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Precision Cosmology from Redshift-space galaxy Clustering

~ Progress of high-precision template for BAOs ~

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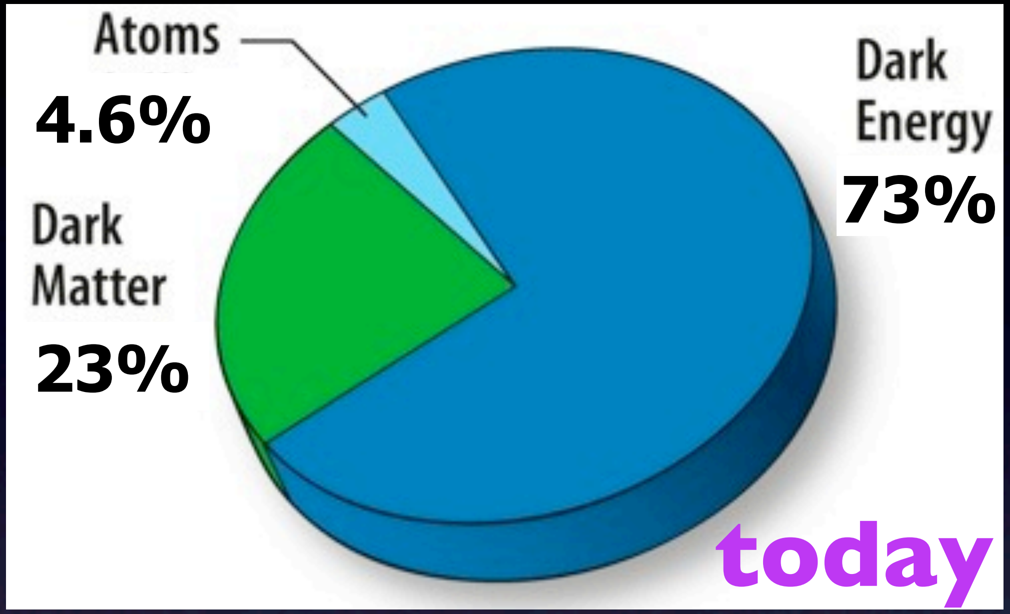
Contents

- Classic method to measure the clustering anisotropies of galaxies is renewed with a great interest to clarify the nature of dark energy and to test theory of gravity.
- Accurate theoretical models for power spectrum have made a rapid progress, and are now available, taking fully account of the effect of clustering anisotropies.
- Large N-body simulations reveal a new feature of clustering anisotropies in halo catalogs, which sensitively depends on clustering bias. Only the improved model can account for this.

Introduction

Lambda CDM model

- Standard cosmological model characterized by 6 parameters



- Flat universe filled with the unknowns energy contents

SN Ia obs.

Late-time cosmic acceleration

(Perlmutter et al. '99; Riess et al. '98)

Possible solution ?

Dark energy: dynamical scalar field or cosmological const.

Modified gravity: IR modification to general relativity

“beyond Lambda CDM model”

Q Dark energy or Modified gravity ?

✓ Nature of cosmic acceleration

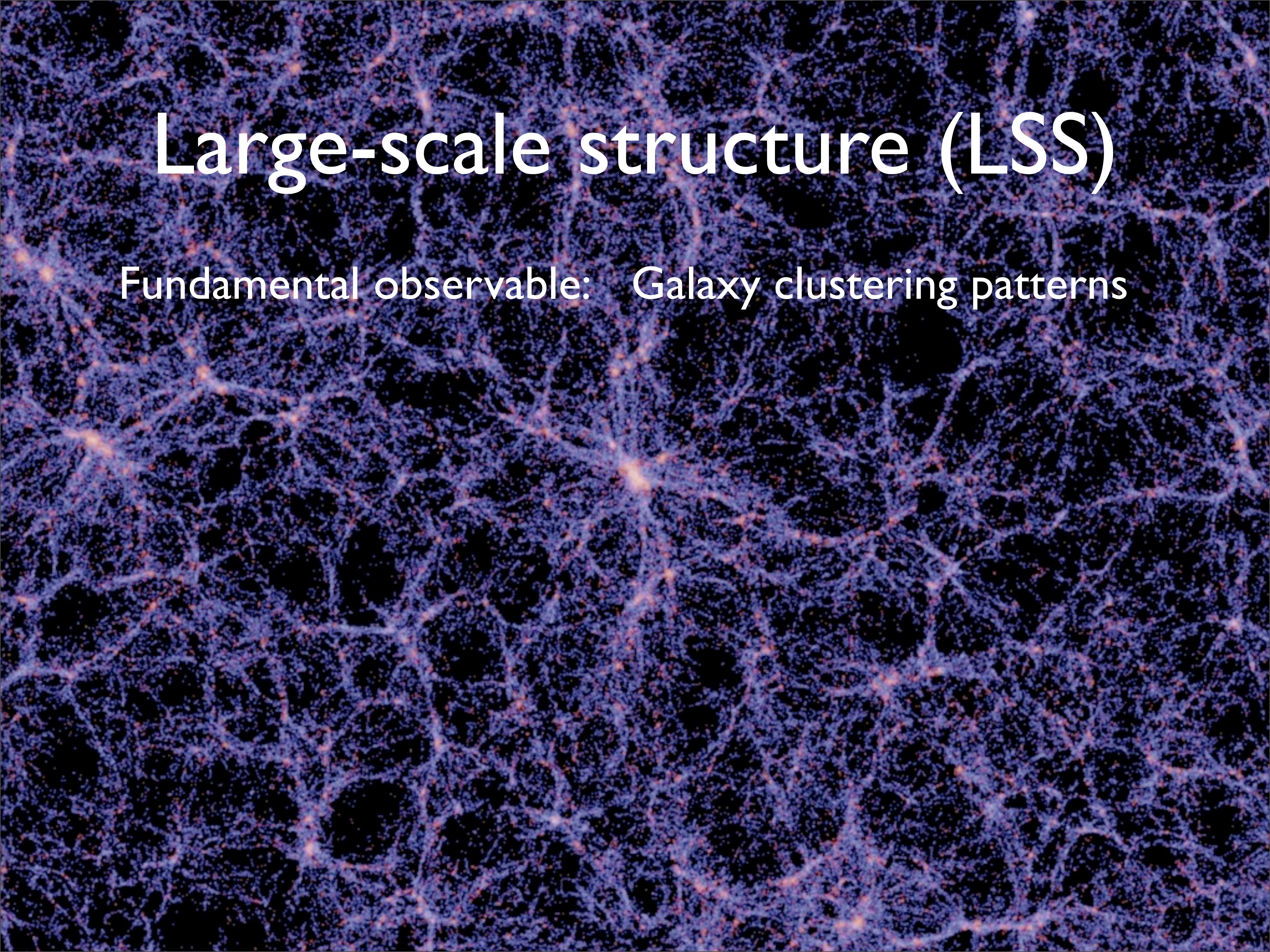
✓ Test of gravity on cosmological scales

Key Precision measurements of { **Cosmic expansion** / **Growth of structure** }

Need independent and complementary probes
other than CMB and SN Ia

Large-scale structure (LSS)

Fundamental observable: Galaxy clustering patterns



Cosmological information in LSS

All information is encoded in statistical quantities:

Power spectrum $P(k)$, or correlation function $\xi(r)$

Shape & amplitude

Historical record of the primordial Universe

(Initial condition & late-time evolution)

Additional information coming from observational effect :

Alcock-Paczynski effect

Redshift distortion effect

Galaxy clustering offers unique opportunity

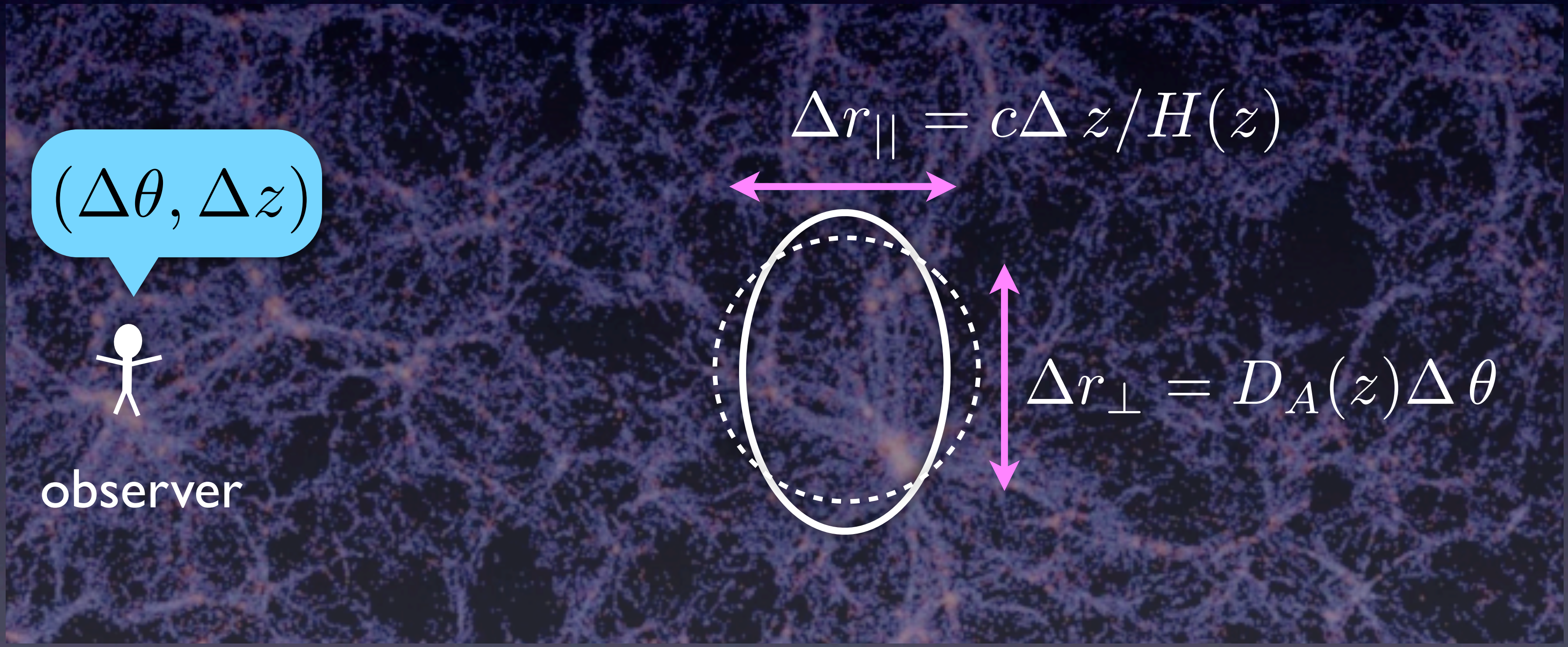
With BAOs as standard ruler,

measurements of these are now top priority in future surveys

Alcock-Paczynski (A-P) effect

Alcock & Paczynski ('79)

Anisotropies caused by apparent mismatch of underlying cosmological models



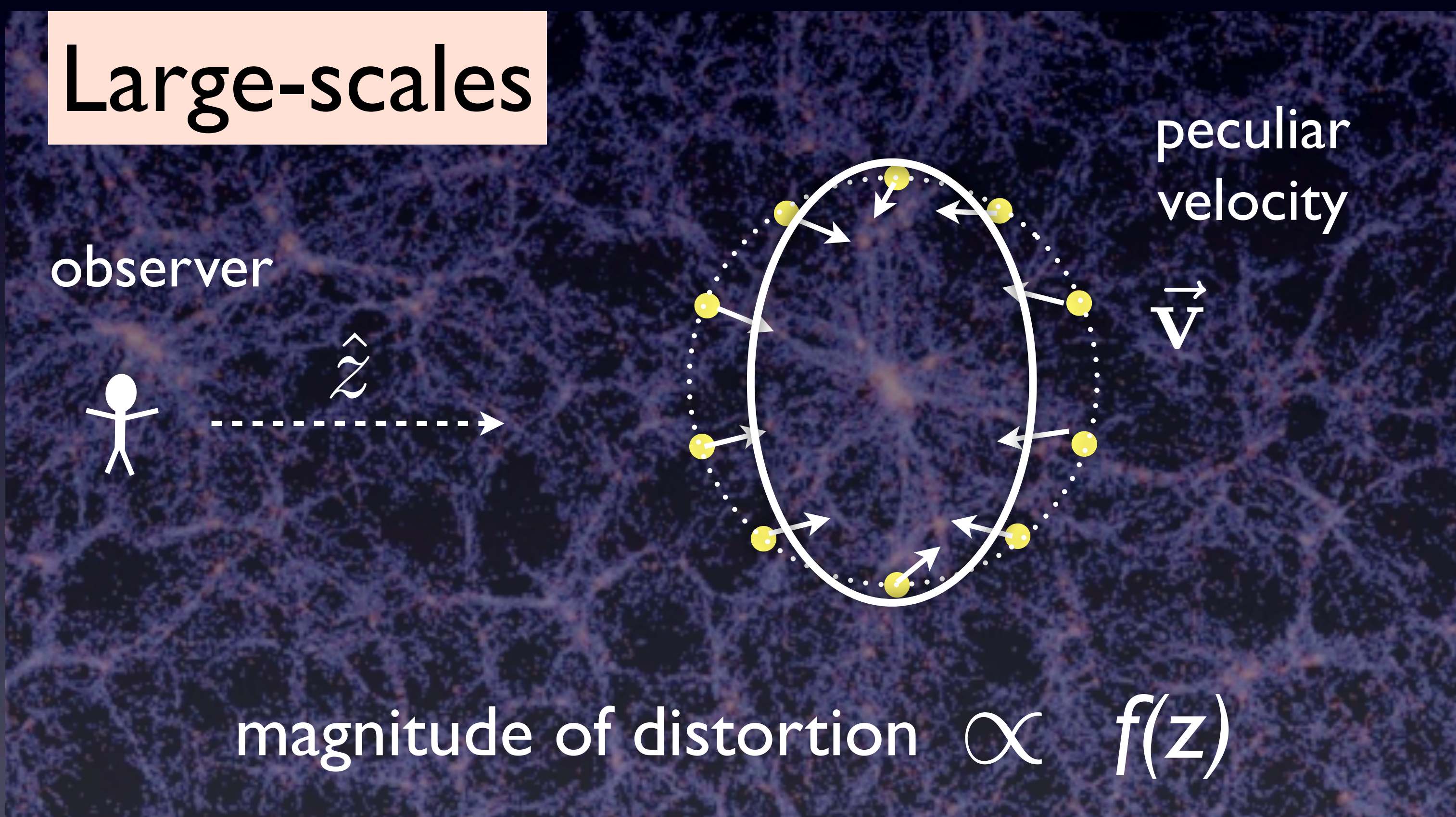
Using BAO as standard ruler,

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

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

Redshift distortion (RD) effect

Anisotropies caused by peculiar velocity of galaxies through redshift measurements



redshift space

$$\vec{\mathbf{s}} = \vec{\mathbf{r}} + \frac{(\vec{\mathbf{v}}\cdot\hat{\mathbf{z}})}{a\,H(z)}\,\hat{\mathbf{z}}\ ;$$

real space

growth-rate parameter

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

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

Linder ('05)

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

e.g., Linder ('08); Guzzo et al. ('08); Yamamoto et al. ('08); Song & Dore ('09); Percival & White ('09); White, Song & Percival ('09); Song & Percival ('09); Blake et al. ('11)

Revival of classic method

Measuring clustering anisotropies is not a new method

A-P effect

Matsubara & Suto ('96)

Ballinger, Peacock & Heavens ('96)

Use global shape of power spectrum/correlation function to determine Ω_Λ

RD effect

Hamilton ('92)

Adopt GR valid over cosmological scales to determine $\Omega_{\rm m}$

温故知新 (learning from the past)

Complementarity

g(z): growth factor

Method	Observable	Measure
SN Ia	Light curves of distant SNe	$D_L(z)$
Weak lensing	Shear field from galaxy images	$D_A(z)$, $g(z)$
Clusters	Number density of clusters	$D_A(z)$, $H(z)$, $g(z)$
Galaxy clustering	Spatial clustering of galaxies	$D_A(z)$, $H(z)$, $f(z)$

Advantage:
galaxy clustering provides a way to separately measure D_A, H, & f

New ideas & innovation

Through RD effect, galaxy clustering further provides statistical information of velocity field

→ alternative probe of structure formation

- Reconstruction of velocity power spectrum

Song & Kayo ('10), Tang, Kayo & Takada ('11)

⟶ Coherent combination to constrain dark energy (Song '11)

- Alternative probe of bulk flow Song et al ('11a,b)

Improved technique to reduce 'noises' has been developed

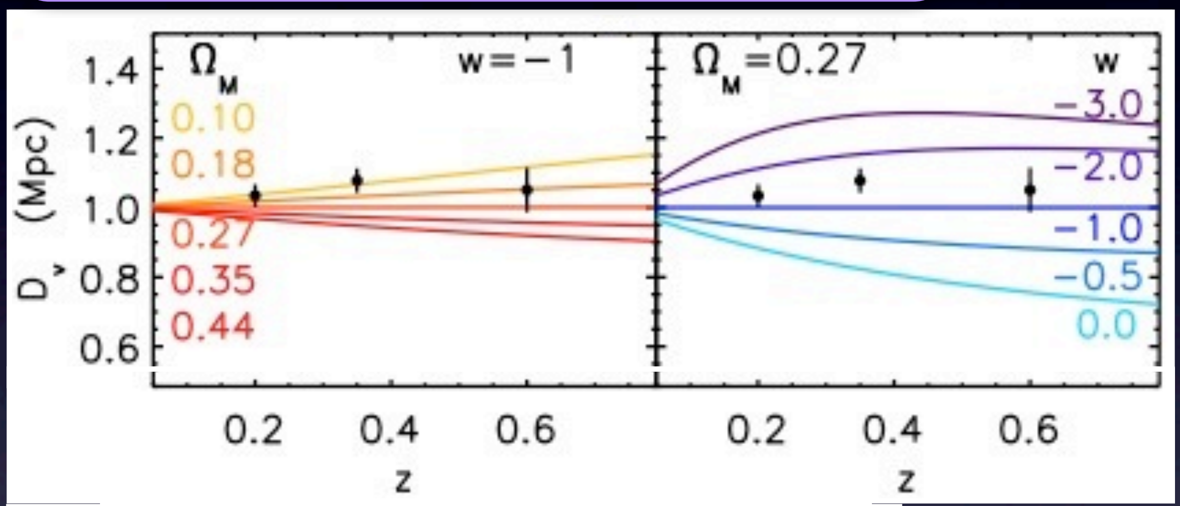
- Reducing cosmic variance McDonald & Seljak ('09)
- Reducing shot noise/stochasticity Seljak et al. ('09), Hamaus et al. ('10)
- Reducing Finger-of-God damping Hikage, Takada & Spergel ('11)

Latest results

$$D_V(z) \equiv \left[(1+z)^2 D_A(z)^2 \frac{cz}{H(z)} \right]^{1/3}$$

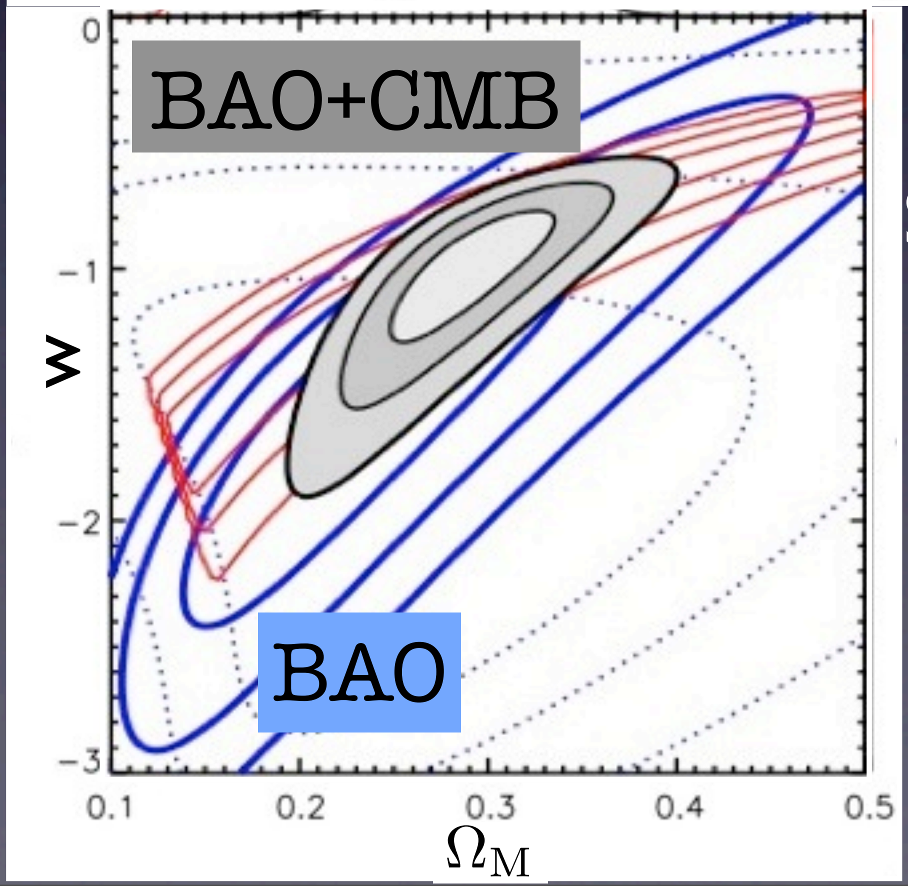
Blake et al. arXiv:1105.2862

arXiv:1104.2908



WiggleZ++

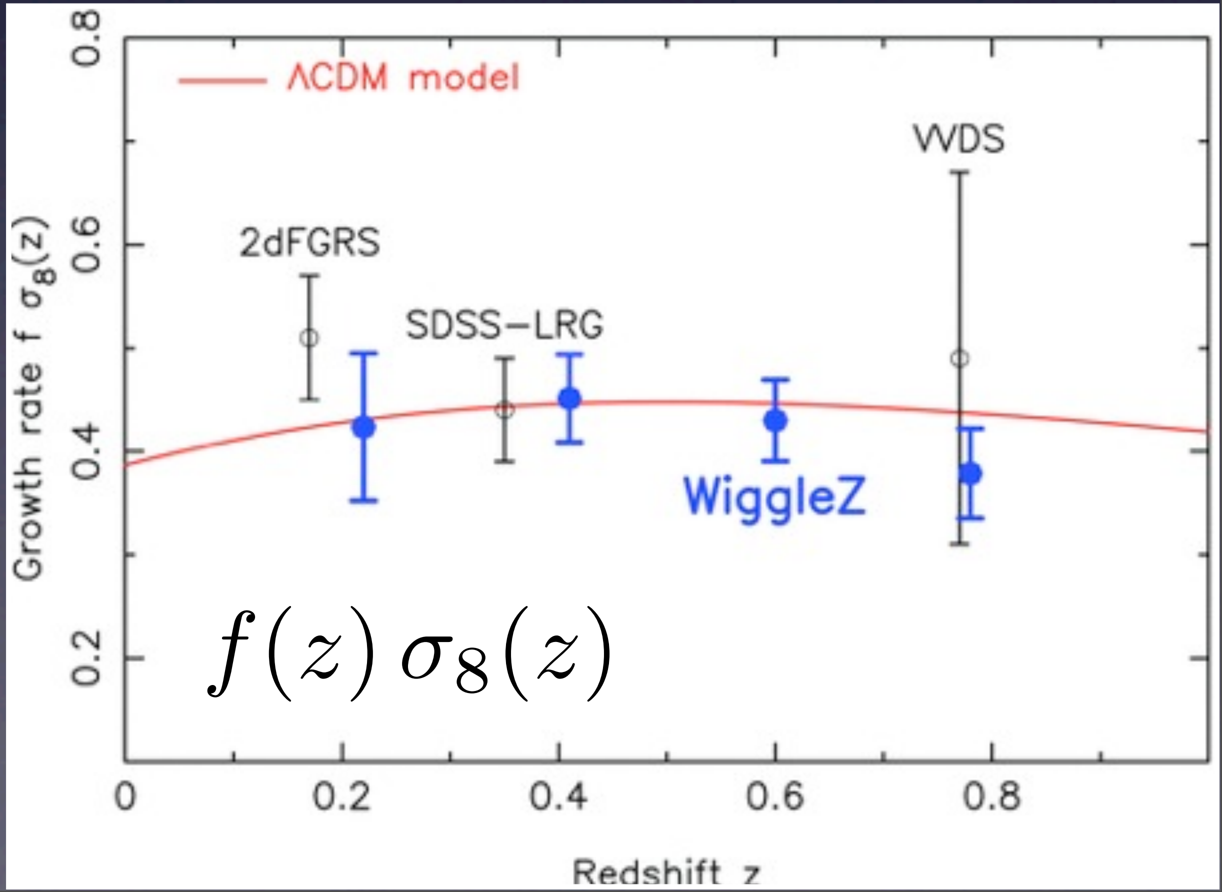
(WiggleZ: ~150,000 galaxies)



SDSS DR7 LRG

(z=0.2 & 0.35)

WiggleZ (z=0.6)



On-going/up-coming surveys

Spectroscopic surveys aiming at precision measurements of $f(z)$ and/or $H(z)$ & $D_A(z)$

Ground		***Space***
WiggleZ		WFIRST
BOSS		EUCLID
HETDEX	FastSound	
SuMIRe-PFS	VIPERS	
Big-BOSS	GAMA	

Subaru

Theoretical challenges

For fruitful science from high-precision measurements,

Accurate theoretical template

for power spectrum/correlation function

is crucial and highly demanding

Reducing the systematics is a big issue:

- **Non-linear gravitational evolution**
- **Non-linear redshift distortions**
- **Galaxy biasing**

Small, but non-negligible
at ~1% precision

Forward modeling approach

‘First-principle’ calculations of P(k) & ξ(r)
based on perturbation theory (PT) of LSS

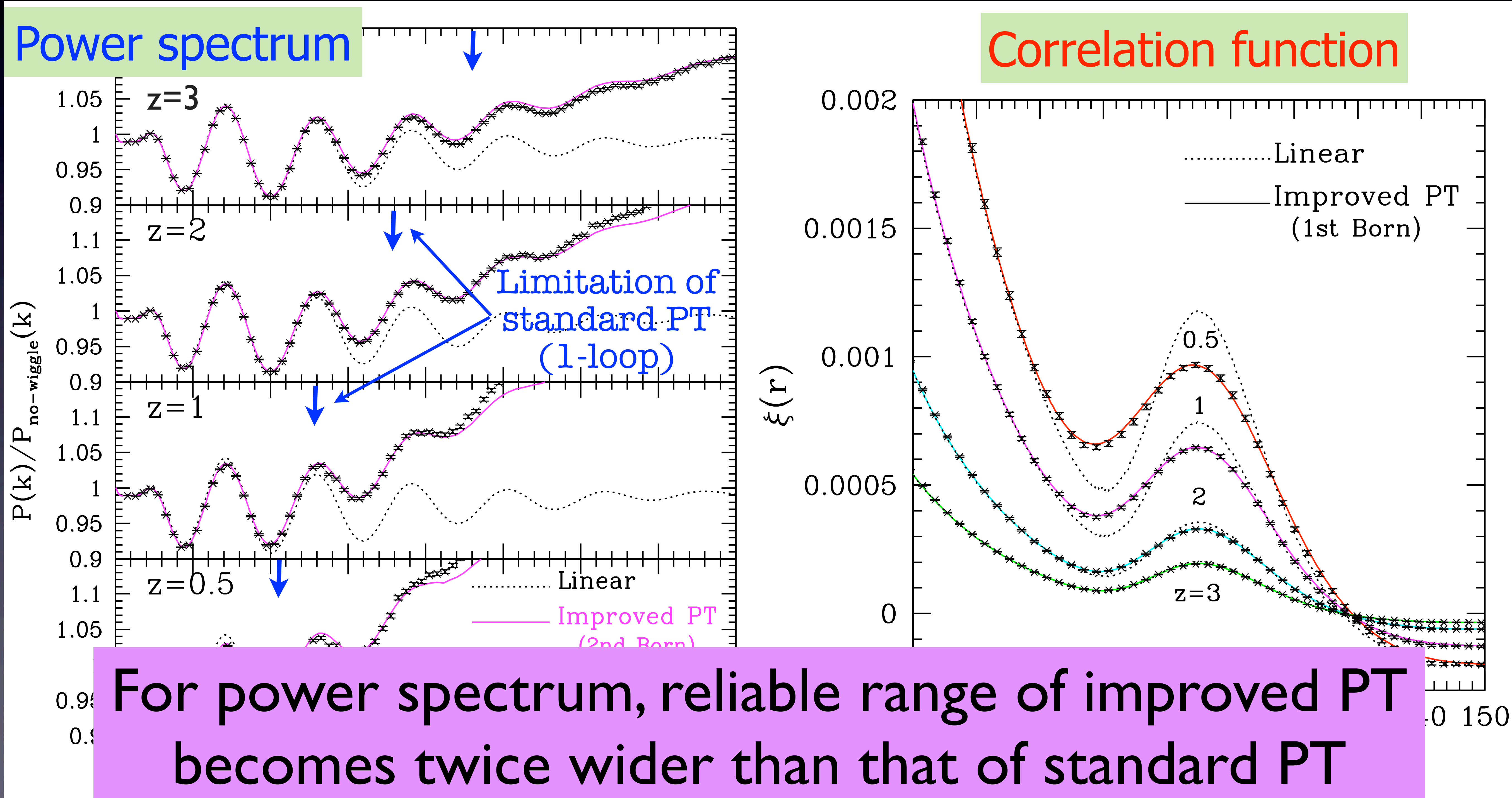
Development of improved treatment of PT

Renormalized PT	Crocce & Scoccimarro (‘06ab, ’08)
Closure theory	AT & Hiramatsu (’08), AT, Nishimichi, Saito & Hiramatsu (’09)
Lagrangian resummation theory	Matsubara (’08), Okamura, AT & Matsubara (’11)
Regularized PT	Bernardeau, Crocce & Scoccimarro (’08), Bernardeau, AT, Crocce & Scoccimarro (in prep.)

For BAO scales of our interest ($k<0.2\sim0.3$ h/Mpc @ $0.5<z<1.5$),
non-linear gravitational evolution is now under control

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 distortions

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)

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

- Power spectrum amplitude

Enhancement	$\boxed{\text{Kaiser effect}}$	$\propto f(z)$	(small-k)
Suppression	Finger-of-God effect		(large-k)

Redshift-space power spectrum

Exact expression

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

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

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

(Popular) streaming 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)

... still phenomenological

An improved model

AT, Nishimichi & Saito ('10)

Low-k expansion from exact formula

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

Damping func.

Non-linear 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

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

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%)

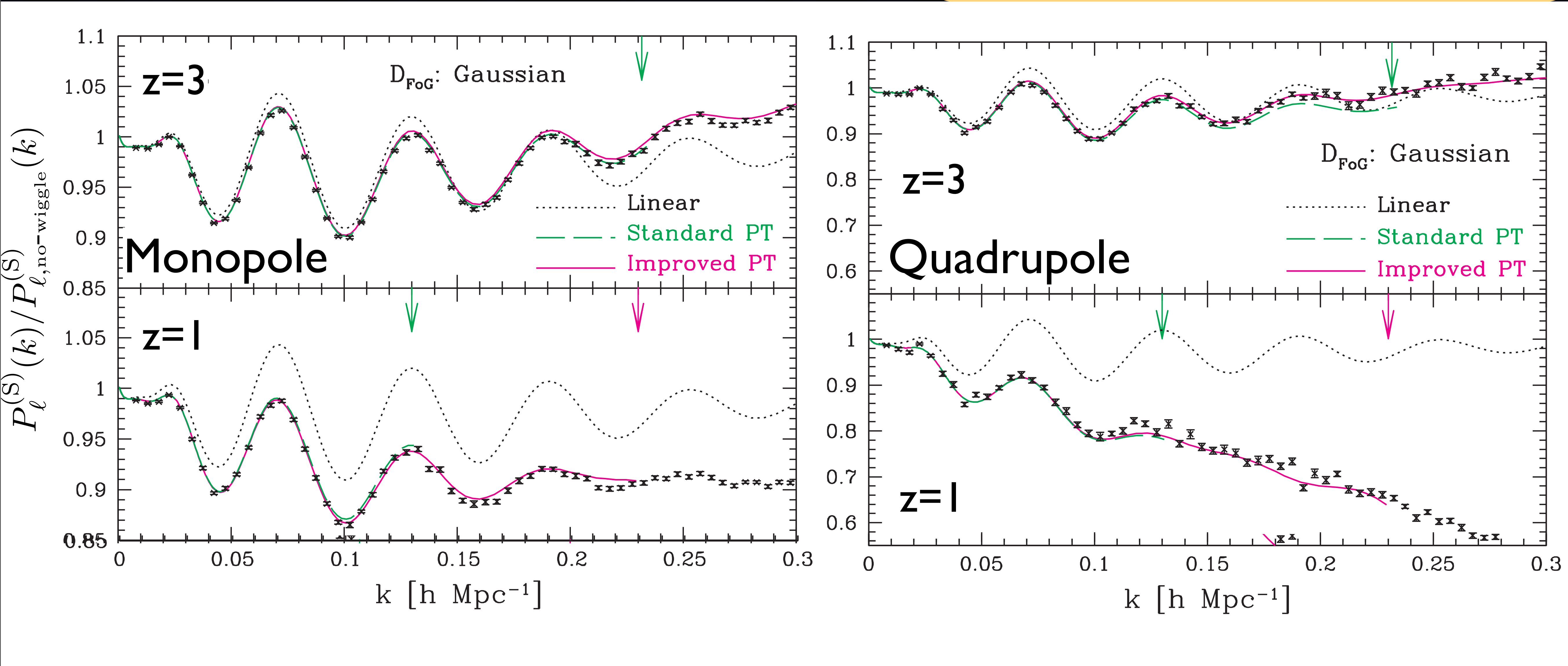
$$F(\boldsymbol{p}) \equiv \frac{p_z}{p^2}\left\{P_{\delta\theta}(p) - \frac{p_z^2}{p^2}P_{\theta\theta}(p)\right\}$$

These also depend on 'f'

Role of corrections in dark matter

Improved model

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

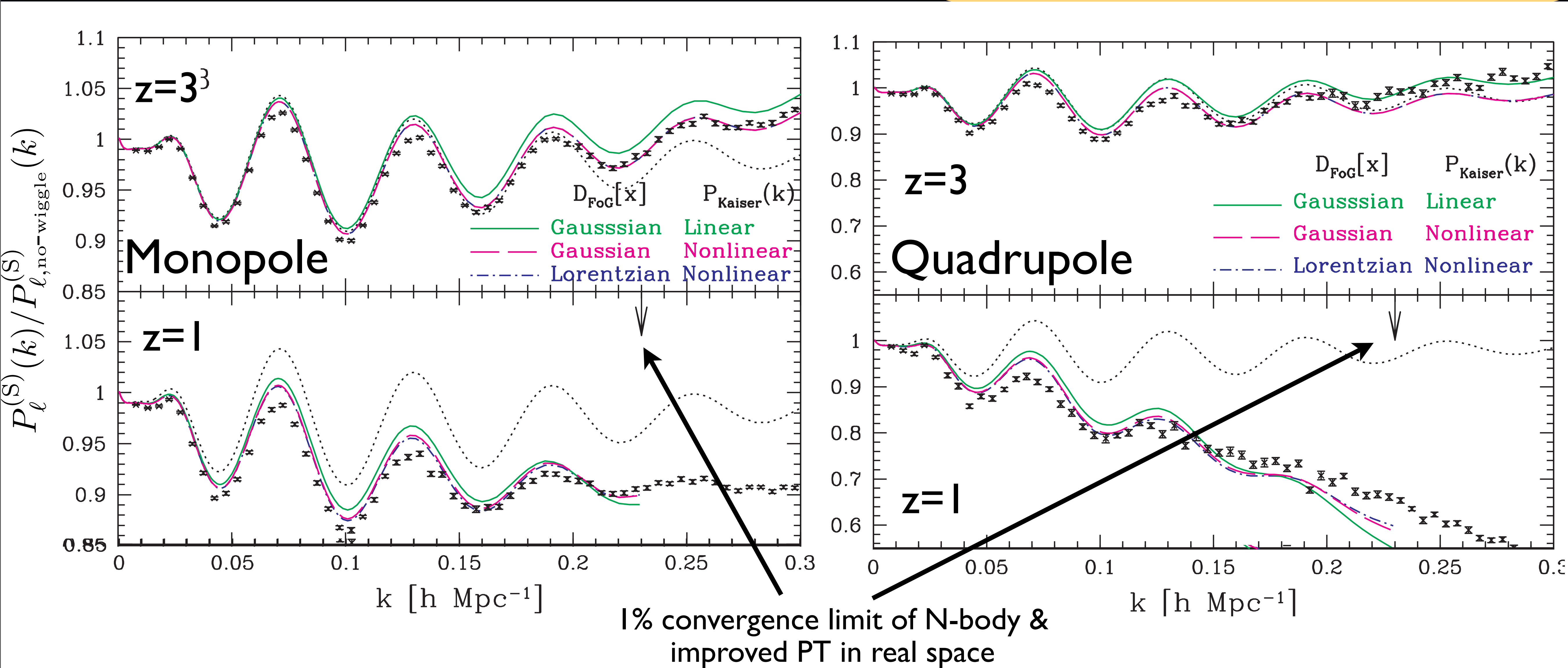


AT, Nishimichi & Saito ('10)

Role of corrections in dark matter

Streaming model

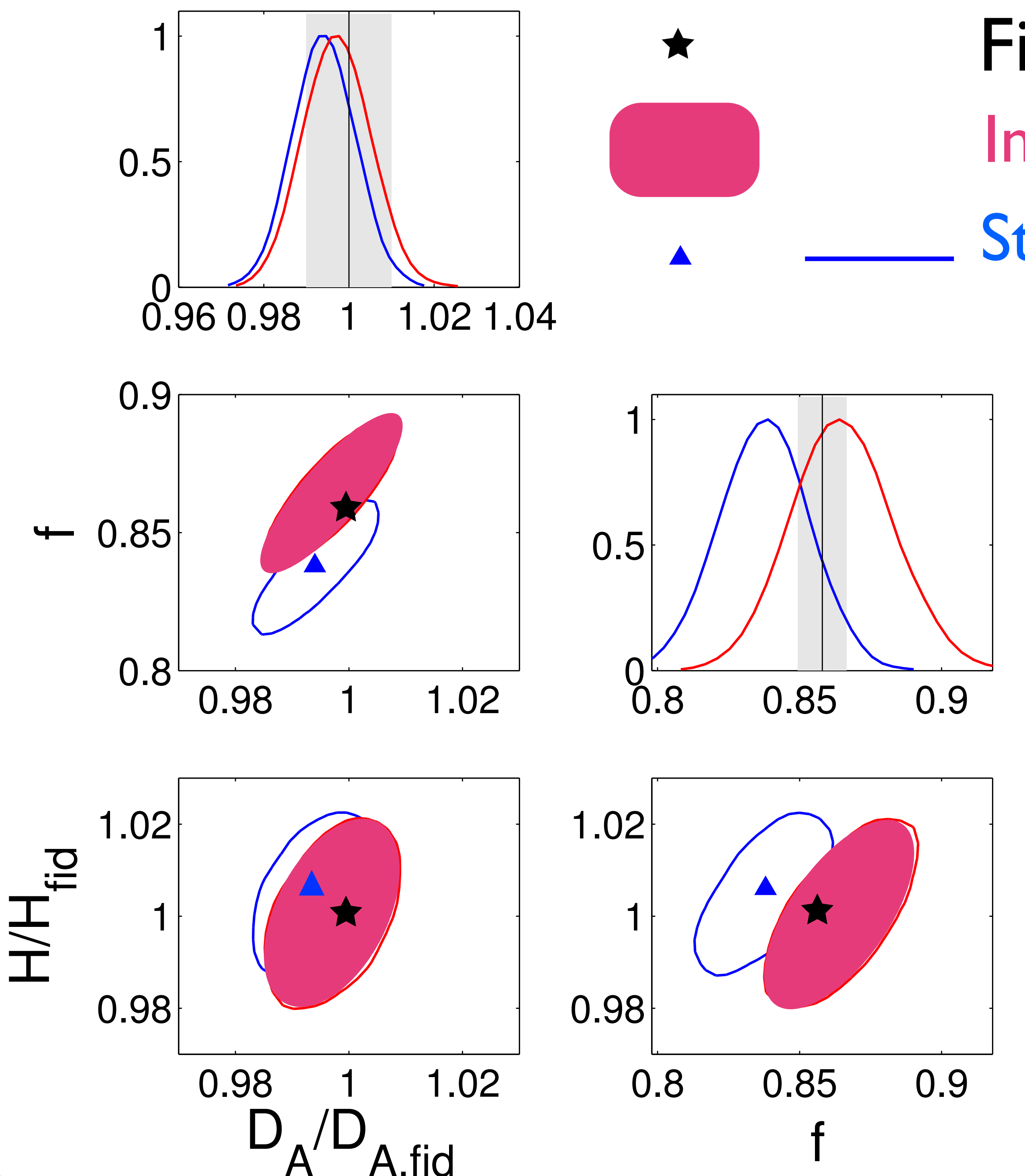
$$P^{(\mathrm{S})}(k,\mu) = \sum_{\ell=\mathrm{even}} P_\ell^{(\mathrm{S})}(k)\,\mathcal{P}_\ell(\mu)$$



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

Blind test: recovery of DA, H & f

AT, Nishimichi & Saito ('10)



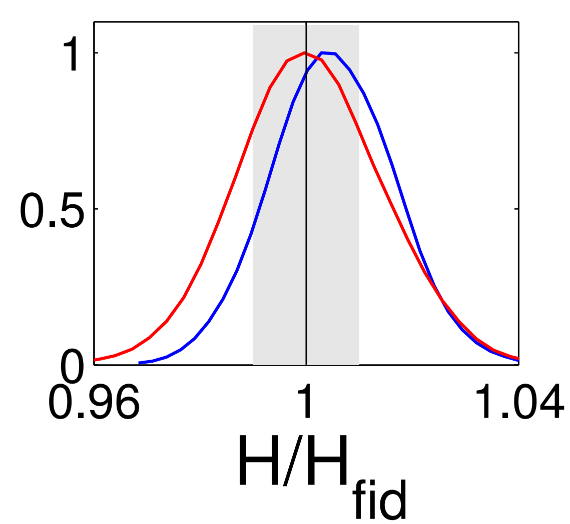
Fiducial

Improved model

Streaming model
(w/o corrections)

Fitting to P0 & P2 of N-body data
to estimate (DA, H, f)

using MCMC



Improved model of redshift distortions correctly recovers the input values

Testing PT models against redshift-space halo clustering

T. Nishimichi & AT, arXiv:1106.4562

From dark matter to halos

The improved PT model has successfully passed several tests in the case of dark matter clustering

As a natural step,

"Test against redshift-space halo clustering"

Why halo ?

- Physically well-defined objects easy to handle by N-body simulations
- Reconstruction technique for halo density field from LRG samples
- Annoying Finger-of-God damping is expected to be small

Reid, Spergel & Bode ('09)
Reid et al. ('10)

Halo clustering from N-body simulations

Nishimichi & AT ('11)

Large N-body simulations (L_{box}=1.14Gpc/h, N=1,028^3) with 15 realizations

- 9 halo catalogs sampled over wide-mass range @ z=0.35

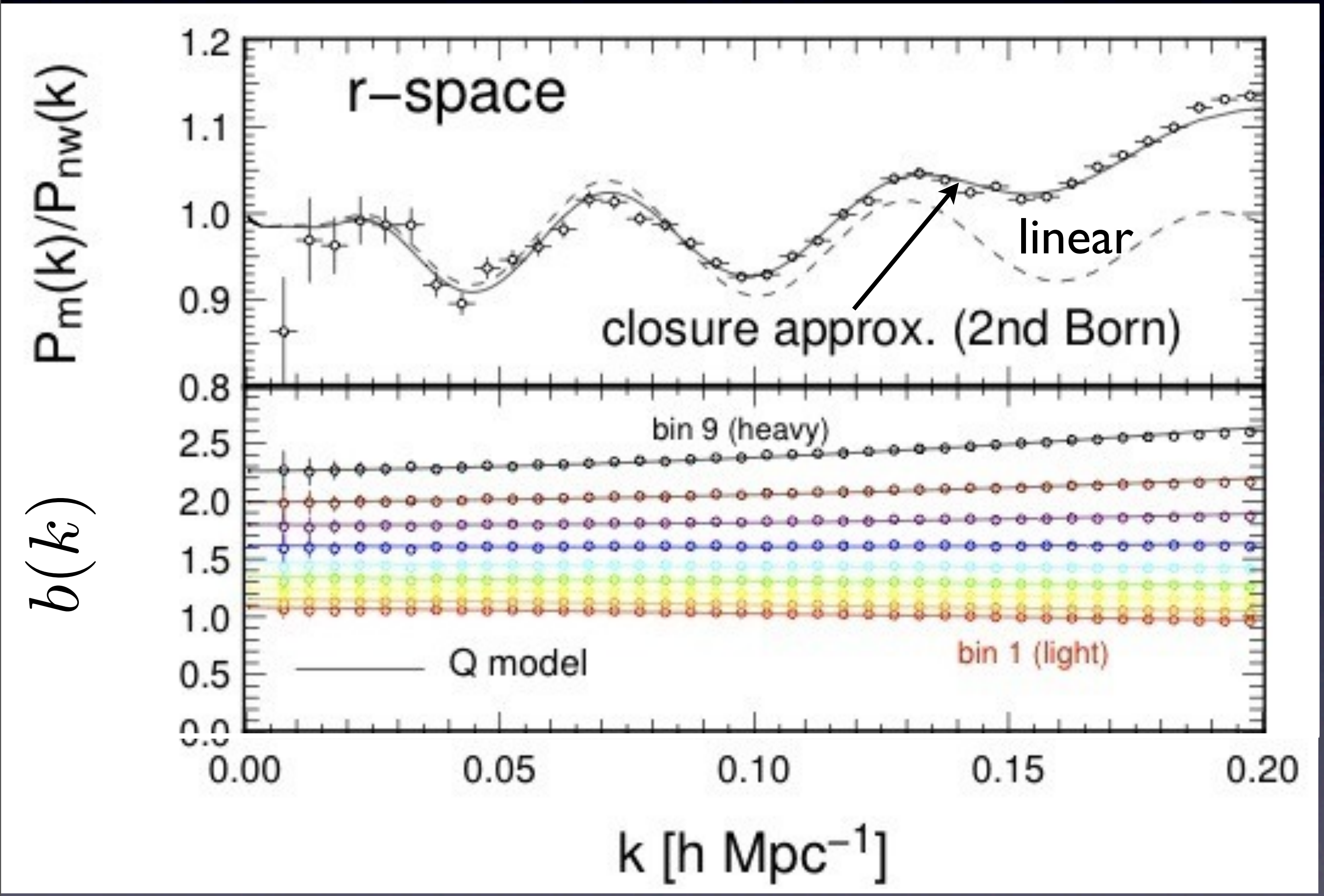
$$\overline{M}_{\mathrm{h},i} \subset [3\times10^{12},\ 7\times10^{13}]\ h^{-1}M_\odot$$

- Volume & number density roughly match those of SDSS DR7 LRG

TABLE II: Summary of the halo catalogs. The minimum, maximum and mean mass ($M_{\rm min}$, $M_{\rm max}$ and $\overline{M}_{\rm h}$) are in units of $h^{-1}M_\odot$, while the halo number density (n_h) is in $h^3{\rm Mpc}^{-3}$. The bias parameter, b_0, is defined in Eq. (15). See Sec. IV A for more detail.

Sample	bin 1 (light)	bin 2	bin 3	bin 4	bin 5	bin 6	bin 7	bin 8	bin 9 (heavy)
$M_{\rm min}$	1.77×10^{12}	2.49×10^{12}	3.54×10^{12}	4.98×10^{12}	7.09×10^{12}	1.00×10^{13}	1.42×10^{13}	2.01×10^{13}	2.84×10^{13}
$M_{\rm max}$	5.54×10^{12}	1.02×10^{13}	1.74×10^{13}	2.66×10^{13}	4.04×10^{13}	6.76×10^{13}	1.19×10^{14}	2.08×10^{14}	-
$\overline{M}_{\rm h}$	2.96×10^{12}	4.65×10^{12}	7.08×10^{12}	9.37×10^{12}	1.47×10^{13}	2.18×10^{13}	3.21×10^{13}	4.63×10^{13}	7.03×10^{13}
n_h	1.57×10^{-3}	1.26×10^{-3}	9.46×10^{-4}	6.87×10^{-4}	4.87×10^{-4}	3.47×10^{-4}	2.43×10^{-4}	1.64×10^{-4}	1.09×10^{-4}
b_0	1.08	1.16	1.25	1.35	1.47	1.62	1.80	1.99	2.26

Real-space clustering



PT model prediction works very well at k<0.2 h/Mpc

Halo bias possesses (very) weak scale-dependence

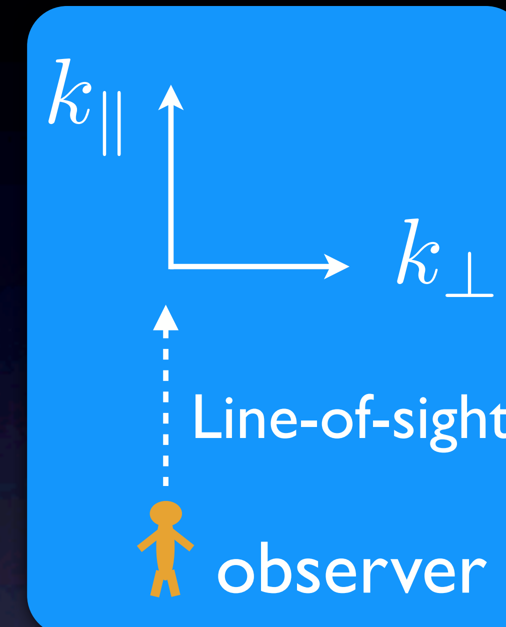
$$b(k) = P_{\rm hm}(k)/P_{\rm m}(k)$$

Adopting a scale-dependent linear bias, $\delta_{\rm h}(\vec{\boldsymbol{k}}) = b(k)\delta_{\rm m}(\vec{\boldsymbol{k}})$

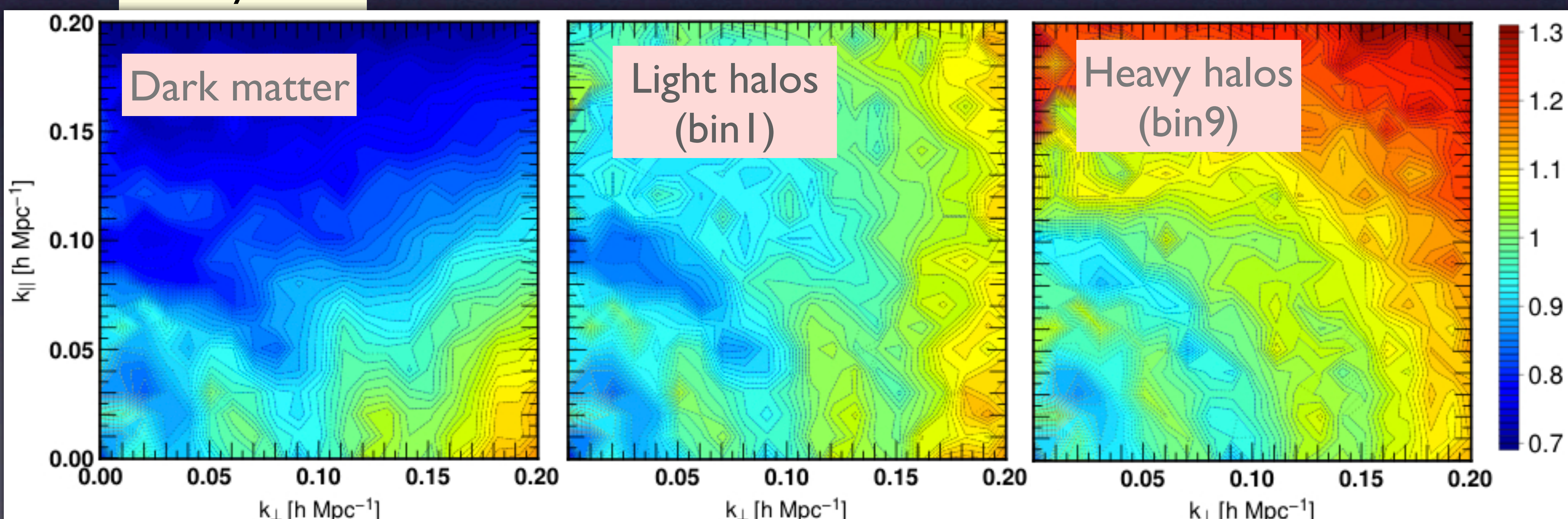
PT models are compared with simulations (--> Next slides)

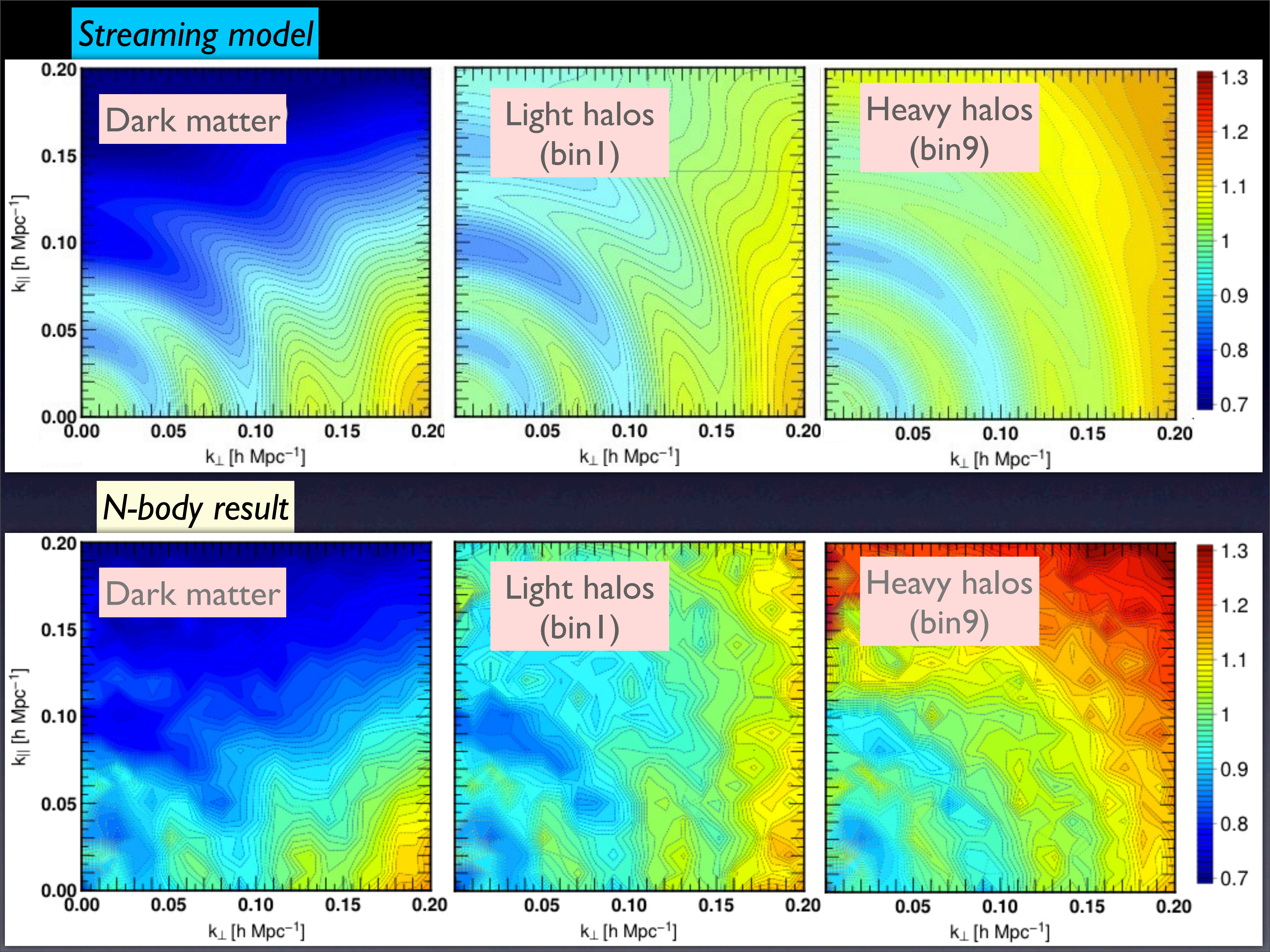
Power spectrum in 2D

$$\frac{P_{\rm halo}(k_{||}, k_{\perp})}{(b^2 + f\,\mu^2)^2 P_{\rm lin,no\text{-}wiggle}(k)}$$



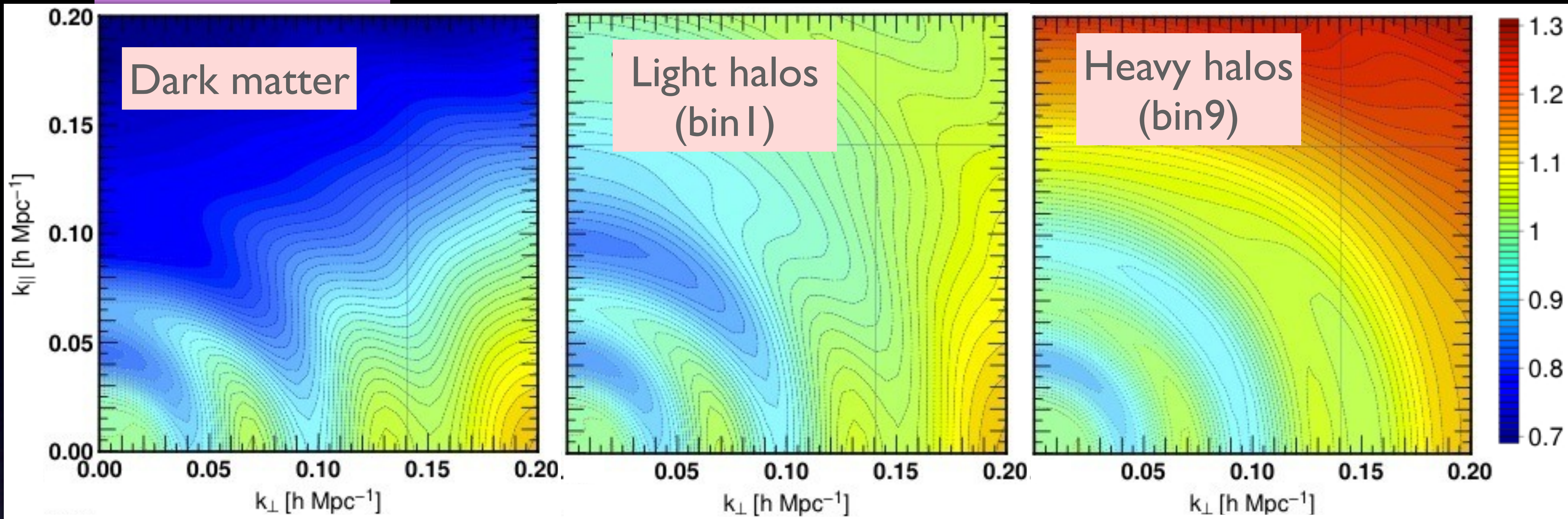
N-body result ‘shot-noise’ corrected



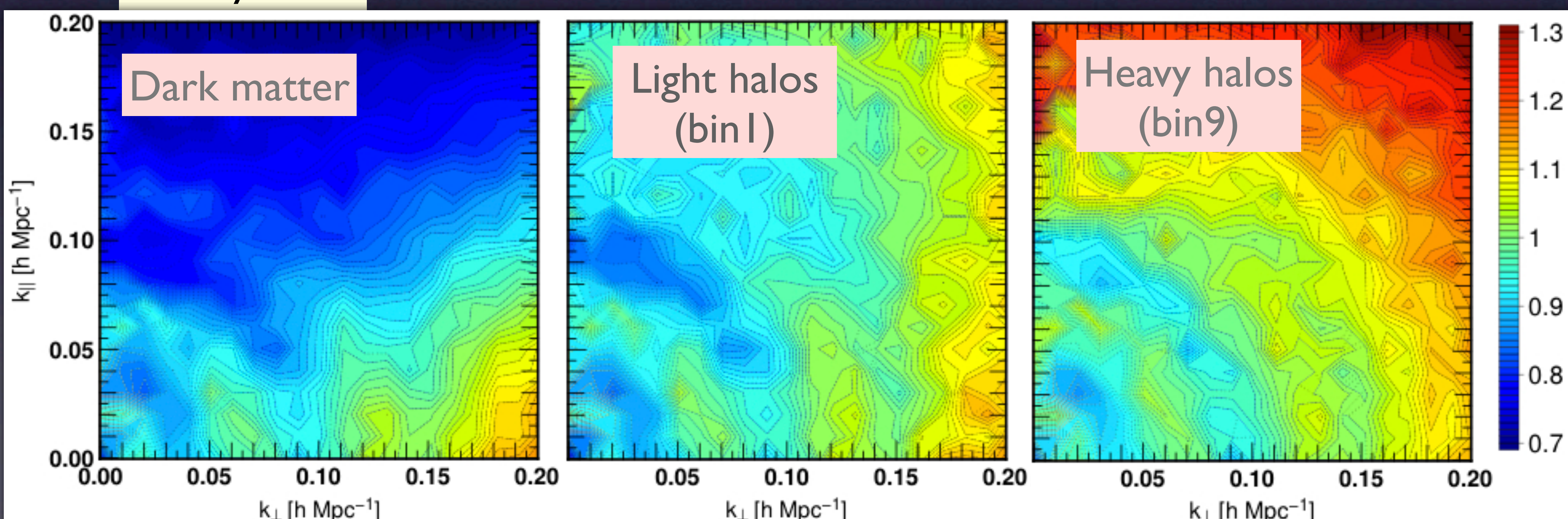


Streaming model
Dark matter
Light halos (bin1)
Heavy halos (bin9)
N-body result
Dark matter
Light halos (bin1)
Heavy halos (bin9)
k|| [h Mpc⁻¹]
k⊥ [h Mpc⁻¹]
0.00
0.05
0.10
0.15
0.20
0.7
0.8
0.9
1
1.1
1.2
1.3

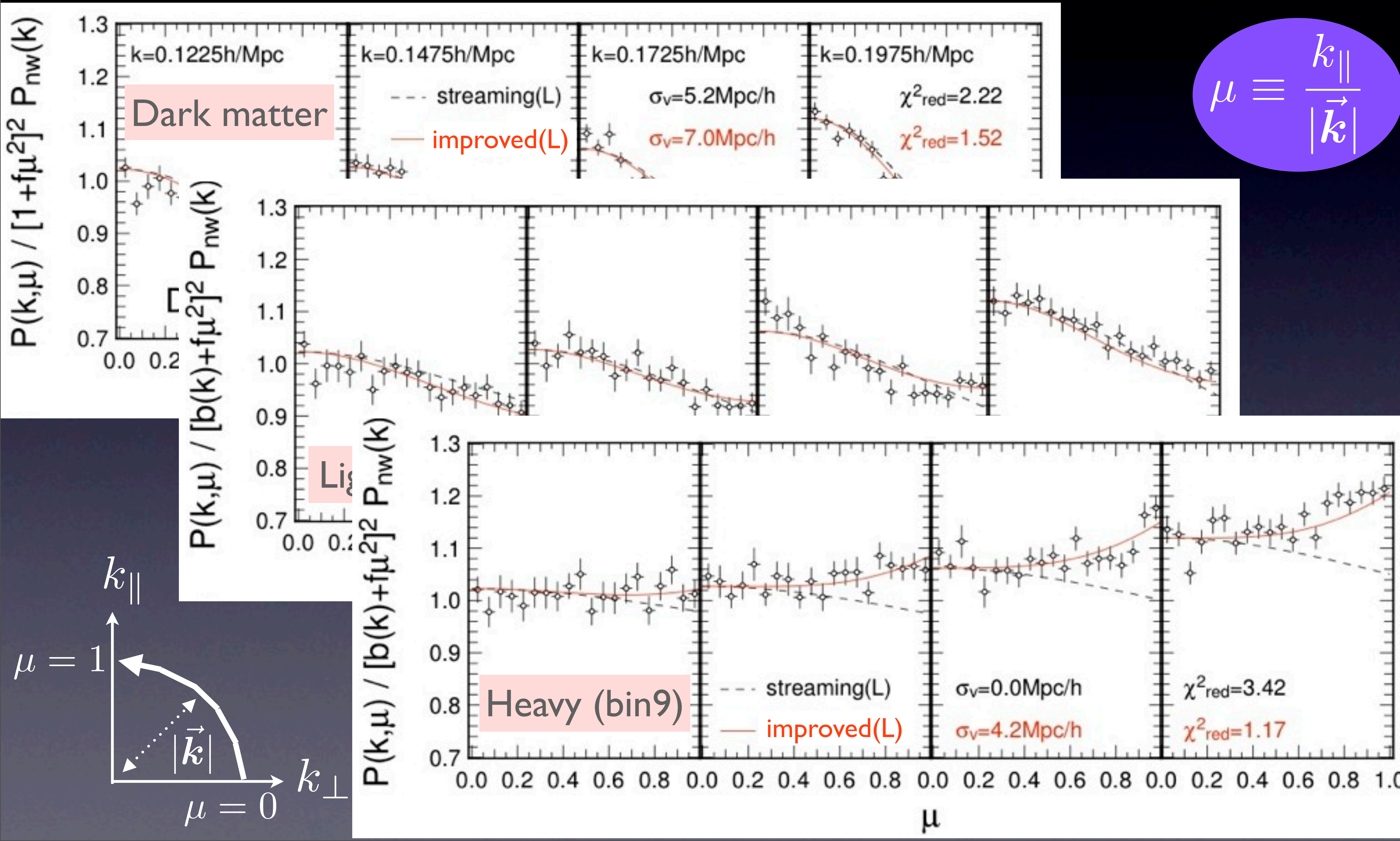
Improved model



N-body result



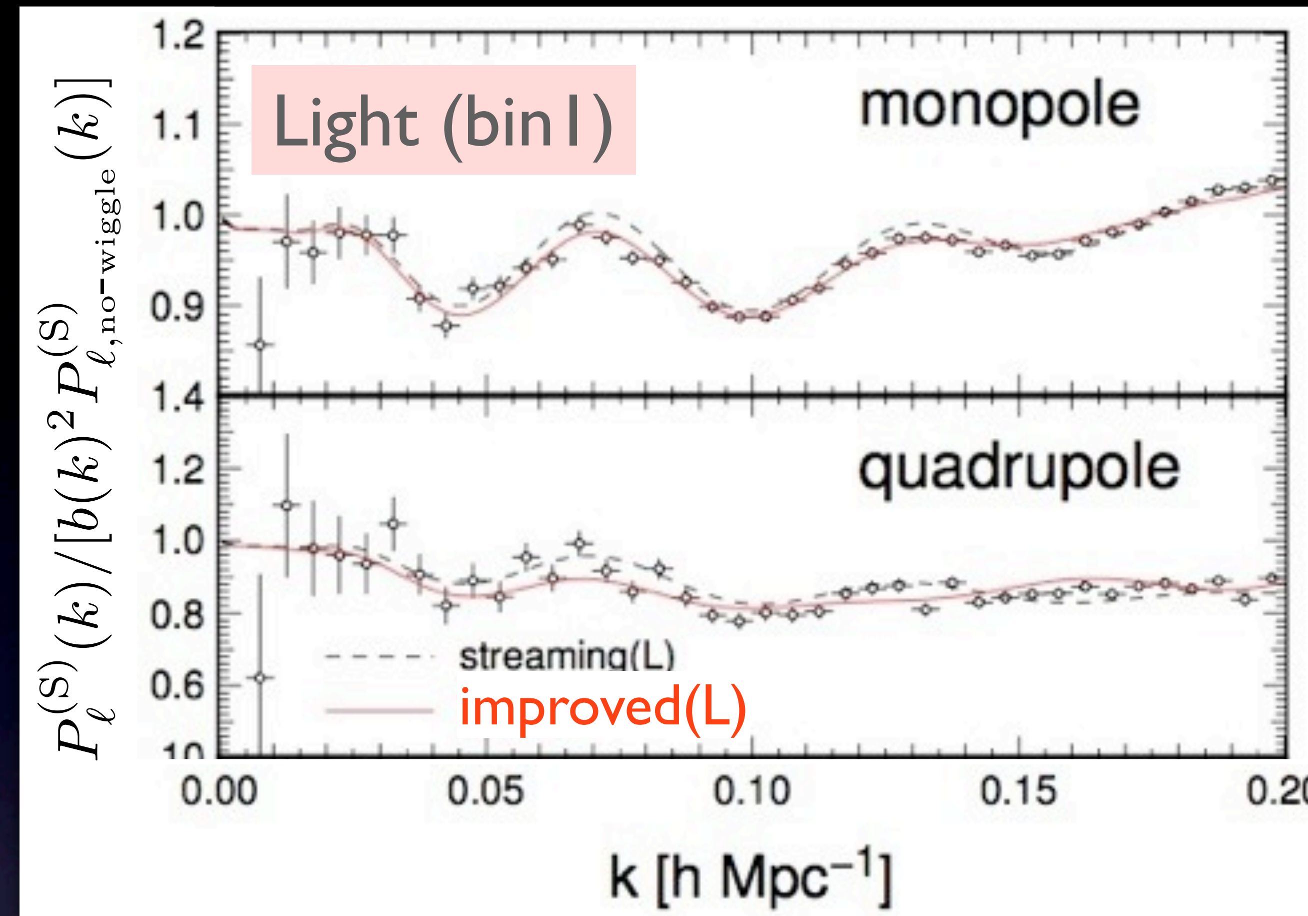
Power spectrum in 2D

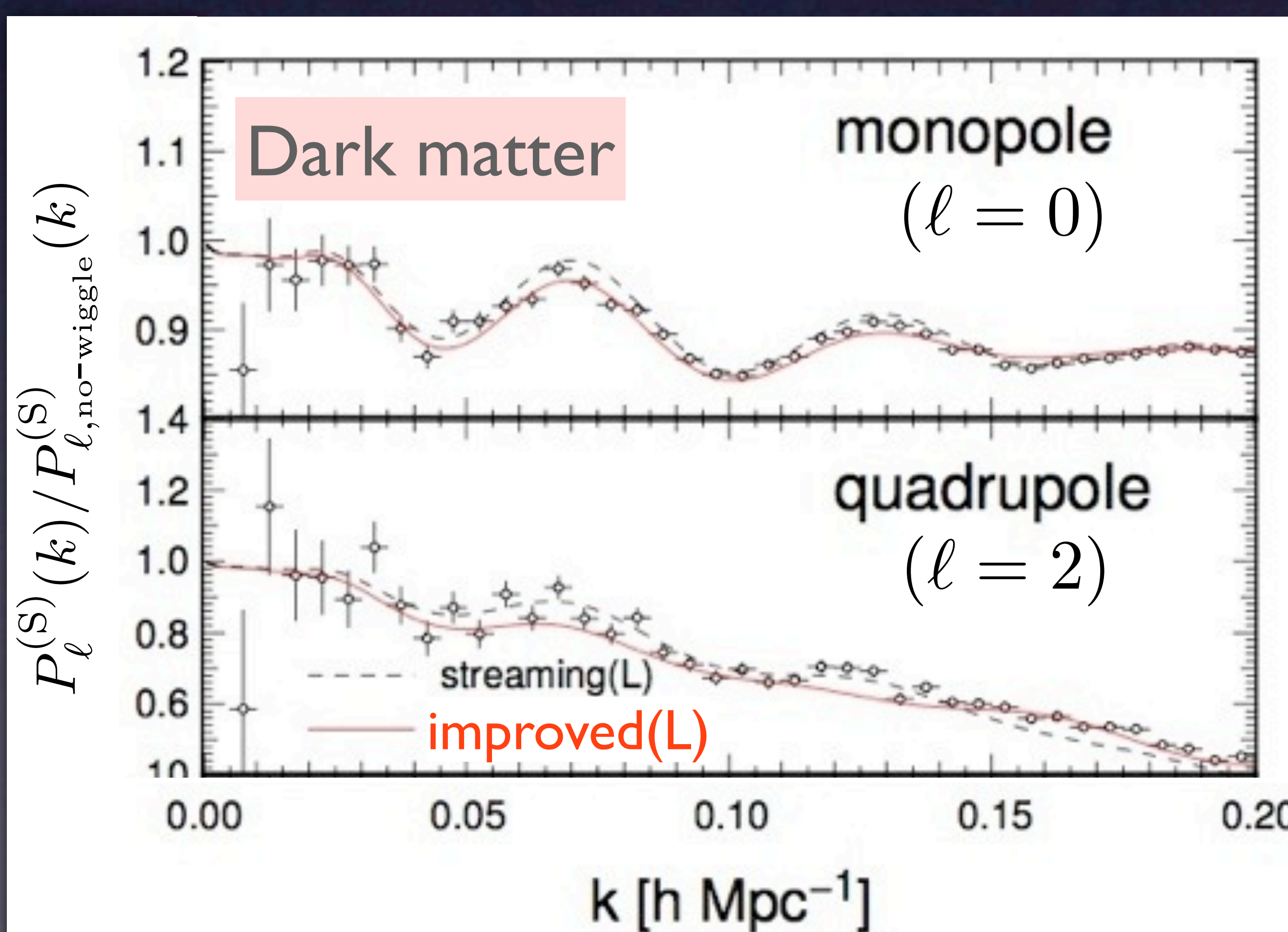


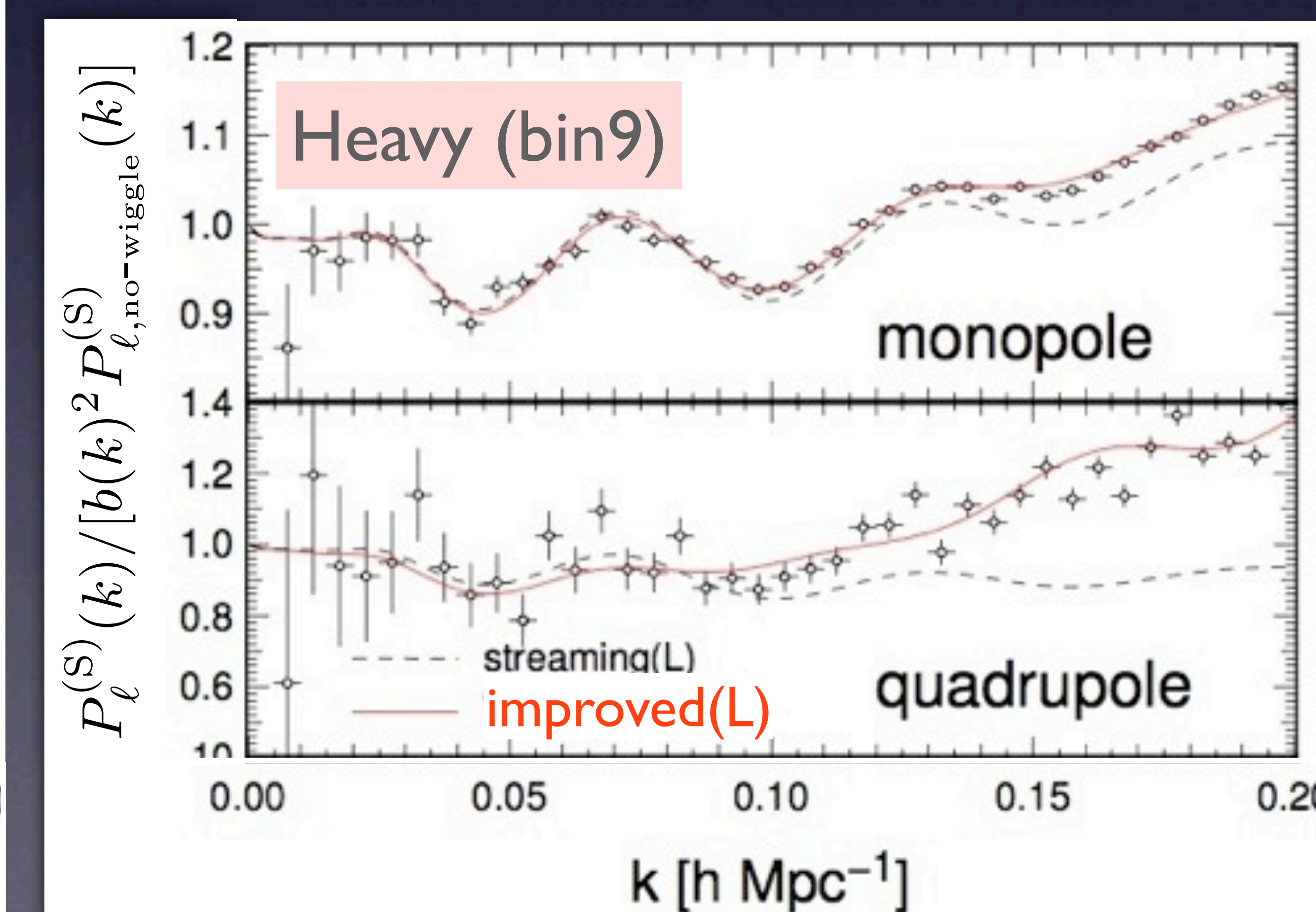
$$\mu \equiv \frac{k_\parallel}{|\vec{k}|}$$

Multipole power spectra

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



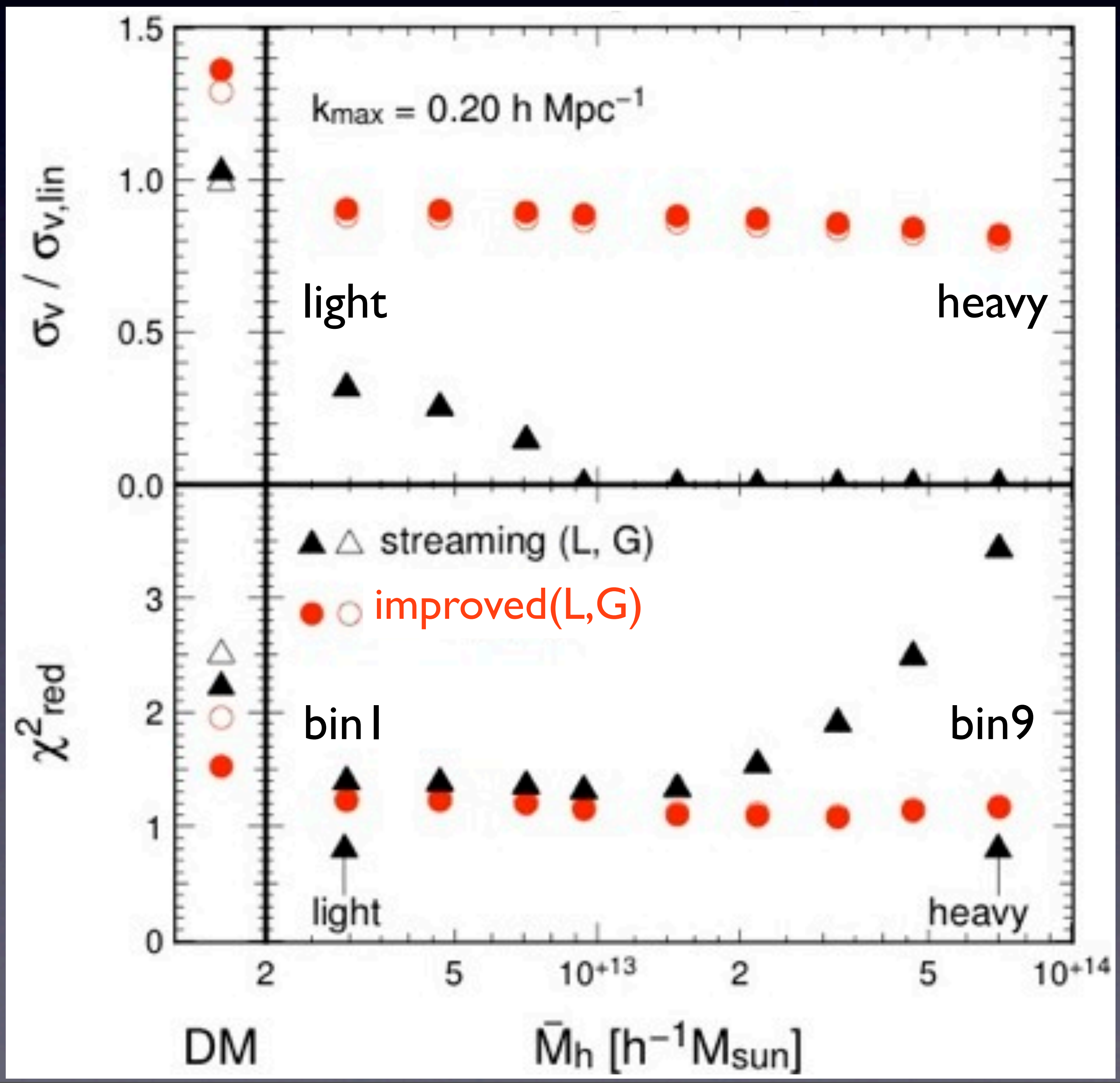




Halo mass dependence

Choice of damping func.

L: Lorentzian, G: Gaussian



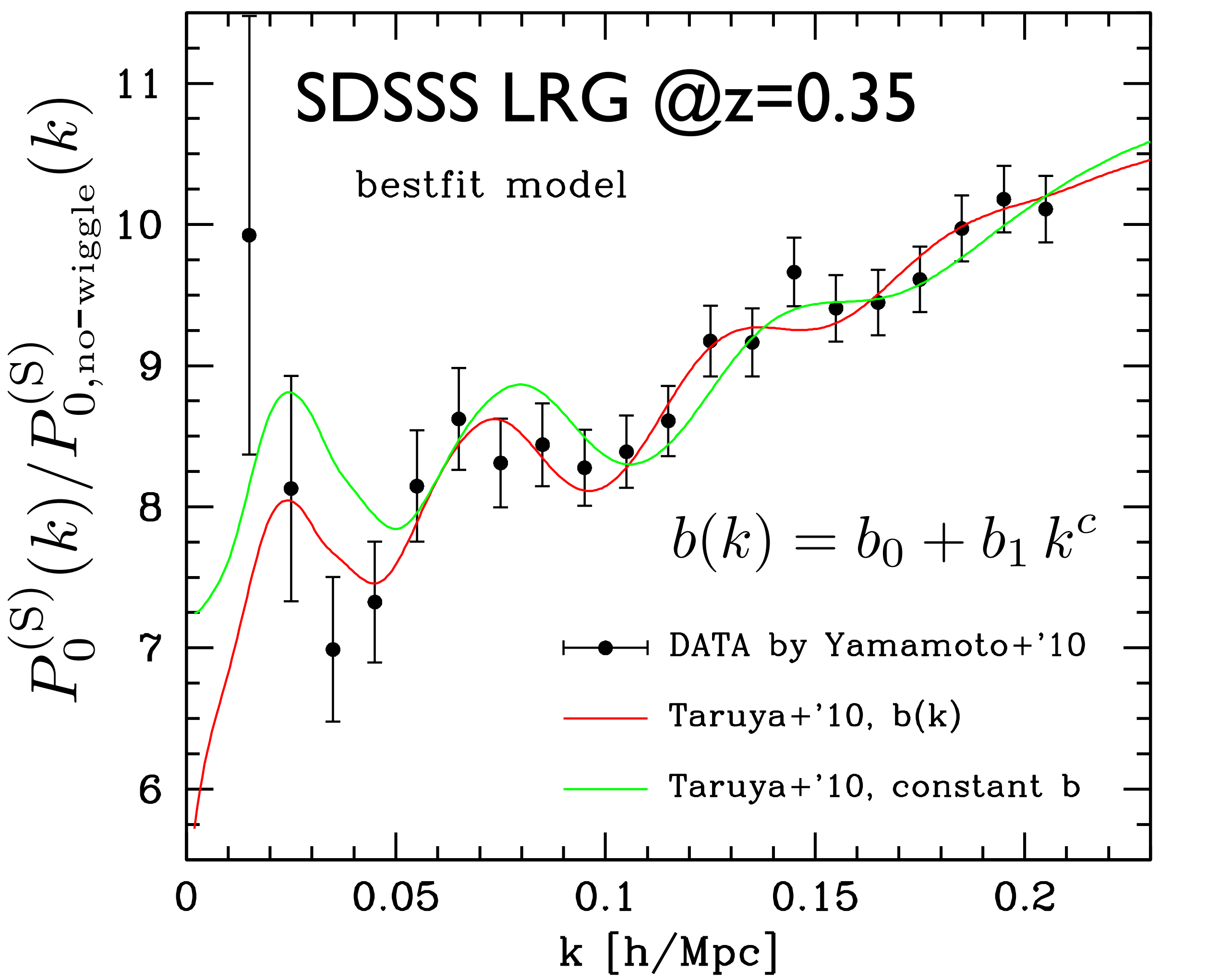
Fitted results of velocity dispersion

Goodness of fit

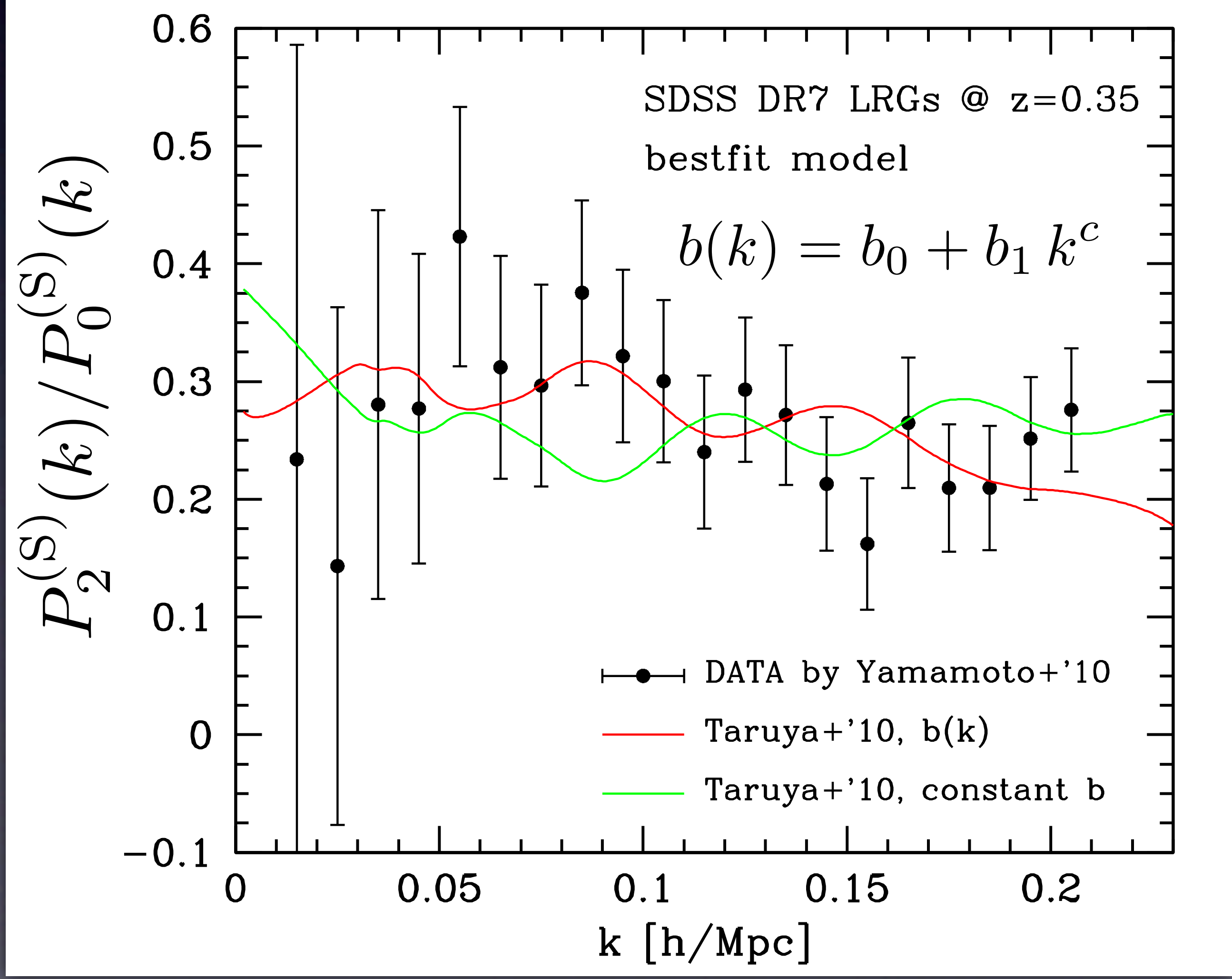
SDSS DR7 LRG samples

Assuming linear scale-(in)dependent bias,
monopole & quadrupole spectra ⟶ fit to PT model

Monopole



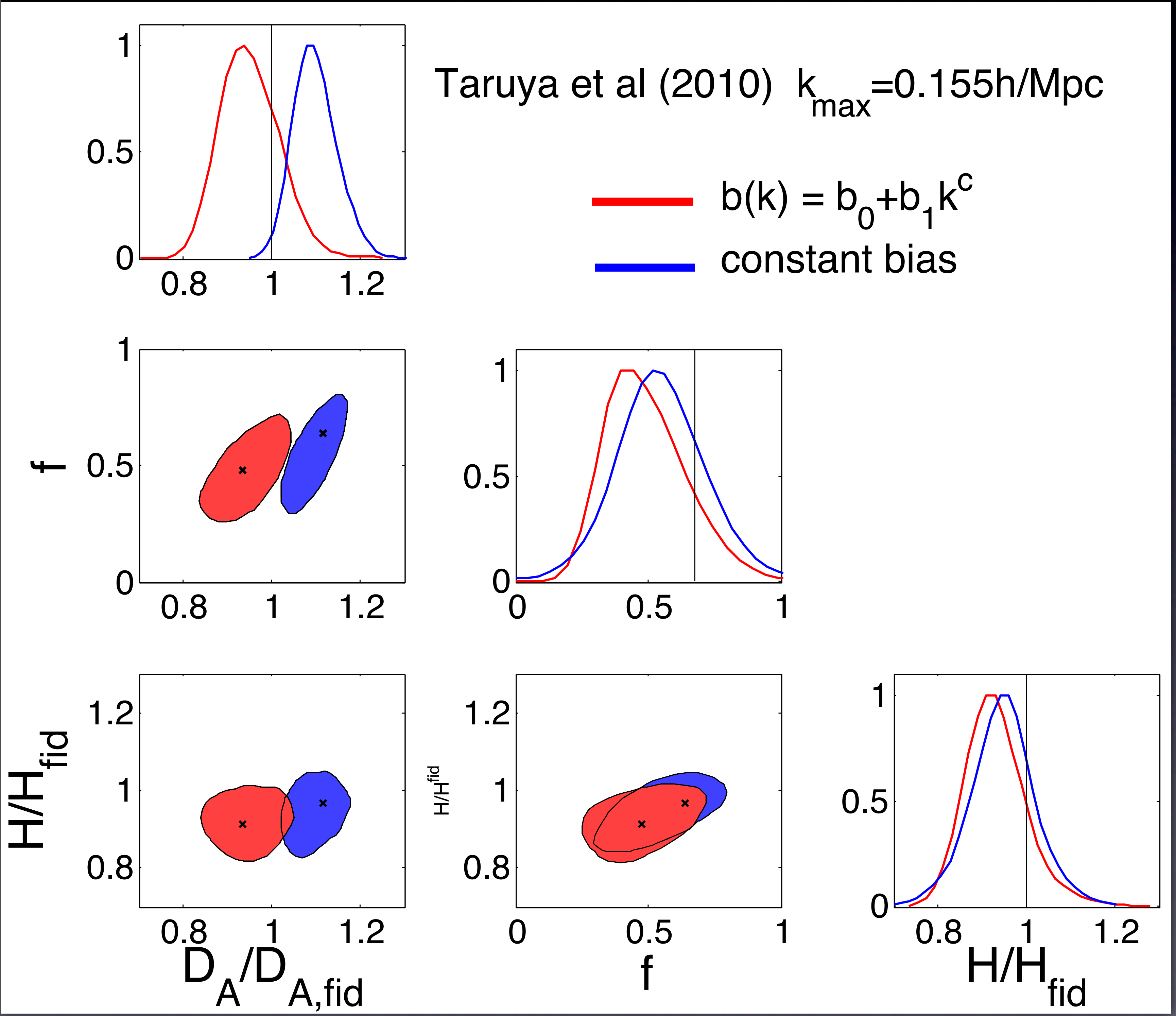
Quadrupole-to-Monopole ratio



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

Resultant constraint on DA is rather sensitive to the galaxy bias

Summary

Clustering anisotropies by AP & RD effects offer unique probe to precisely measure cosmic expansion & growth of structure

- Key science of galaxy surveys in the coming decade
- New ideas & innovations
- Precision power spectrum template from perturbation theory

New effect of non-linear RD amplified by galaxy/halo bias

$\longrightarrow$ Failure of popular "streaming model"

Impacts of precision model of RD on future measurements

The understanding of galaxy bias is still crucial issue