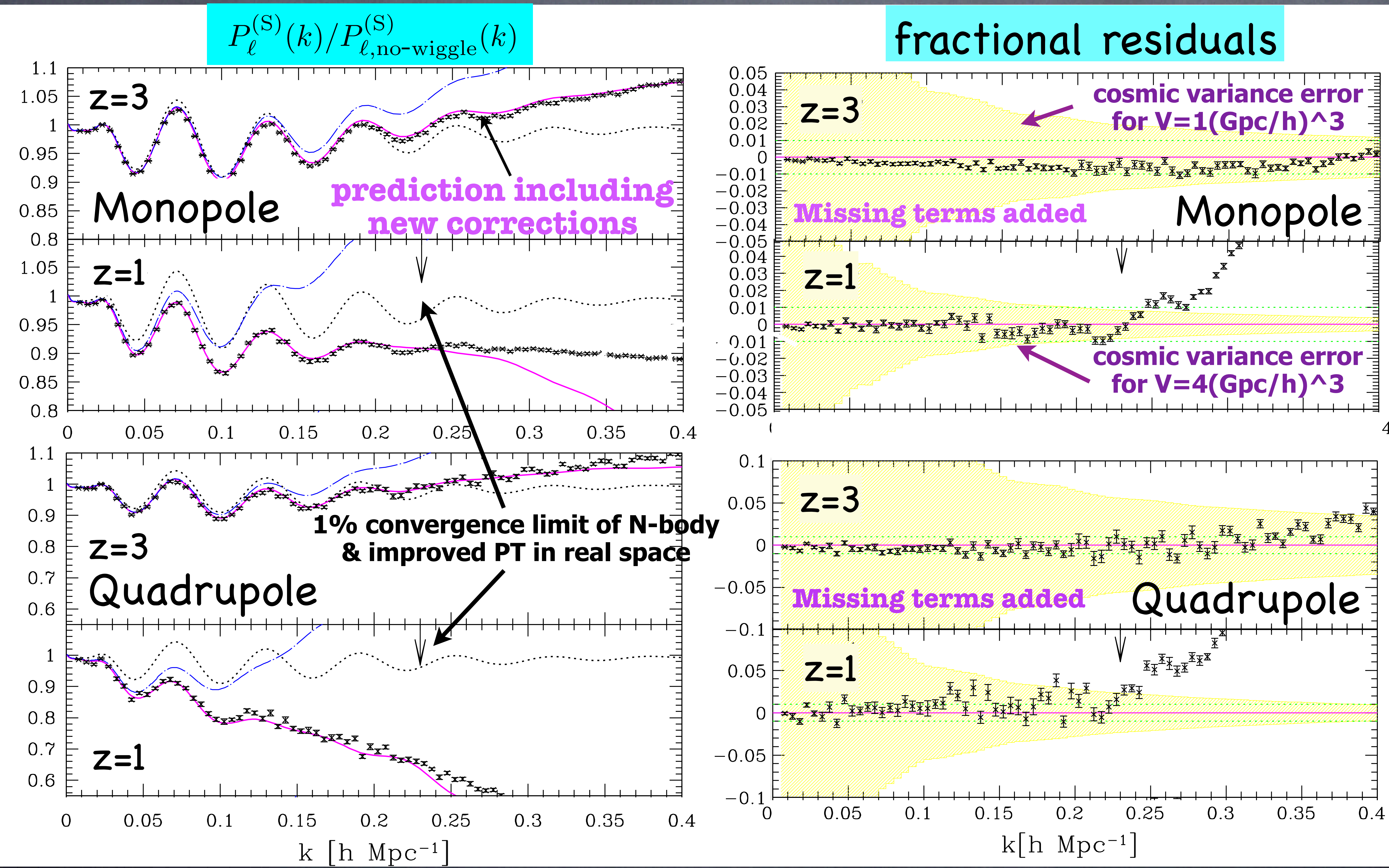
$$B(k,\mu)=(k\mu)^2\int\frac{d^3\boldsymbol{p}}{(2\pi)^3}F(\boldsymbol{p})F(\boldsymbol{k}-\boldsymbol{p})$$

small in amplitude (<1-2%)

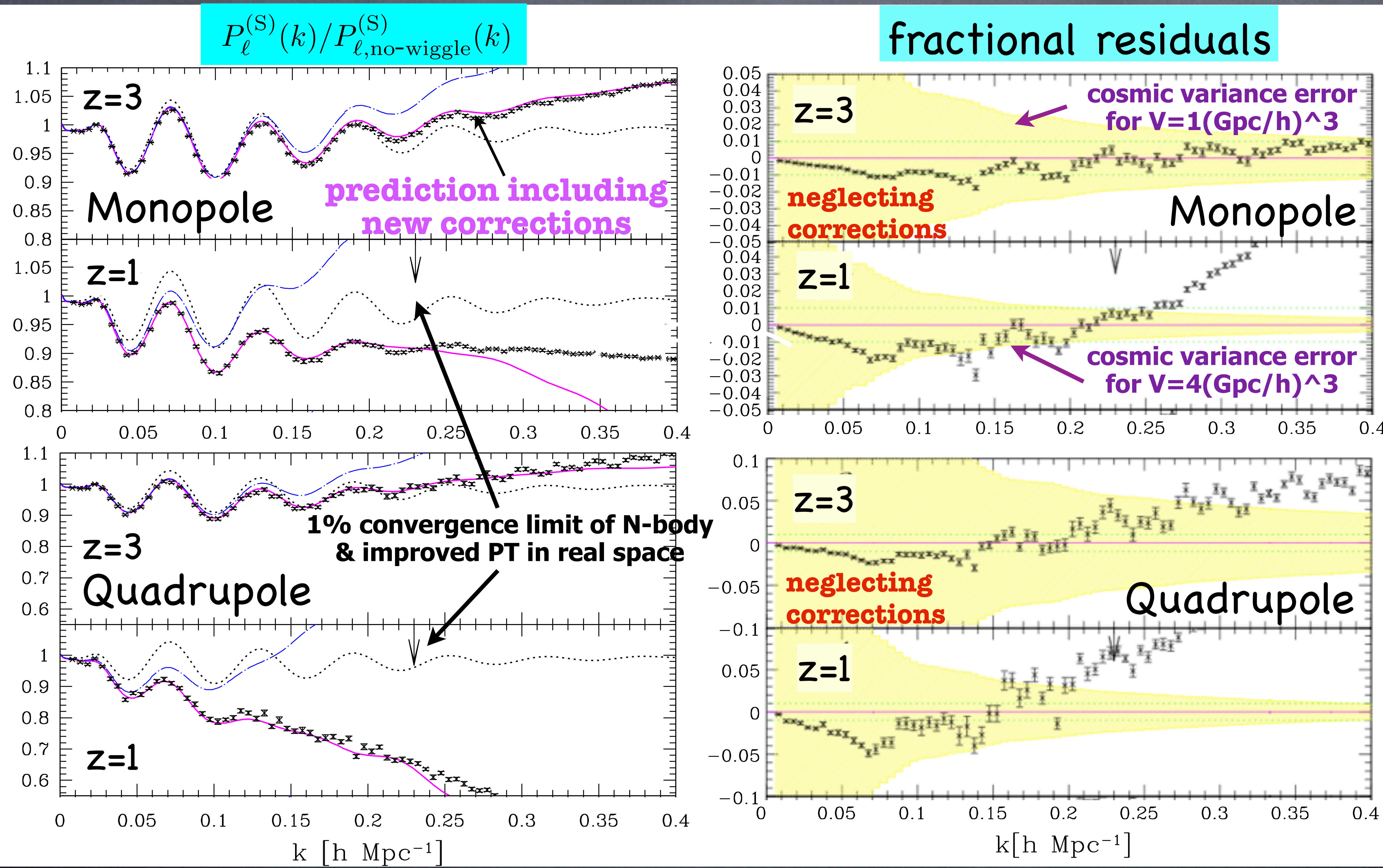
$$F(\boldsymbol{p})\equiv\frac{p_z}{p^2}\left\{P_{\delta\theta}(p)-\frac{p_z^2}{p^2}P_{\theta\theta}(p)\right\}$$

These also depend on 'f'

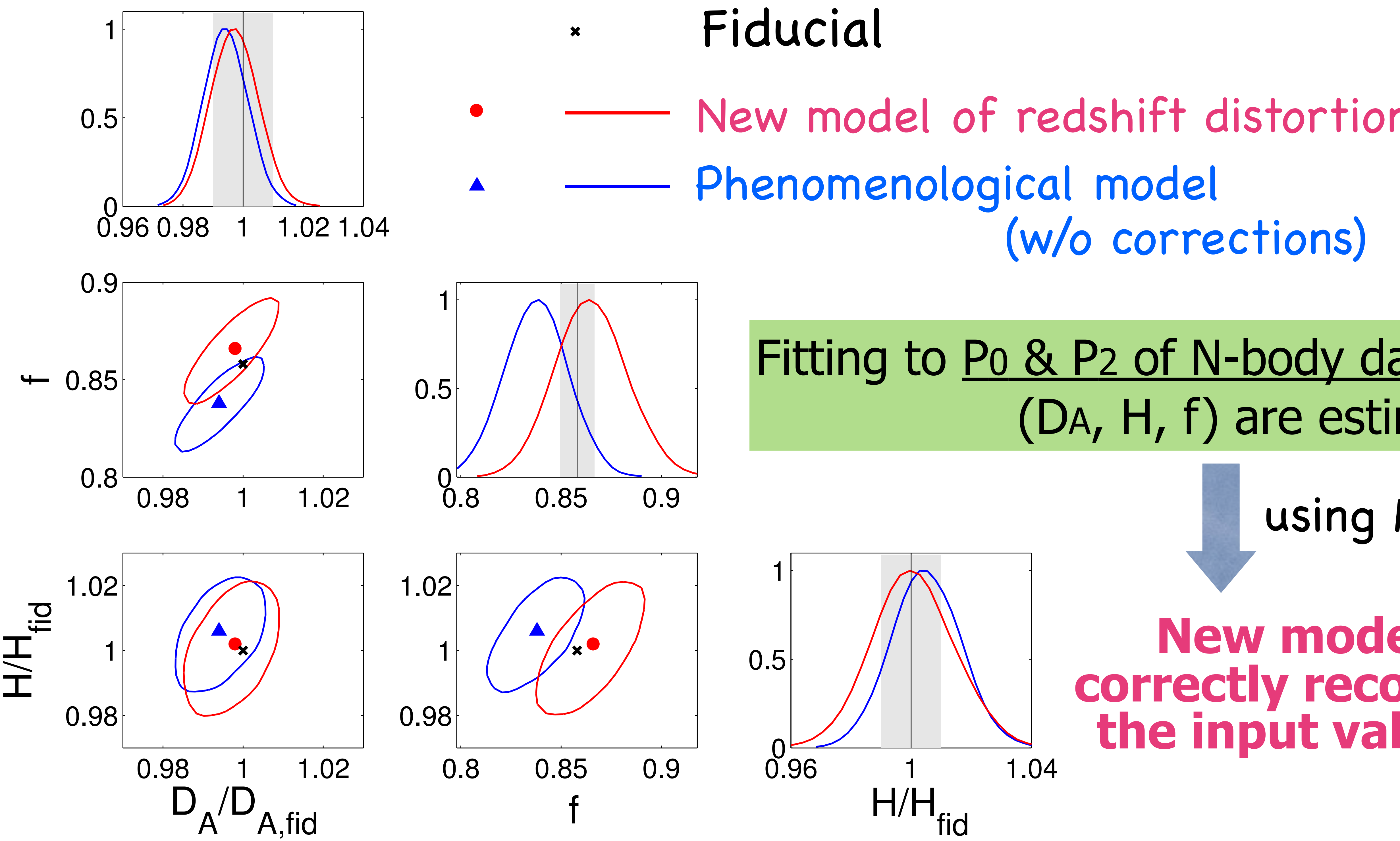
Results including corrections



Results including corrections



Check: recovery of D_A, H & f



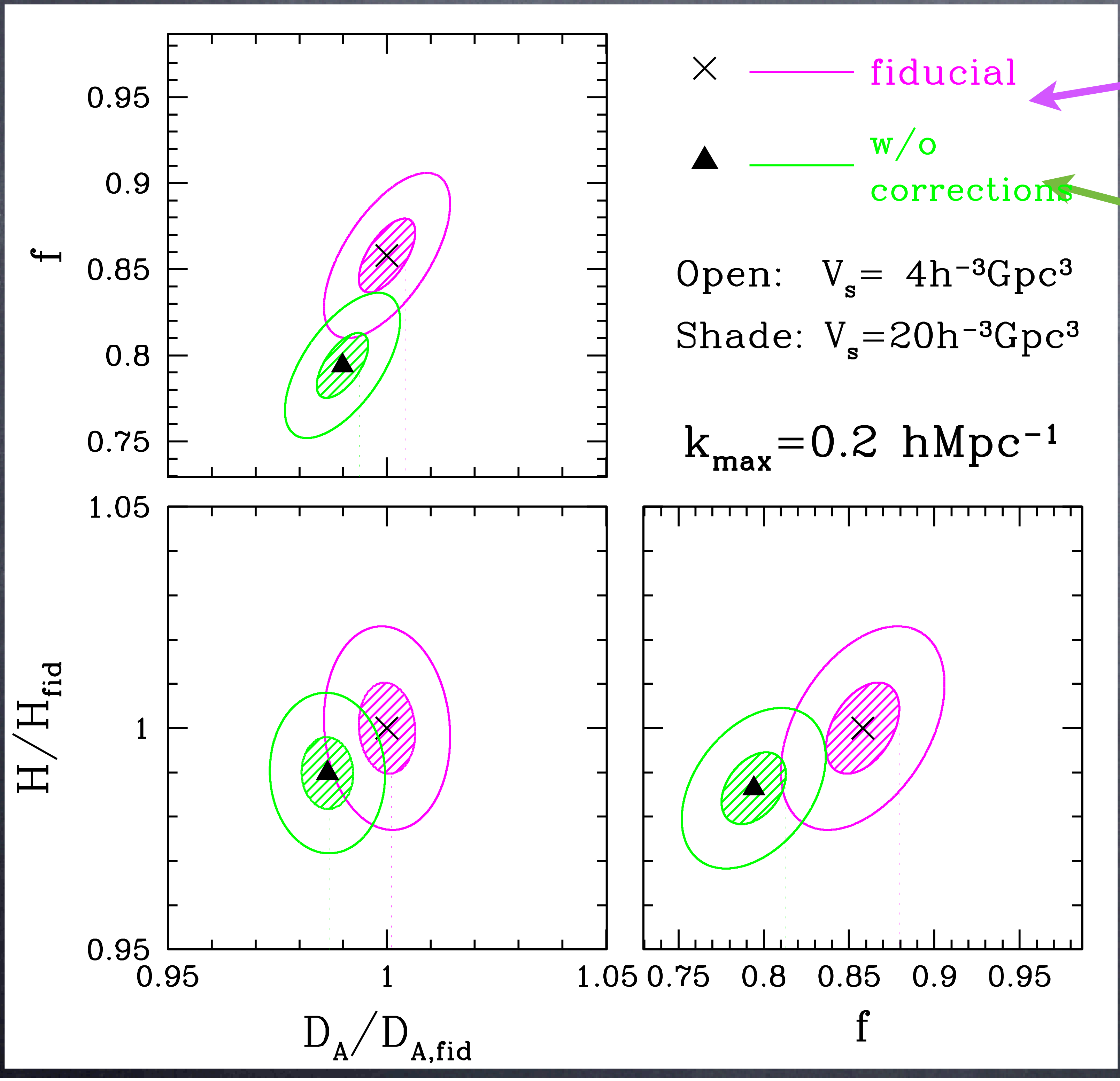
Fitting to P_0 & P_2 of N-body data, (D_A, H, f) are estimated

using MCMC

New model correctly recovers the input values

Impacts on future observations

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:

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

cannot be negligible even for stage III-class surveys

Summary

Modeling BAOs in 2D taking account of the effects of both non-linear clustering & redshift distortion

A new model of redshift distortion

Fisher-matrix analysis on systematic bias

- With improved PT, a (sub-)percent precision is achieved for predictions, and the model can correctly recover D_A, H & f

- Systematic bias caused by incorrect model assumption of redshift distortion would produce

$$\begin{cases} D_A(z)\,\&\,H(z) & \text{: small, but non-negligible (1\textasciitilde 2\%)} \\ f(z) & \text{: significant (\textasciitilde 5\%)} \end{cases}$$

crucial for stage III surveys

Appendix

Modeling non-linear P(k)

Analytic calculation based on perturbation theory (PT)

would be very useful complementary to N-body simulations

Perturbative expansion of (CDM+baryon) system described as pressureless fluid:

Density fluctuation

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

⇒

Power spectrum

$$\left\langle \delta(\vec{k})\delta(\vec{k}') \right\rangle = (2\pi)^3\, \delta_{\rm D}(\vec{k}+\vec{k}')\, P(k)$$

◆ Standard PT — Jeong & Komatsu (2006)

◆ Improved perturbation theory

- Renormalized Perturbation Theory (**RPT**) — Crocce & Scoccimarro (2008)
- **Closure Approximation (CLA)** — AT & Hiramatsu (2008)

Standard PT vs. Improved PT

$$P^{(mn)}(k) \sim \left\langle \delta^{(m)} \delta^{(n)} \right\rangle$$

Standard PT

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

Linear (tree) $\propto D^2(t)$ **1-loop** $\propto D^4(t)$ **2-loop** $\propto D^6(t)$

Straightforward calculation based on naïve expansion

Improved PT (CLA)

Initial P(k)

$$P(k;t) = \underline{G^2(k\,|\,t,t_0)}\, P(k;t_0) + \underline{\int\!\!\int ds\,dt\; G(k\,|\,s,t_0)\; G(k\,|\,t,t_0)\, \Phi_{1-\text{loop}}\,[\,P(k);s,t\,]}$$

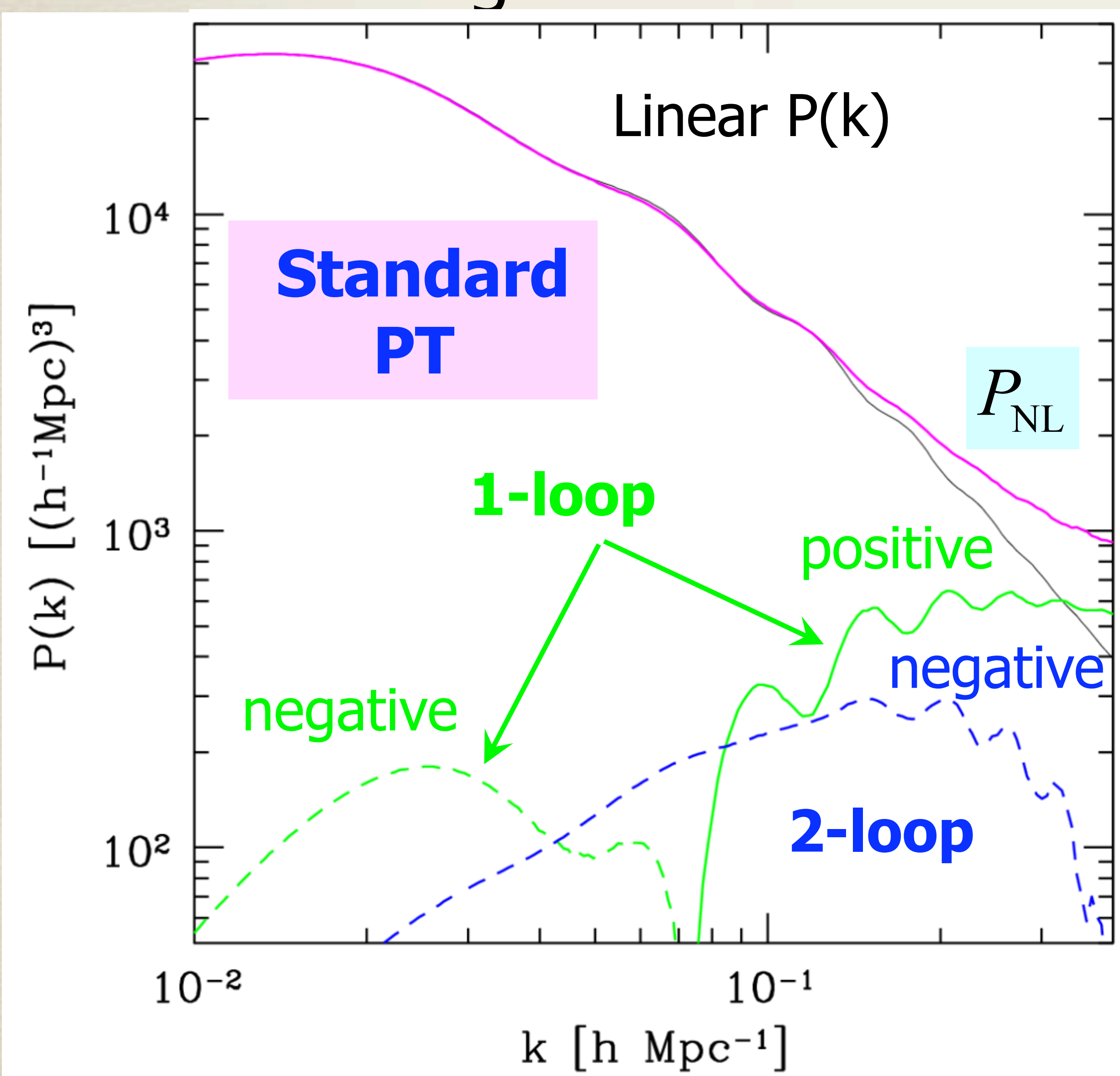
propagator **Mode-coupling term**

Non-perturbative effects is incorporated through **propagator**

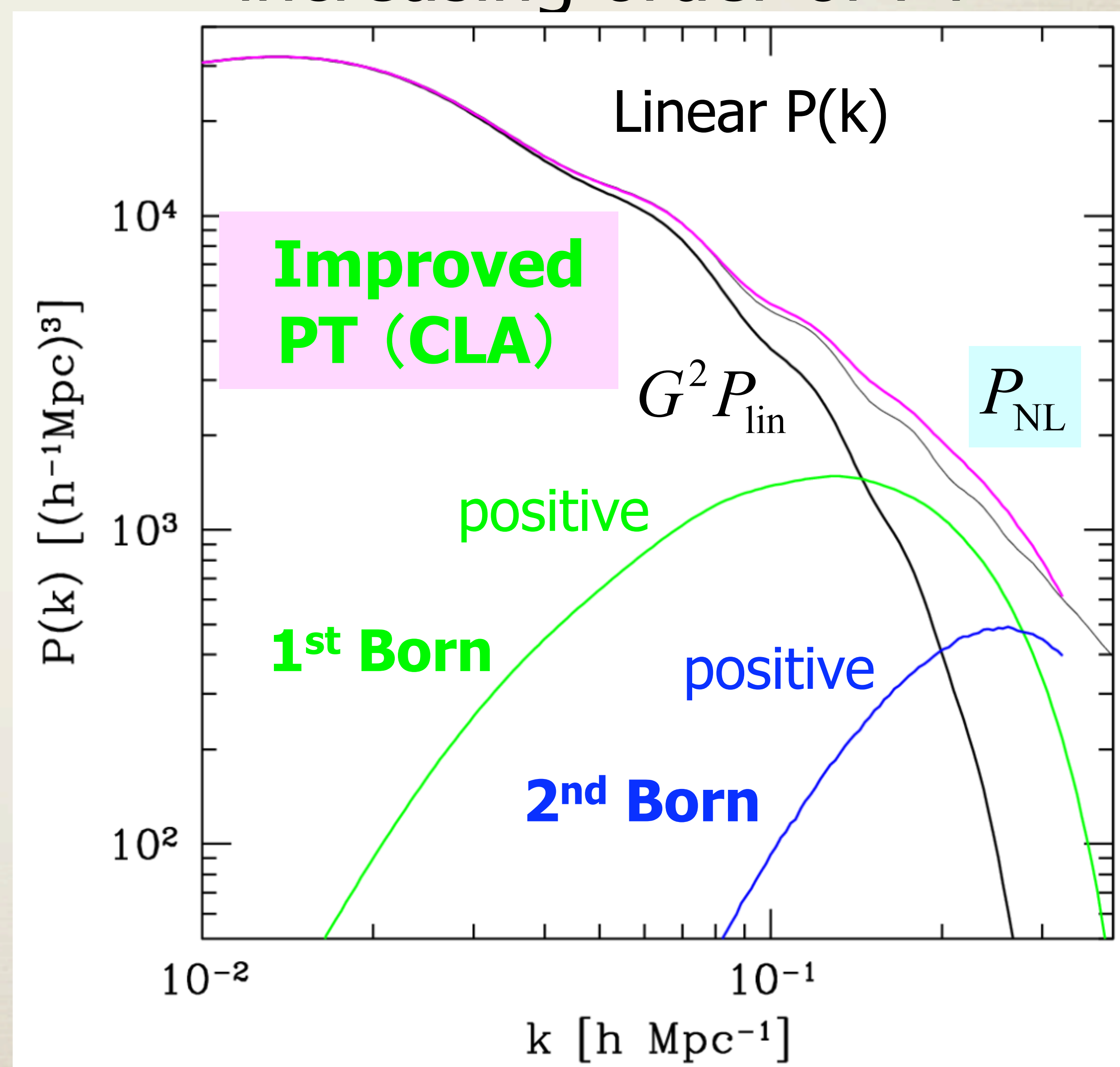
Iteratively evaluate mode-coupling term by Born approximation

Convergence of PT expansions

All contributions become comparable at low-z, positivity is not guaranteed



Contributions are all positive, shifted to higher k as increasing order of PT



Phenomenological models

$$P^{(\mathrm{S})}(k,\mu) = \underbrace{D[k\mu f\,\sigma_{\rm v}]}_{\text{Damping func.}}\;\underbrace{(1+f\,\mu^2)^2}_{\text{Linear Kaiser}}\,P_{\delta\delta}(k);\;\; f\equiv d\ln D_+/d\ln a$$

Damping func. **Linear Kaiser**

(Peacock & Dodds ('94); Cole et al.('95); Ballinger et al. ('96); Magira et al. ('00))

fitting parameter
(1D velocity dispersion)

$$P^{(\mathrm{S})}(k,\mu) = \underbrace{D[k\mu f\sigma_{\rm v}]}_{\text{Damping func.}}\;\underbrace{\left\{P_{\delta\delta}(k) - 2f\,\mu^2 P_{\delta v}(k) + f^2\mu^4 P_{vv}(k)\right\}}_{\text{Non-linear Kaiser}}$$

Damping func. **Non-linear Kaiser**

(Scoccimarro ('04); Percival & White ('09); Shoji et al. ('09))

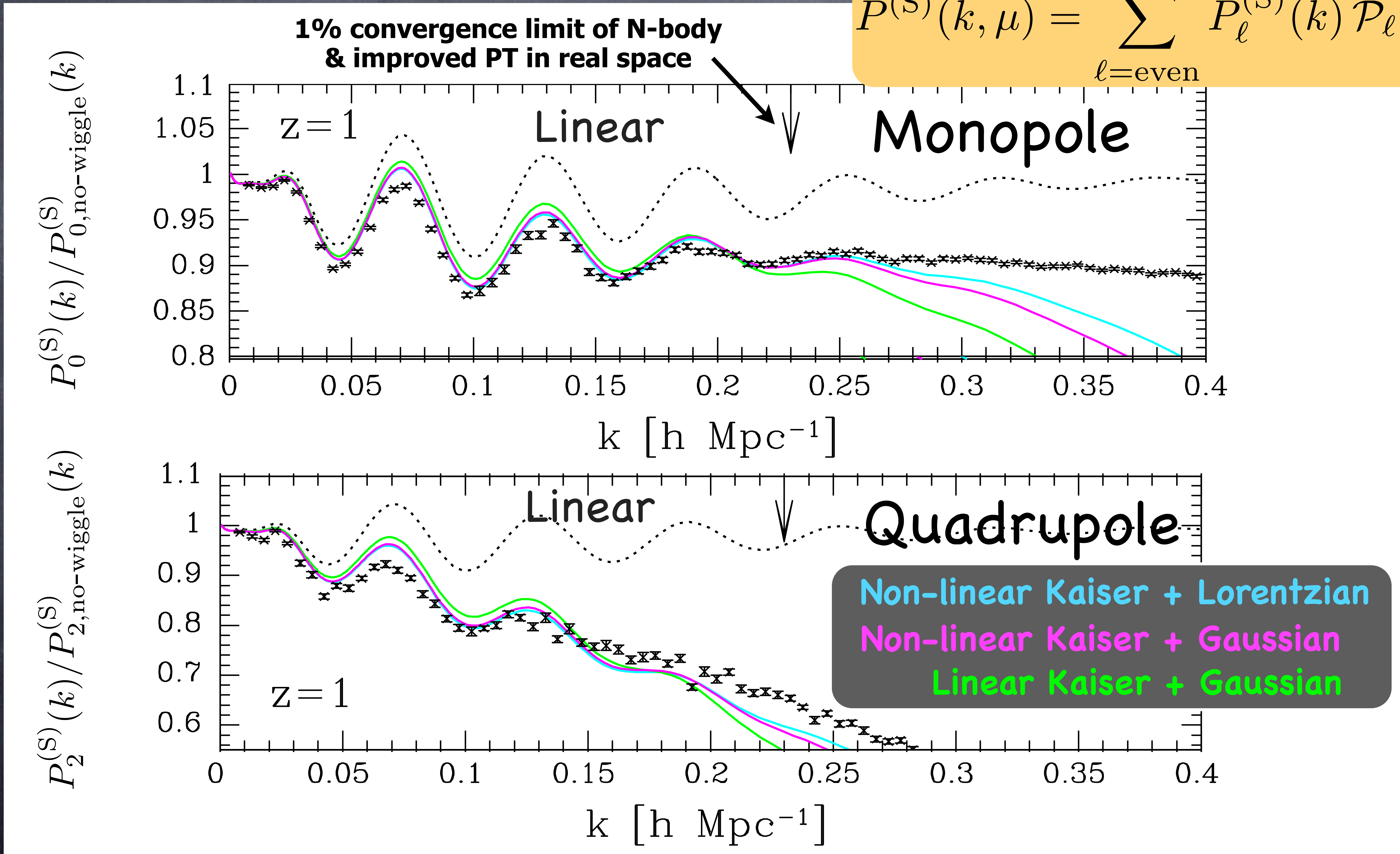
Damping func.

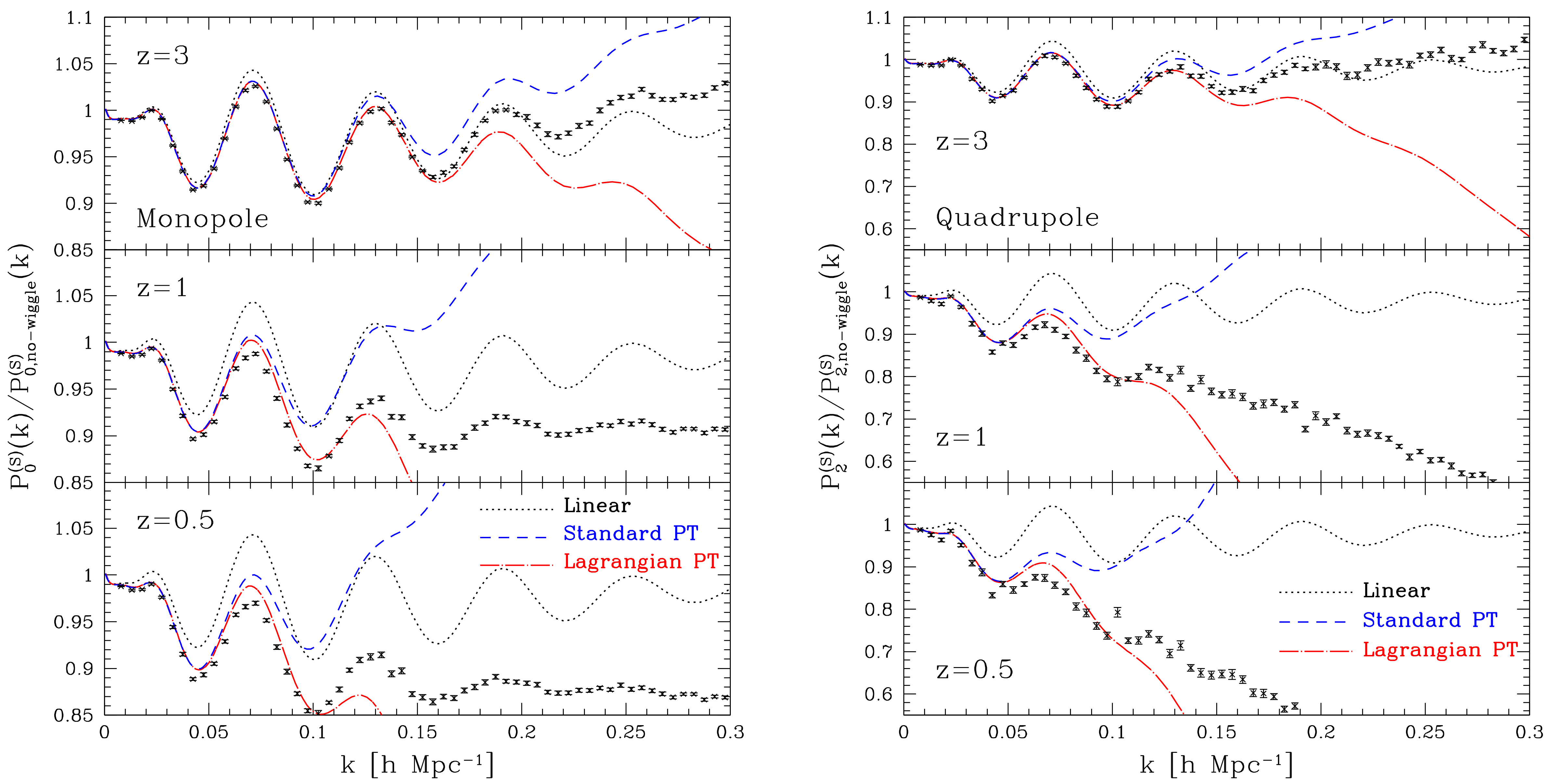
Finger-of-God effect

$$D[\,x\,] = \begin{cases} 1/(1+x^2) & \text{Lorentzian} \\ \exp\{-x^2\} & \text{Gaussian} \end{cases}$$

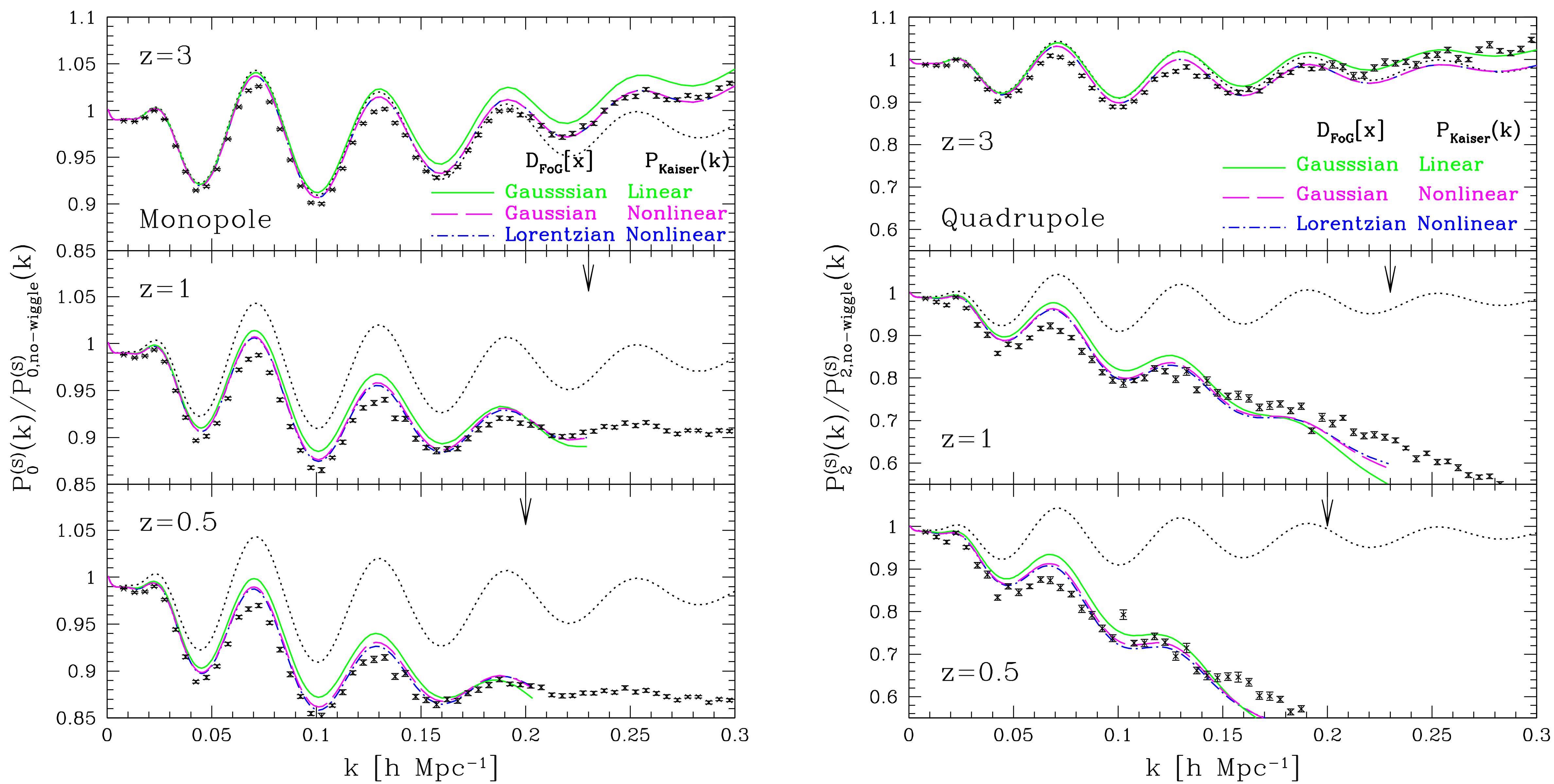
Comparison with N-body simulation

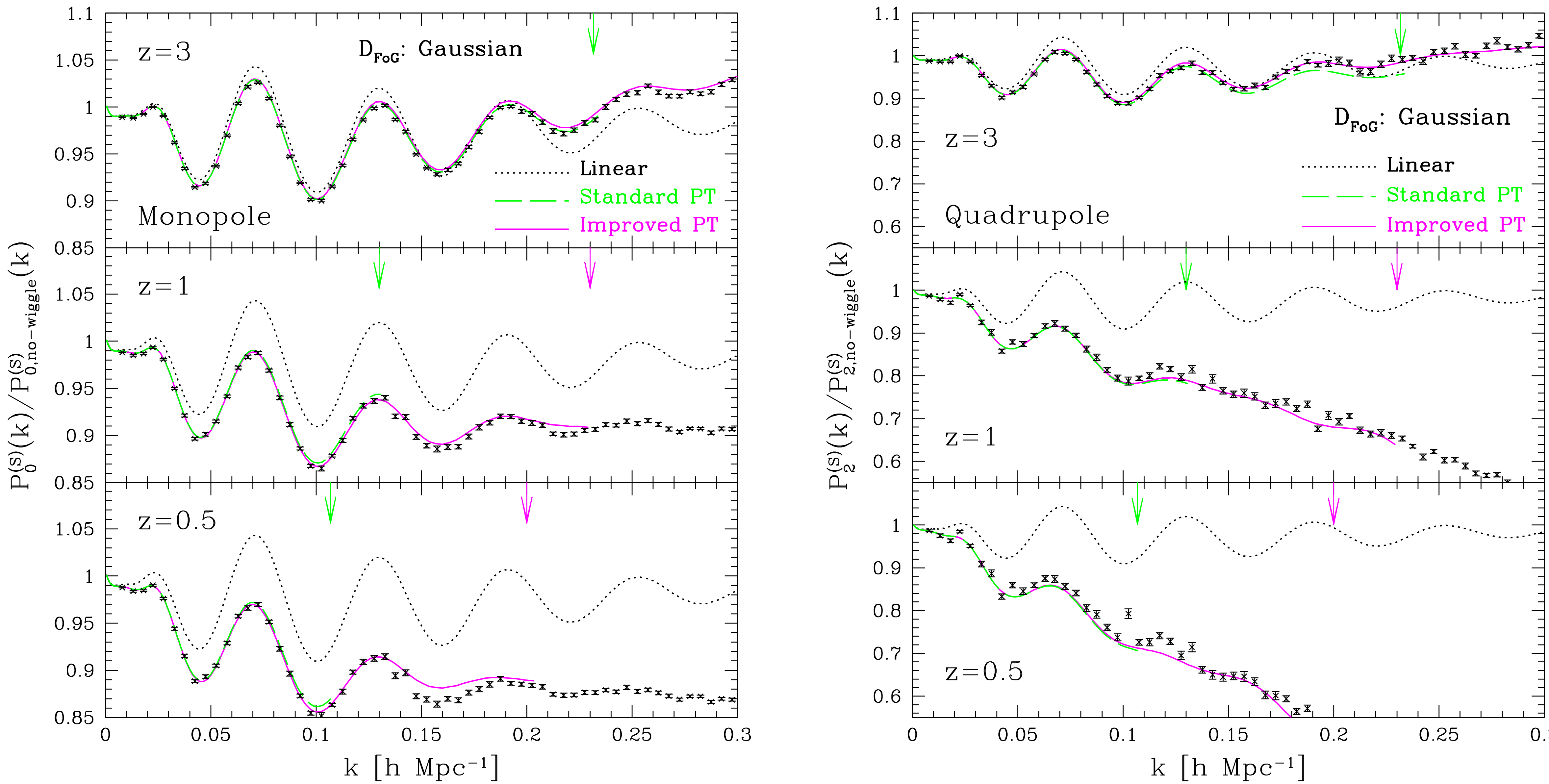
$$P^{(\mathrm{S})}(k,\mu) = \sum_{\ell=\mathrm{even}} P_\ell^{(\mathrm{S})}(k)\,\mathcal{P}_\ell(\mu)$$



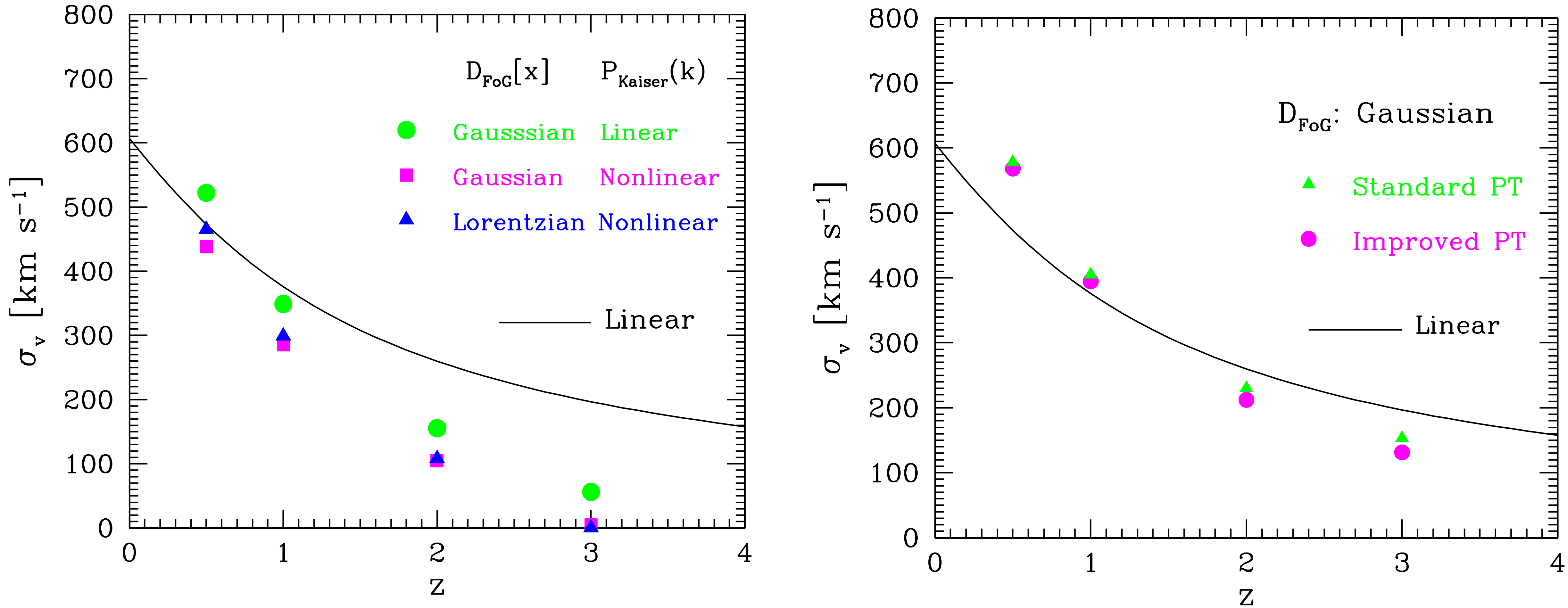


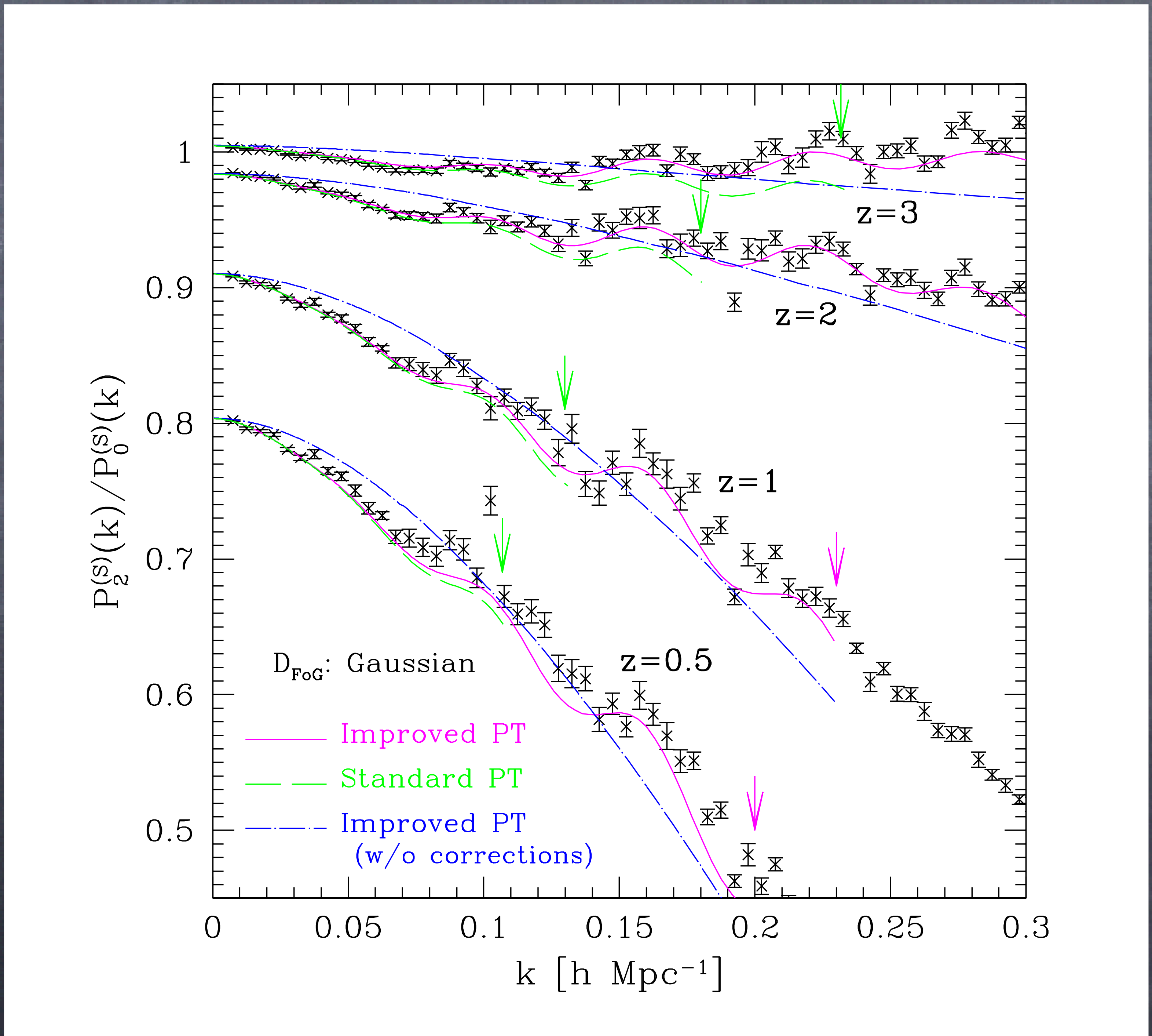
z=3
Monopole
z=1
z=0.5
Linear
Standard PT
Lagrangian PT
$P_0^{(S)}(k)/P_{0,\mathrm{no-wiggle}}^{(S)}(k)$
k [h Mpc⁻¹]
z=3
Quadrupole
z=1
z=0.5
Linear
Standard PT
Lagrangian PT
$P_2^{(S)}(k)/P_{2,\mathrm{no-wiggle}}^{(S)}(k)$
k [h Mpc⁻¹]


z=3
Monopole
$D_{FoG}[x]$ $P_{Kaiser}(k)$
Gausssian Linear
Gaussian Nonlinear
Lorentzian Nonlinear
z=1
z=0.5
$P_0^{(S)}(k)/P_{0,no-wiggle}^{(S)}(k)$
k [h Mpc^{-1}]
z=3
Quadrupole
$D_{FoG}[x]$ $P_{Kaiser}(k)$
Gausssian Linear
Gaussian Nonlinear
Lorentzian Nonlinear
z=1
z=0.5
$P_2^{(S)}(k)/P_{2,no-wiggle}^{(S)}(k)$
k [h Mpc^{-1}]

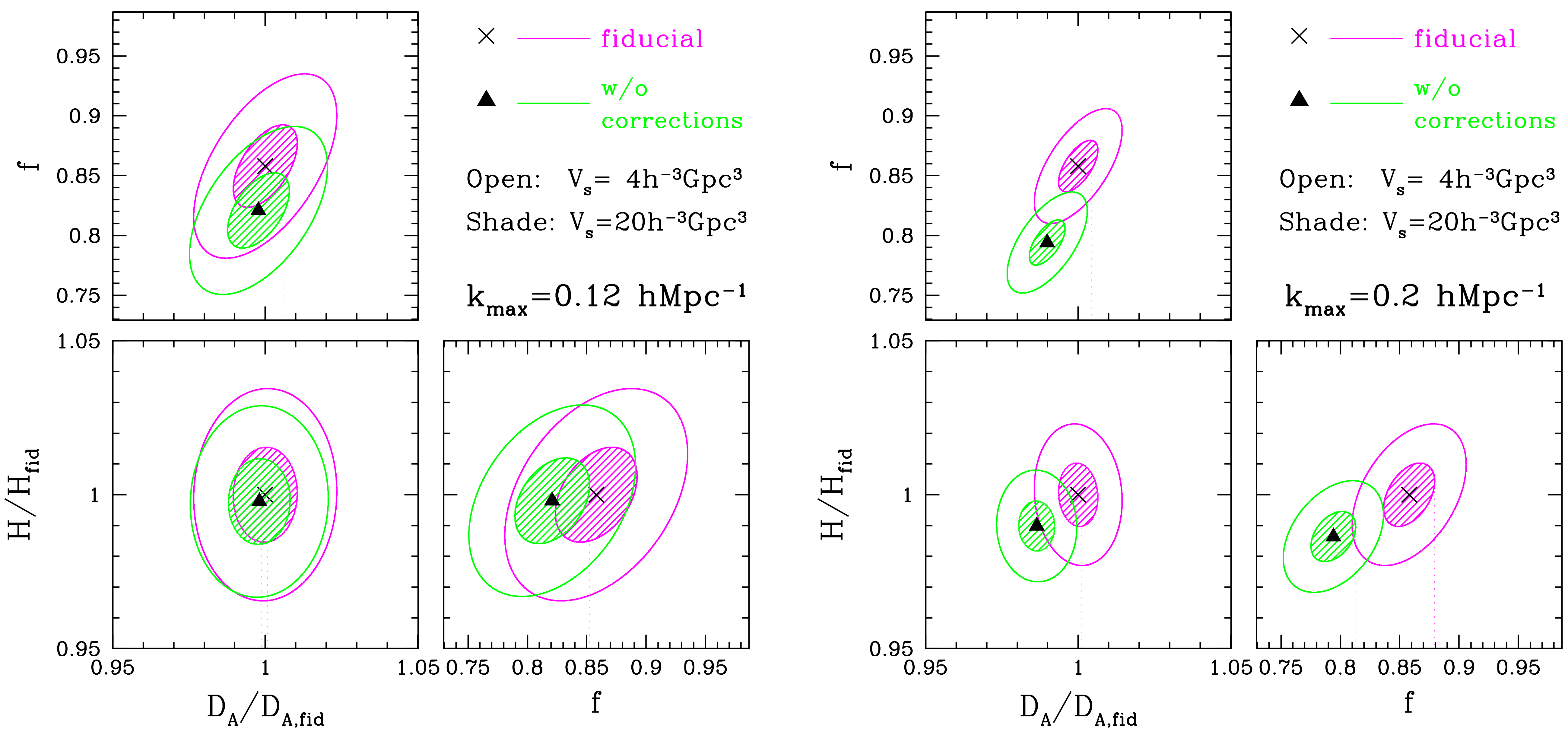


z=3
D_{FoG}: Gaussian
Linear
Standard PT
Improved PT
Monopole
z=1
z=0.5
$P_0^{(S)}(k)/P_{0,no-wiggle}^{(S)}(k)$
k [h Mpc^{-1}]
Quadrupole
$P_2^{(S)}(k)/P_{2,no-wiggle}^{(S)}(k)$


$D_{FoG}[x]$ $P_{Kaiser}(k)$
Gausssian Linear
Gaussian Nonlinear
Lorentzian Nonlinear
Linear
σ_v [km s^{-1}]
z
D_{FoG}: Gaussian
Standard PT
Improved PT
Linear
σ_v [km s^{-1}]
z



1
0.9
0.8
0.7
0.6
0.5
0
0.05
0.1
0.15
0.2
0.25
0.3
k [h Mpc⁻¹]
$P_2^{(S)}(k)/P_0^{(S)}(k)$
z=3
z=2
z=1
z=0.5
D_{FoG}: Gaussian
Improved PT
Standard PT
Improved PT
(w/o corrections)



fiducial
w/o corrections
Open: V_s= 4h^{-3}Gpc^3
Shade: V_s=20h^{-3}Gpc^3
k_{max}=0.12 hMpc^{-1}
f
H/H_{fid}
$D_A/D_{A,fid}$
fiducial
w/o corrections
Open: V_s= 4h^{-3}Gpc^3
Shade: V_s=20h^{-3}Gpc^3
k_{max}=0.2 hMpc^{-1}