24th~26th May 2016
Nonlinear evolution of the LSS of the Universe:
Theory meets Expectations

Redshift space distortions as a probe of gravity

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Plan of talk

My personal perspective on constraining/testing gravity with LSS observations (focusing on RSD)

- Cosmological probe of gravity
- Model-independent approach
- Consistent modified gravity analysis
- Summary

Based on

Song, AT, Linder et al. PRD92, 043522 ('15)
AT, Nishimichi, Bernardeau et al. PRD90, 123515 ('15)
AT, Koyama, Hiramatsu & Oka PRD89, 043509 ('14)

Motivation

Q Is GR valid on cosmological scales ?

- Untested hypothesis in ΛCDM model
- Hint for cosmic acceleration

Framework to describe modified gravity is well (too) developed :

- Systematic construction of *most general scale-tensor theory*

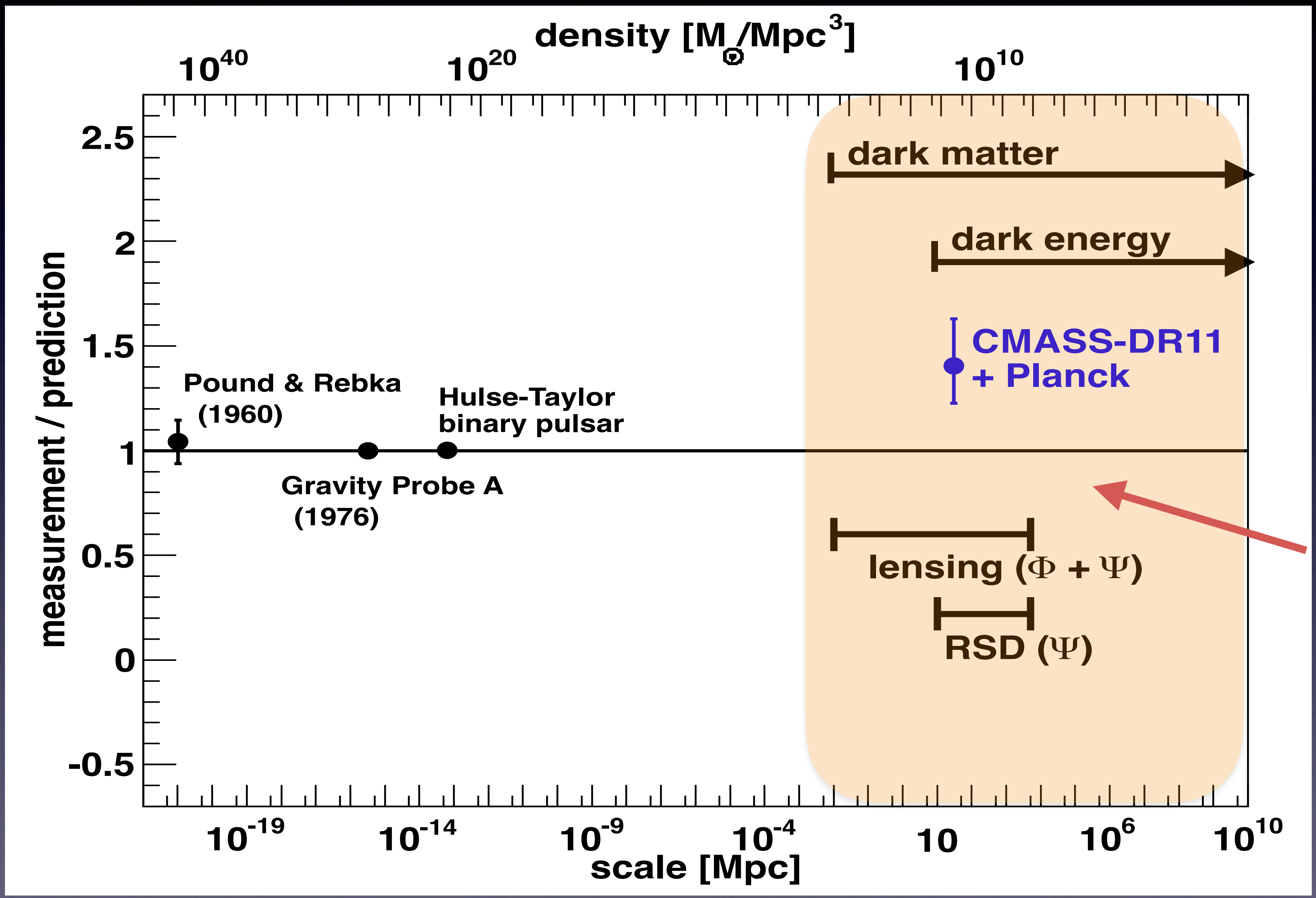
  (Horndeski theory, GLPV theory, EFT approach,…)

- Various *screening mechanisms* that recover GR on small scales

  (Chameleon, Vainshtein, symmetron, K-mouflage, ultra-local, …)

These theoretical attempts have to be tested observationally

Test of GR as function of scales



Cosmological scales

Beutler et al. ('14)

star

galaxy

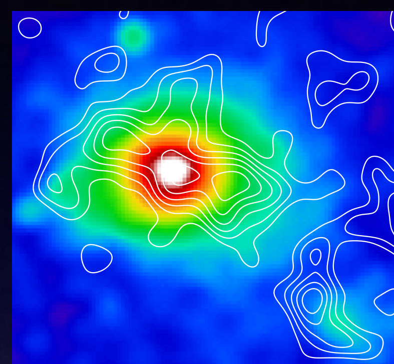
cluster

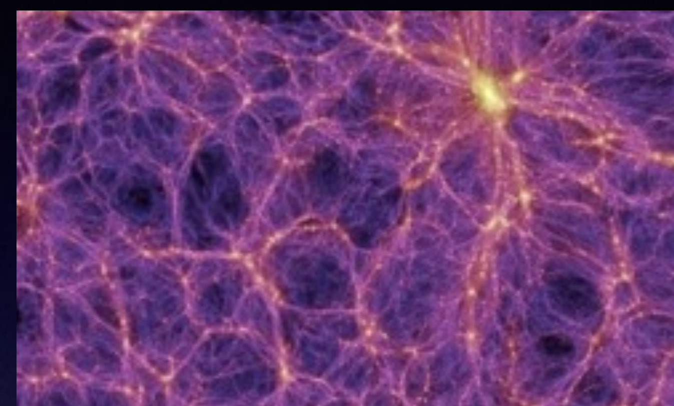
galaxy clustering

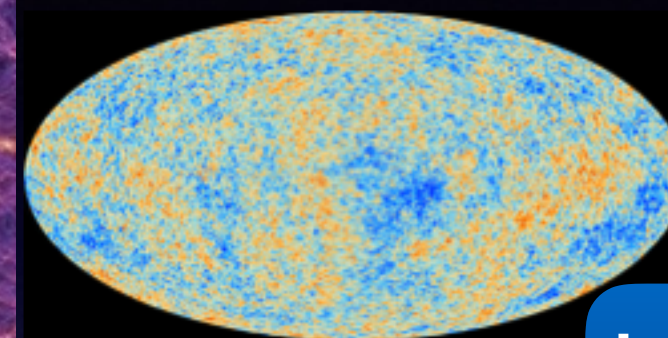
CMB

Gravity on cosmological scales

High density







Small scale (~kpc) ⟷ Large scale (~Gpc)

structure formation modified

recover GR
(by screening mechanism)

fifth force mediated by new scalar d.o.f
➡ cosmic acceleration

galaxy | cluster | galaxy clustering (Lensing / RSD) | CMB

Modification to gravity

Suppose metric theory of gravity:

spacetime metric

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

$\Phi(\vec{x}),\ \Psi(\vec{x})$: potentials $\longleftrightarrow$ matter fluctuations $\delta_{\rm m}(\vec{x}),\ \vec{v}(\vec{x})$

In GR (subhorizon)

$$\frac{1}{a^2}\nabla^2\Phi = 4\pi\,G\,\rho_{\rm m}\,\delta_{\rm m}$$

$$\frac{1}{a^2}\nabla^2(\Phi+\Psi) = 8\pi\,G\,\rho_{\rm m}\,\delta_{\rm m}$$

$$\nabla^2(\Phi-\Psi) = 0$$

In modified gravity

- scalar d.o.f φ appears coupled with <u>scalar-field eq.</u>
- relation btw. Ψ Φ & $\delta_{\rm m}$ becomes non-trivial

Model-independent approach

Phenomenological parameterization:

$$-k^2\Psi = 4\pi\, G\, a^2 \boxed{\mu} \rho_{\rm m}\, \delta_{\rm m}$$

$$-k^2(\Psi + \Phi) = 8\pi\, G\, a^2 \boxed{\Sigma} \rho_{\rm m}\, \delta_{\rm m} \quad \text{or} \quad \boxed{\eta} \equiv \frac{\Phi}{\Psi}$$

Coupled with energy-momentum conservation:

$$\ddot{\delta}_{\rm m} + 2H\dot{\delta}_{\rm m} - 4\pi\, \underline{G_{\rm eff}}\, \delta_{\rm m} = 0 \qquad \text{(Linear)}$$

Linear growth rate: $\boxed{f(z)} \equiv \dfrac{d\ln D_+}{d\ln a} \simeq \{\Omega_{\rm m}(z)\}^{\gamma}$

$(\delta_{\rm m} \propto D_+)$

$(\mathrm{GR}:\ \gamma = 0.55)$

Find or search for any deviation from

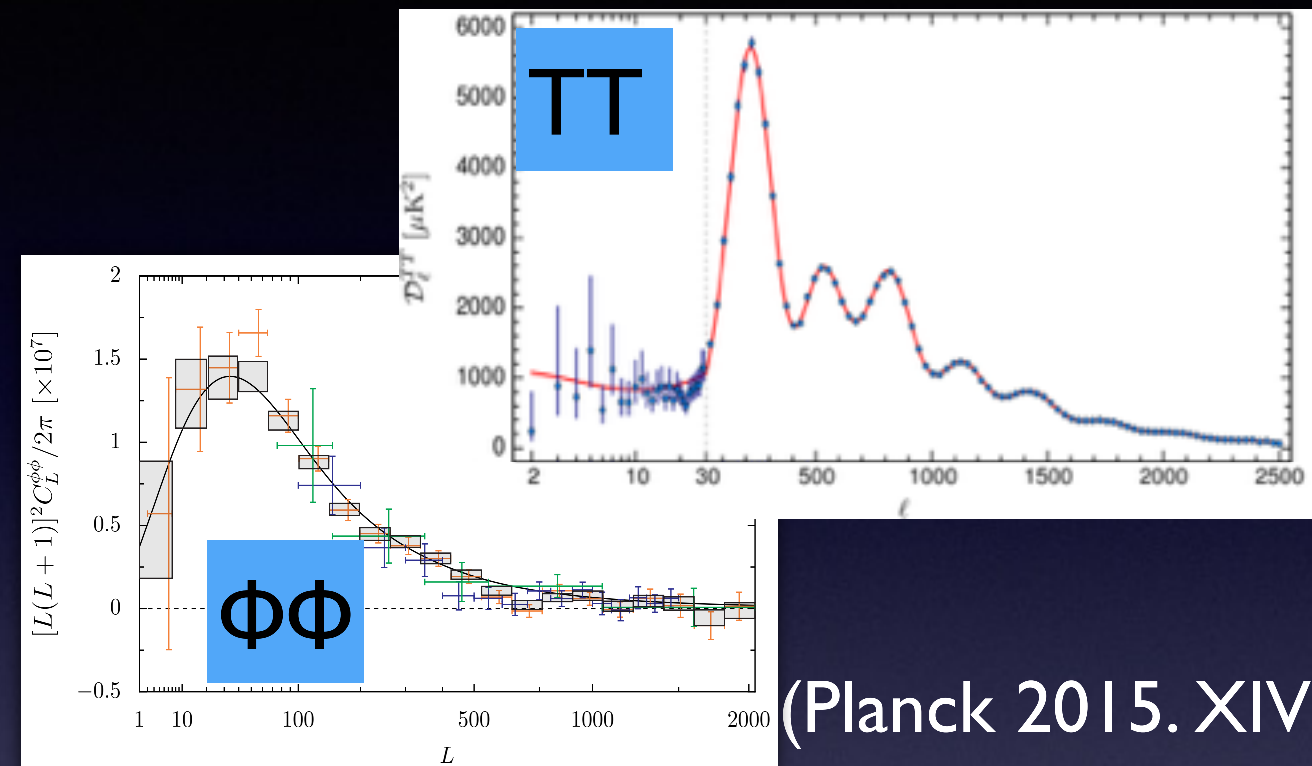
$\mu = \Sigma = \eta = 1$ or $\gamma = 0.55$

Consistency test of GR

Cosmological probe of gravity

- ISW effect $\dfrac{\Delta T}{T} \propto \int dt\,(\dot{\Phi} + \dot{\Psi})$

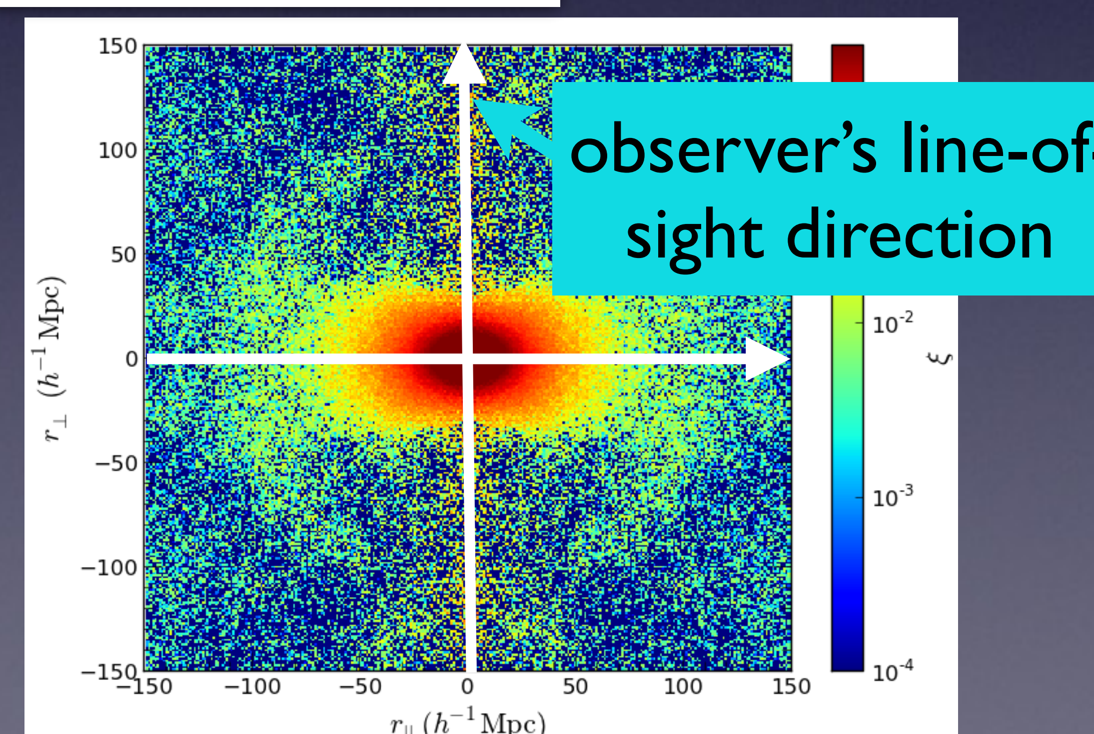
- Weak lensing $\kappa \;\propto\; \nabla^2(\Phi + \Psi)$



(Planck 2015. XIV)

- Redshift-space distortions

$$P^{(\mathrm{S})}(k,\mu) = (1 + f\,\mu^2)^2\, P(k)$$



(Samushia et al. '14)

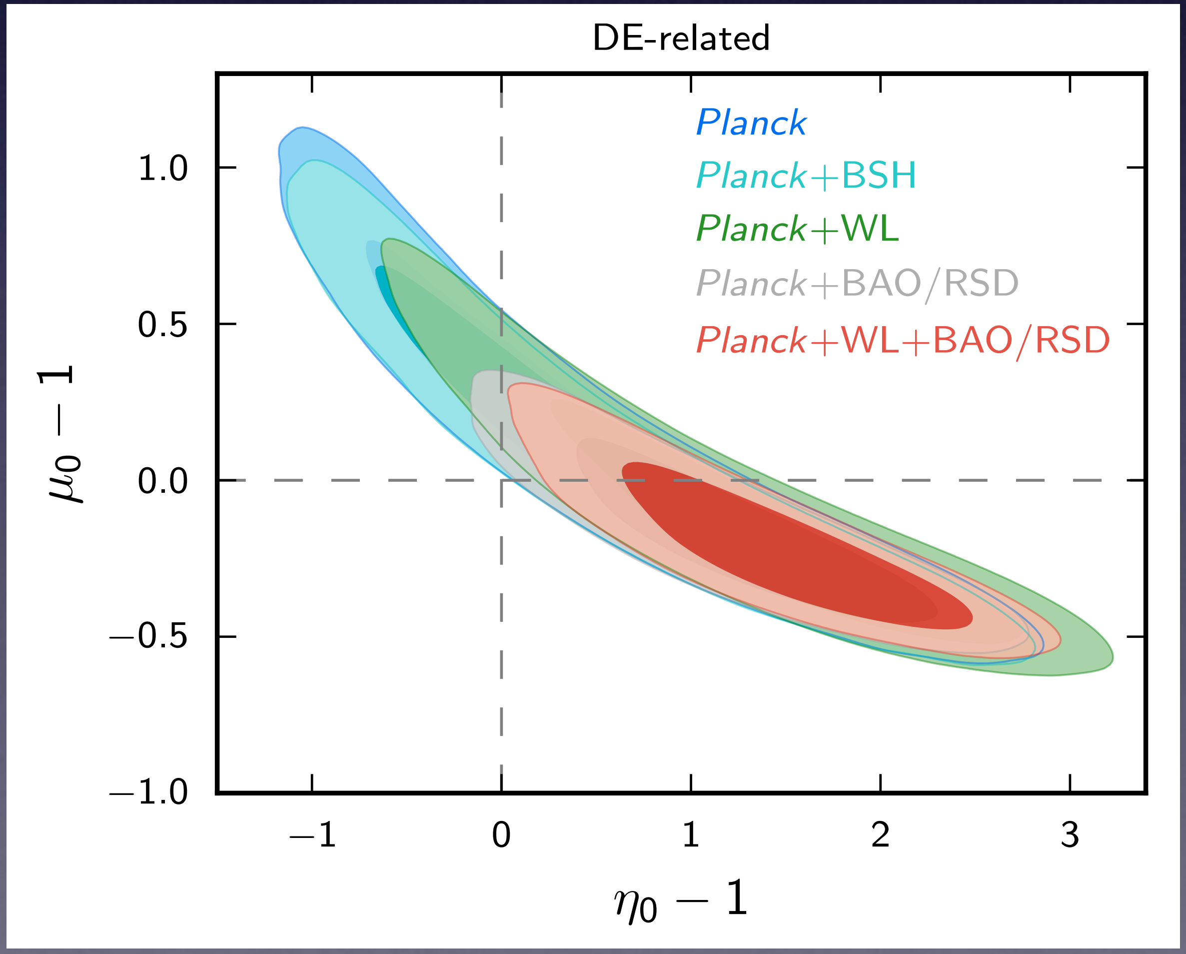
Cluster profile & abundance are also powerful probe (see later)

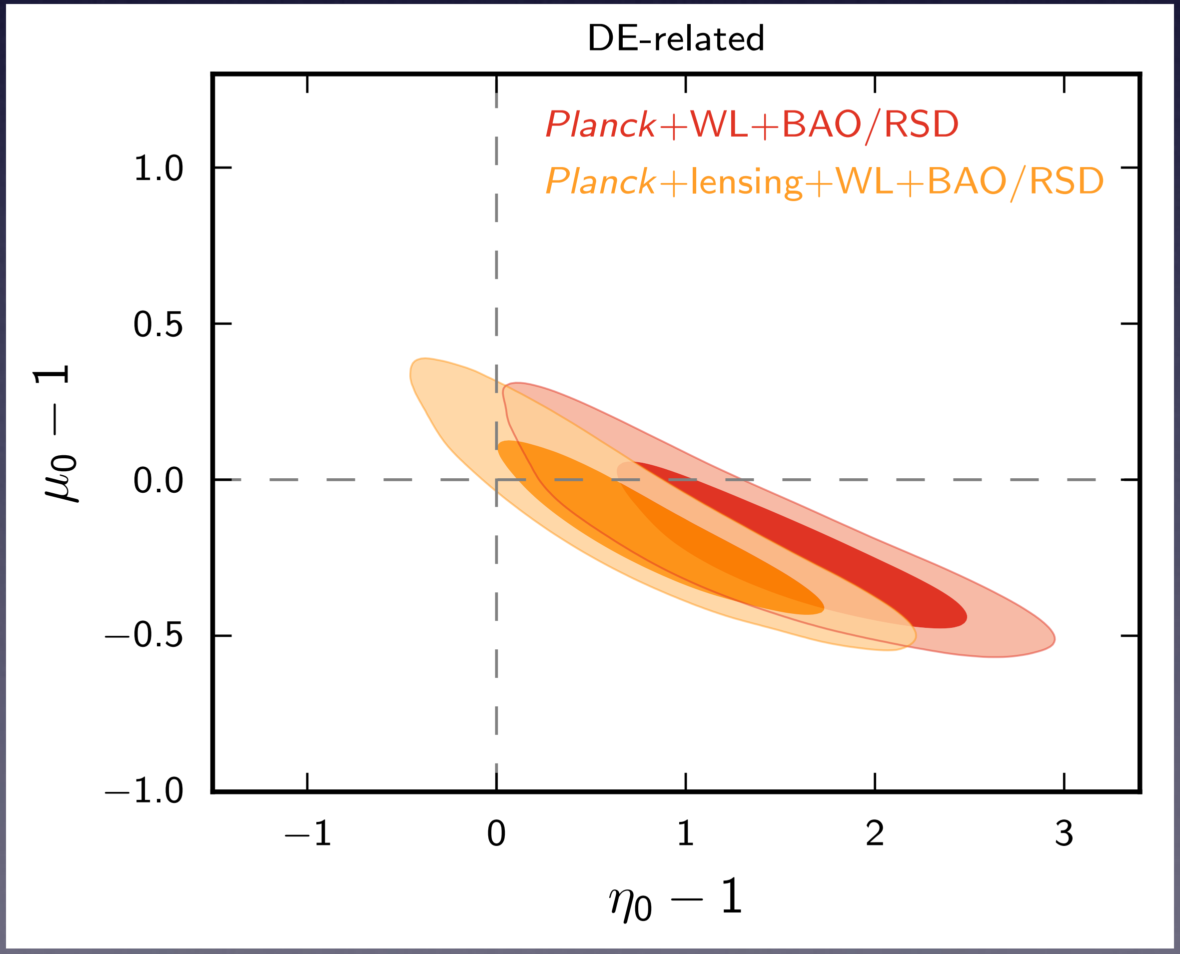
Constraints from CMB

Assuming scale-independent parameters:

$$-k^2\Psi = 4\pi\, G\, a^2 \boxed{\mu} \rho_{\rm m}\, \delta_{\rm m} \qquad \boxed{\eta} \equiv \frac{\Phi}{\Psi}$$

$$\mu(a) - 1 \propto \Omega_{\rm DE}(a)$$
$$\eta(a) - 1 \propto \Omega_{\rm DE}(a)$$



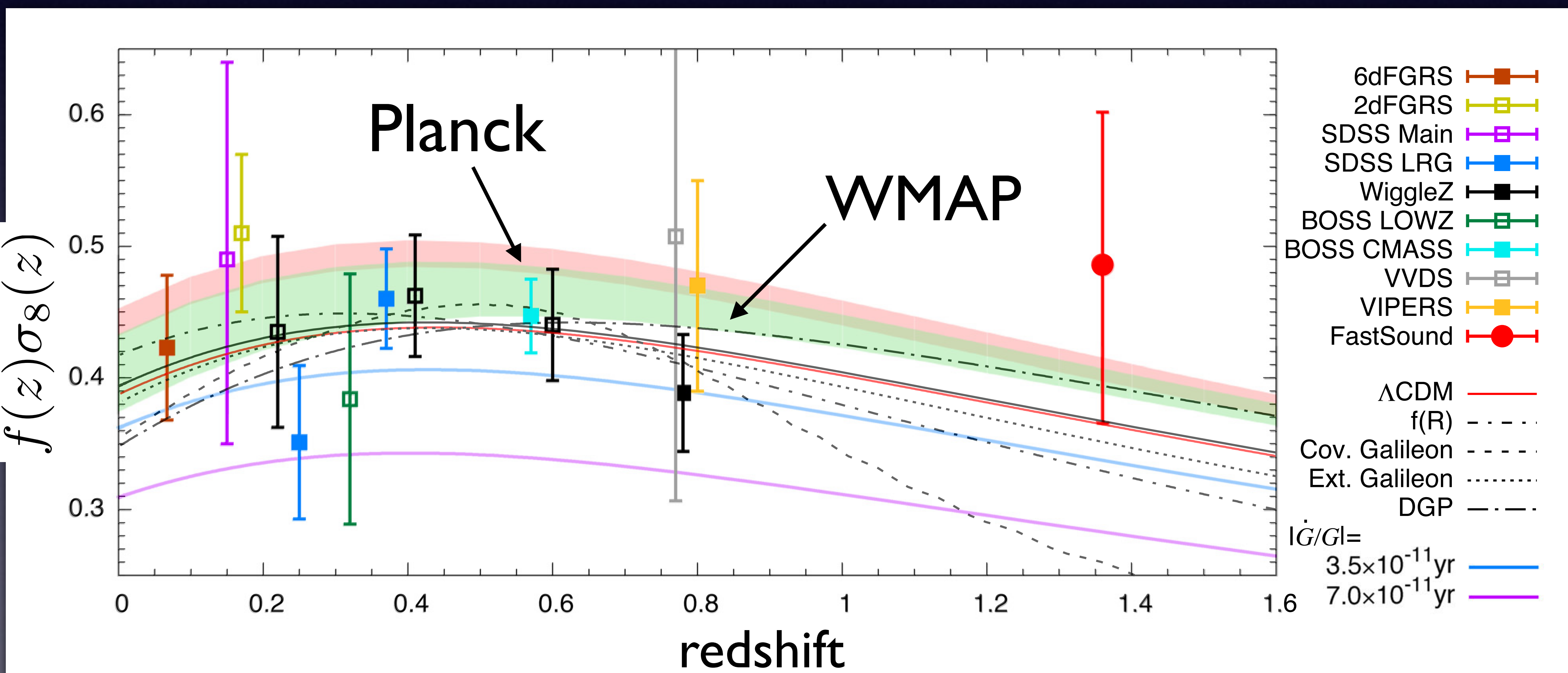


(Planck 2015. XIV)

Constraints from RSD

Assuming scale-independent growth rate:

$$f(z) \equiv \frac{d\ln D_+(a)}{d\ln a} \approx \{\Omega_{\rm m}(z)\}^{0.55} \qquad \text{GR}$$



Okumura et al. ('16)

Remark: practical analysis needs nonlinear modeling

Beyond linear regime

- Precision nonlinear modeling is crucial
- Linear relation between Ψ Φ & $\delta_{\rm m}$ is inadequate

⇒ Nonlinear 5th force (scalaron) comes to play a role

(screening mechanism)

e.g., f(R) gravity

$$\begin{cases} \dfrac{1}{a^2}\nabla^2\Psi = \underline{\dfrac{16\pi G}{3}\rho_{\rm m}\,\delta_{\rm m} - \dfrac{1}{6}\boxed{\delta R}} \\ \nabla^2(\Phi-\Psi) = \nabla^2\delta f_R \end{cases}$$

modified Poisson eq.

scalaron

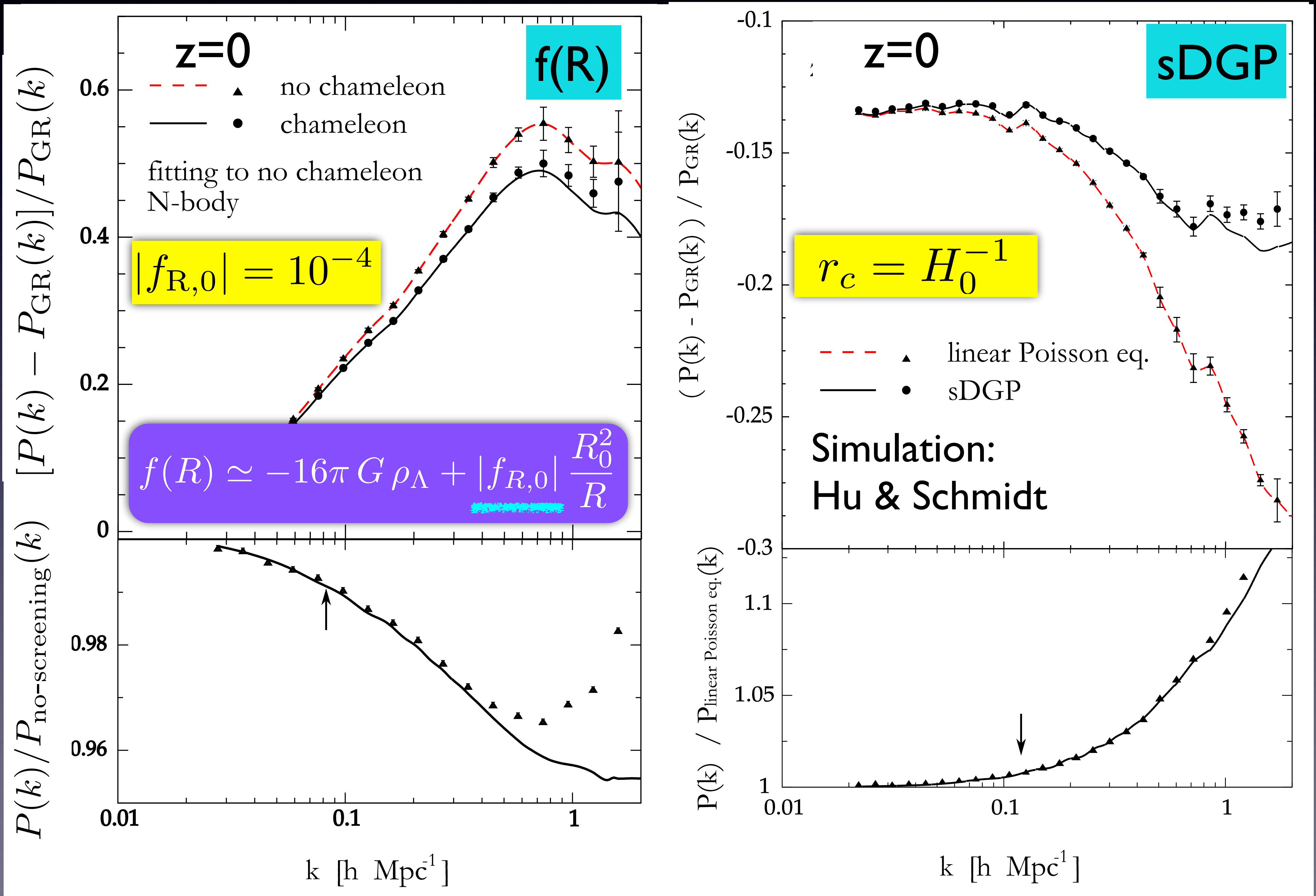
nonlinear function of δf_R

$$\frac{3}{a^2}\nabla^2\delta f_R = -8\pi G\,\rho_{\rm m}\delta_{\rm m} + \boxed{\delta R}\,; \qquad \delta R \equiv R(f_R) - R(\bar{f}_R)$$

······· Difficulty in model-independent approach

Impact of nonlinear 5th force

Koyama, AT & Hiramatsu ('09)

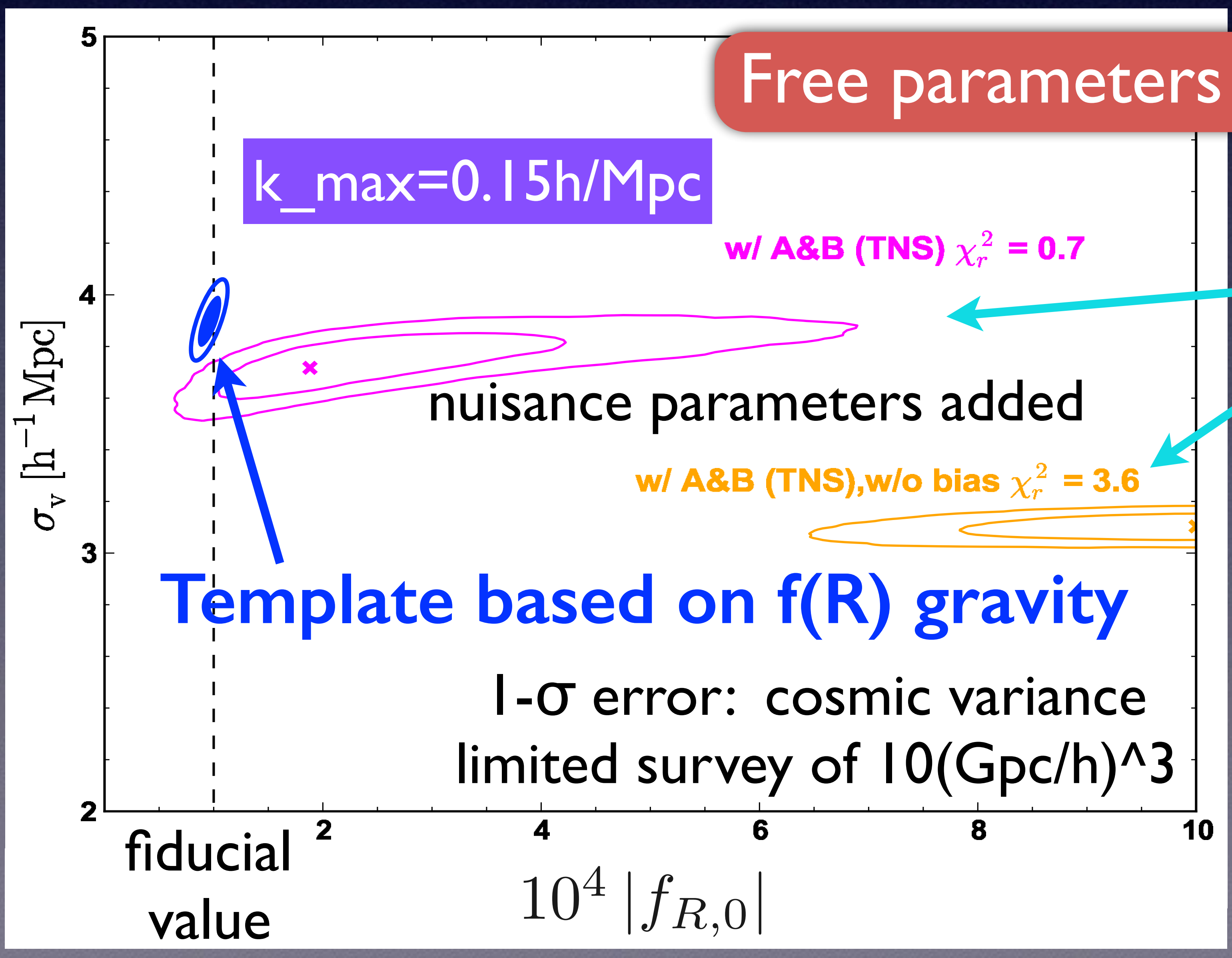


Need for a consistent treatment

GR-based template can lead to a biased constraint

RSD (monopole & quadrupole)

Fitting perturbation theory template to DM simulations



GR-based template

$$P_\ell^{\rm (GR)}(k;f)$$

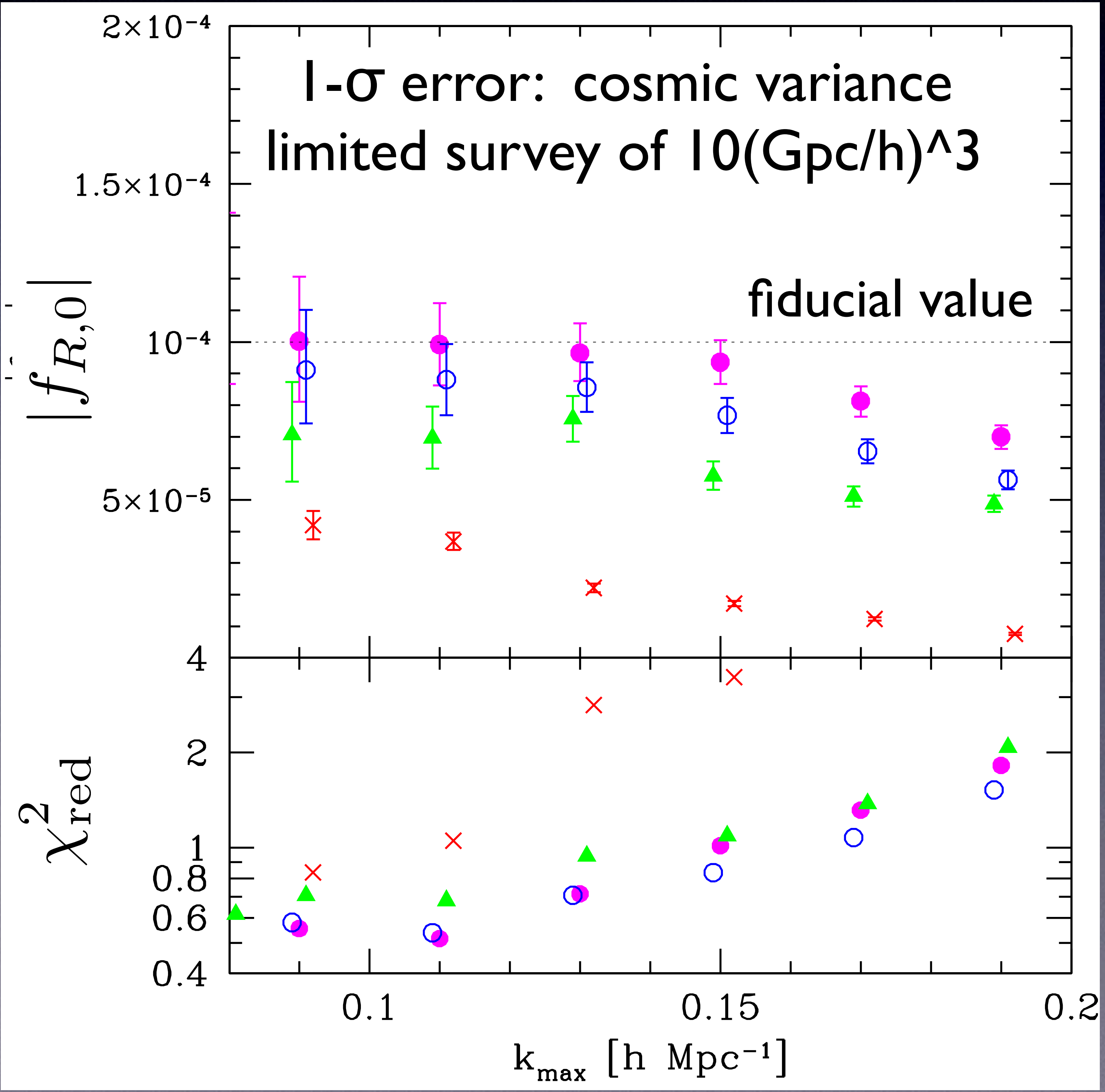
f(R) gravity

AT, Koyama, Hiramatsu & Oka ('14)

(See Barriere et al. '16 for DGP)

Need for an accurate template

Small flaw in RSD model can lead to a biased result



Free parameters : $|f_{R,0}|, \;\; \sigma_{\rm v}$

- TNS model
- TNS, but w/ A & B of GR
- Streaming (w/o A & B)
- Nonlinear Kaiser (w/o A, B, & damping)

AT, Koyama, Hiramatsu & Oka ('14)

Perturbation theory template

Kernel reconstruction approach AT ('16) in prep.

$$\theta \equiv \frac{\nabla \cdot \boldsymbol{v}}{a\,H}$$

PT kernel

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

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$$\delta^{(n)}(\boldsymbol{k};t) = \int \frac{d^3\boldsymbol{k}_1 \cdots d^3\boldsymbol{k}_n}{(2\pi)^{3(n-1)}}\,\delta_{\rm D}(\boldsymbol{k}-\boldsymbol{k}_{12\cdots n})F_n(\boldsymbol{k}_1,\cdots,\boldsymbol{k}_n;t)\,\delta_0(\boldsymbol{k}_1)\cdots\delta_0(\boldsymbol{k}_n),$$

$$\theta^{(n)}(\boldsymbol{k};t) = \int \frac{d^3\boldsymbol{k}_1 \cdots d^3\boldsymbol{k}_n}{(2\pi)^{3(n-1)}}\,\delta_{\rm D}(\boldsymbol{k}-\boldsymbol{k}_{12\cdots n})G_n(\boldsymbol{k}_1,\cdots,\boldsymbol{k}_n;t)\,\delta_0(\boldsymbol{k}_1)\cdots\delta_0(\boldsymbol{k}_n),$$

Numerically solving evolution eqs. for standard PT kernels

$$\widehat{\boldsymbol{\mathcal{L}}}(k_{1\cdots n})\begin{pmatrix} F_n(\boldsymbol{k}_1,\cdots,\boldsymbol{k}_n;a) \\ G_n(\boldsymbol{k}_1,\cdots,\boldsymbol{k}_n;a)\end{pmatrix} = \begin{pmatrix} S_n(\boldsymbol{k}_1,\cdots,\boldsymbol{k}_n;a) \\ T_n(\boldsymbol{k}_1,\cdots,\boldsymbol{k}_n;a)\end{pmatrix}$$

Linear operator

mode-coupling including nonlinear 5th force

Plugging PT kernels into RSD model

AT, Nishimichi & Saito ('10)

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

free parameter

Each term can be constructed with PT kernels based on standard or resummed PT calculations

Perturbation theory template

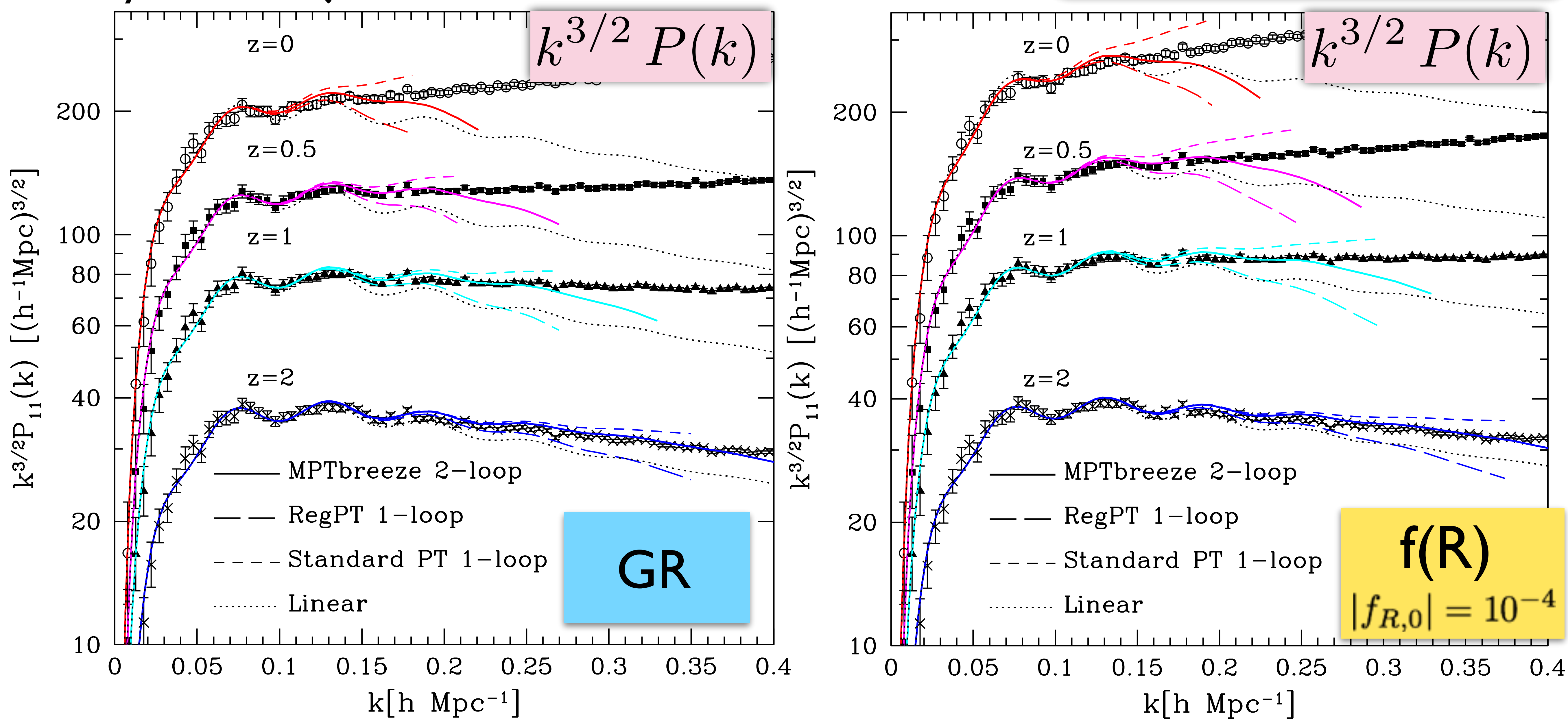
All predictions are made from PT kernels up to 3rd order (i.e., F_2, F_3)

in real space

AT ('16) in prep.

$$f(R) \simeq -16\pi\, G\, \rho_\Lambda + |f_{R,0}|\, \frac{R_0^2}{R}$$

N-body data: Baojiu Li



Perturbation theory template

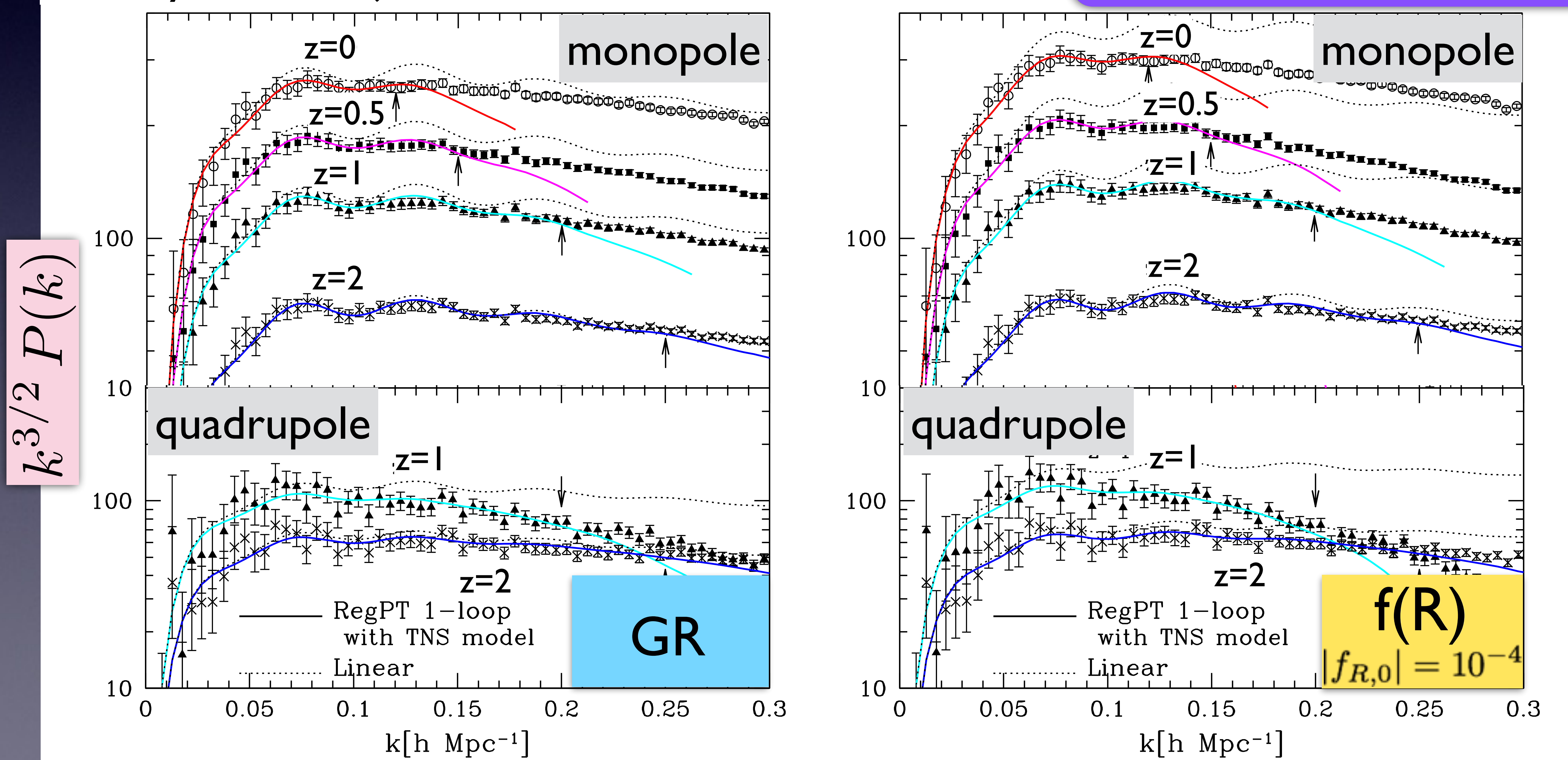
All predictions are made from PT kernels up to 3rd order (i.e., *F*2, *F*3)

in redshift space

AT et al. ('14)

$$f(R) \simeq -16\pi G \rho_\Lambda + |f_{R,0}| \frac{R_0^2}{R}$$

N-body data: Baojiu Li



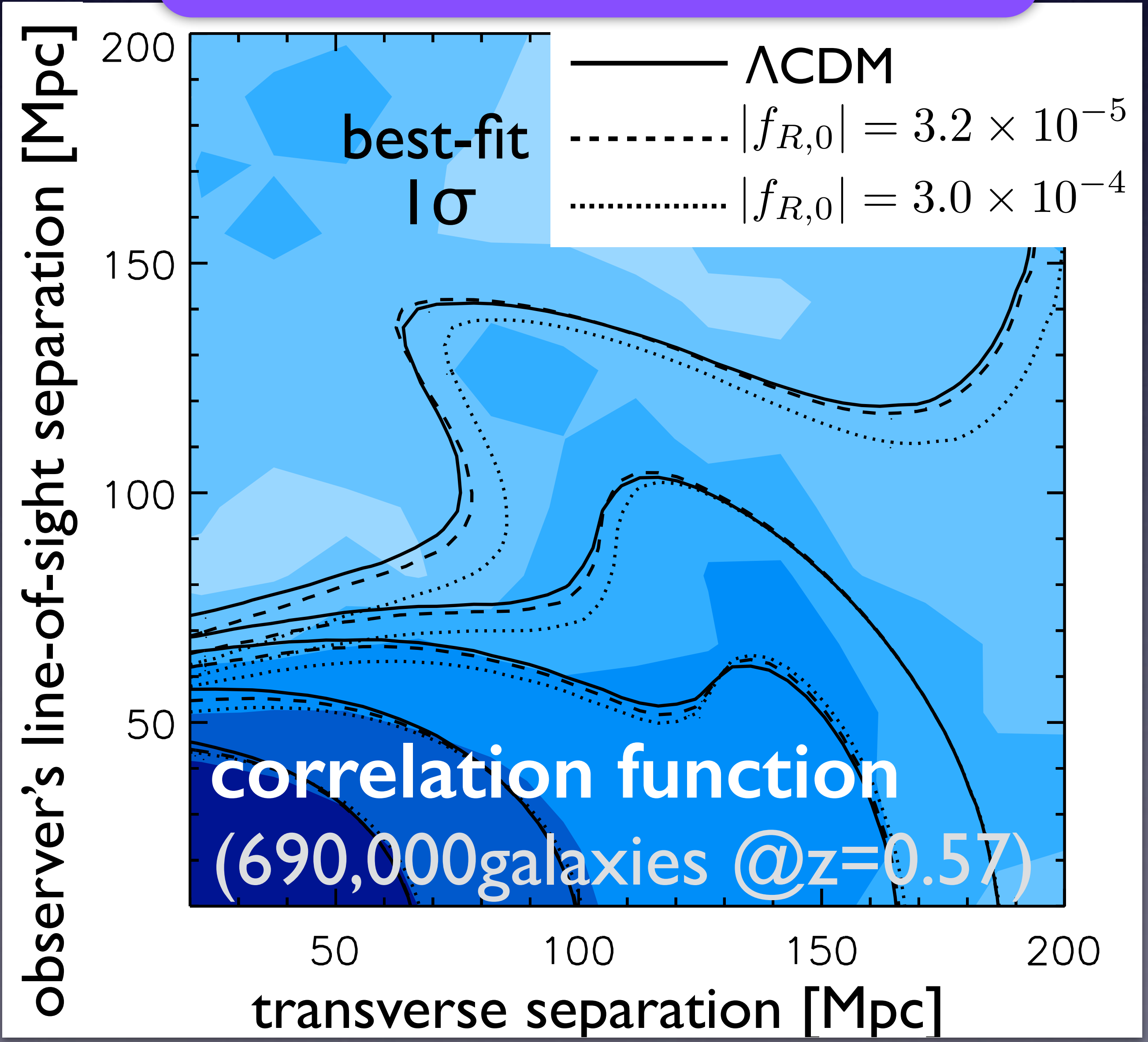
Consistent modified gravity analysis

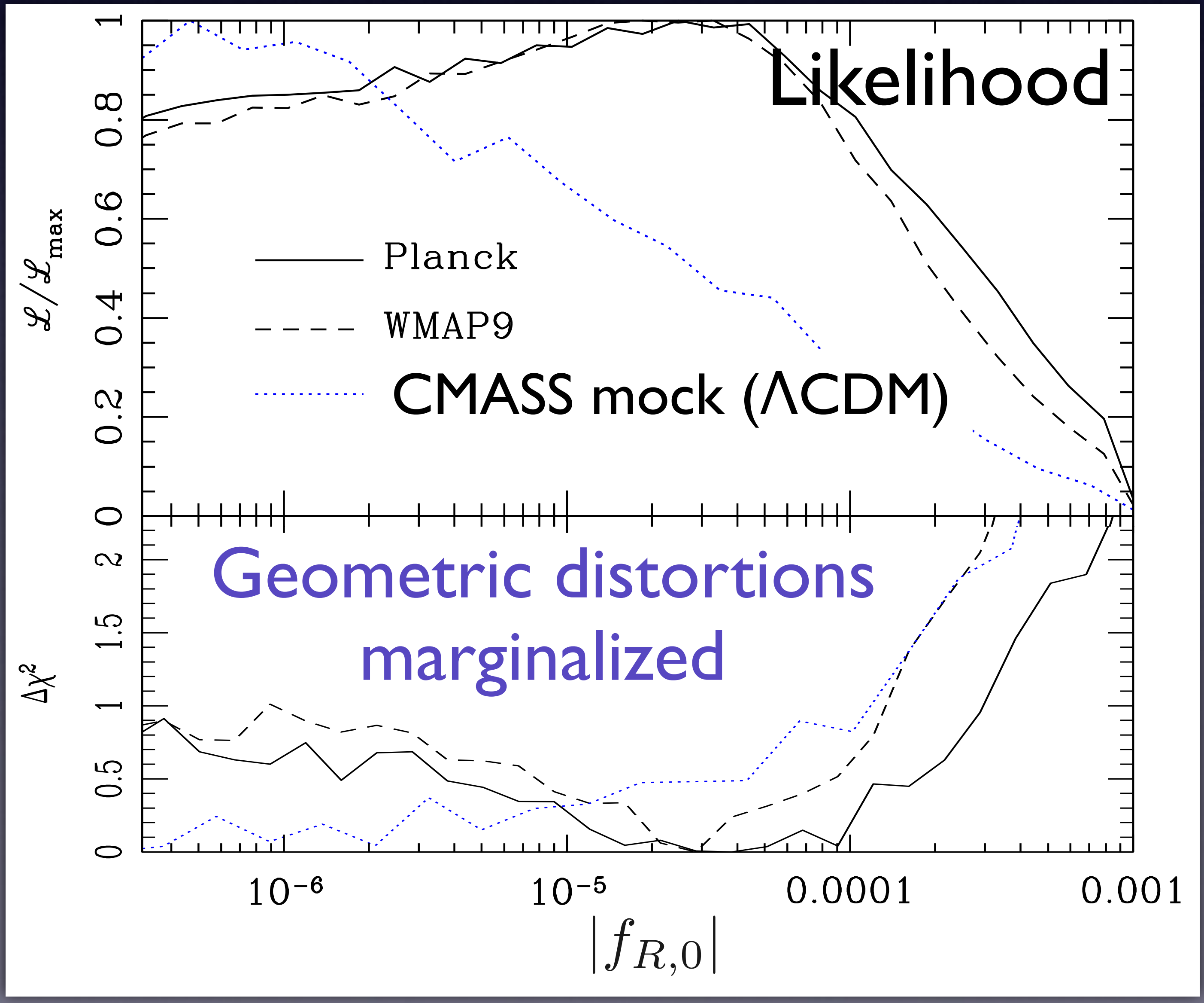
Y-S.Song, AT, Linder, Koyama et al. ('15)

Application of PT template to RSD measurement in BOSS DR11

$$f(R) \simeq -16\pi G \rho_\Lambda + |f_{R,0}| \frac{R_0^2}{R}$$

$$|f_{R,0}| < 8 \times 10^{-4} \quad (2\sigma)$$

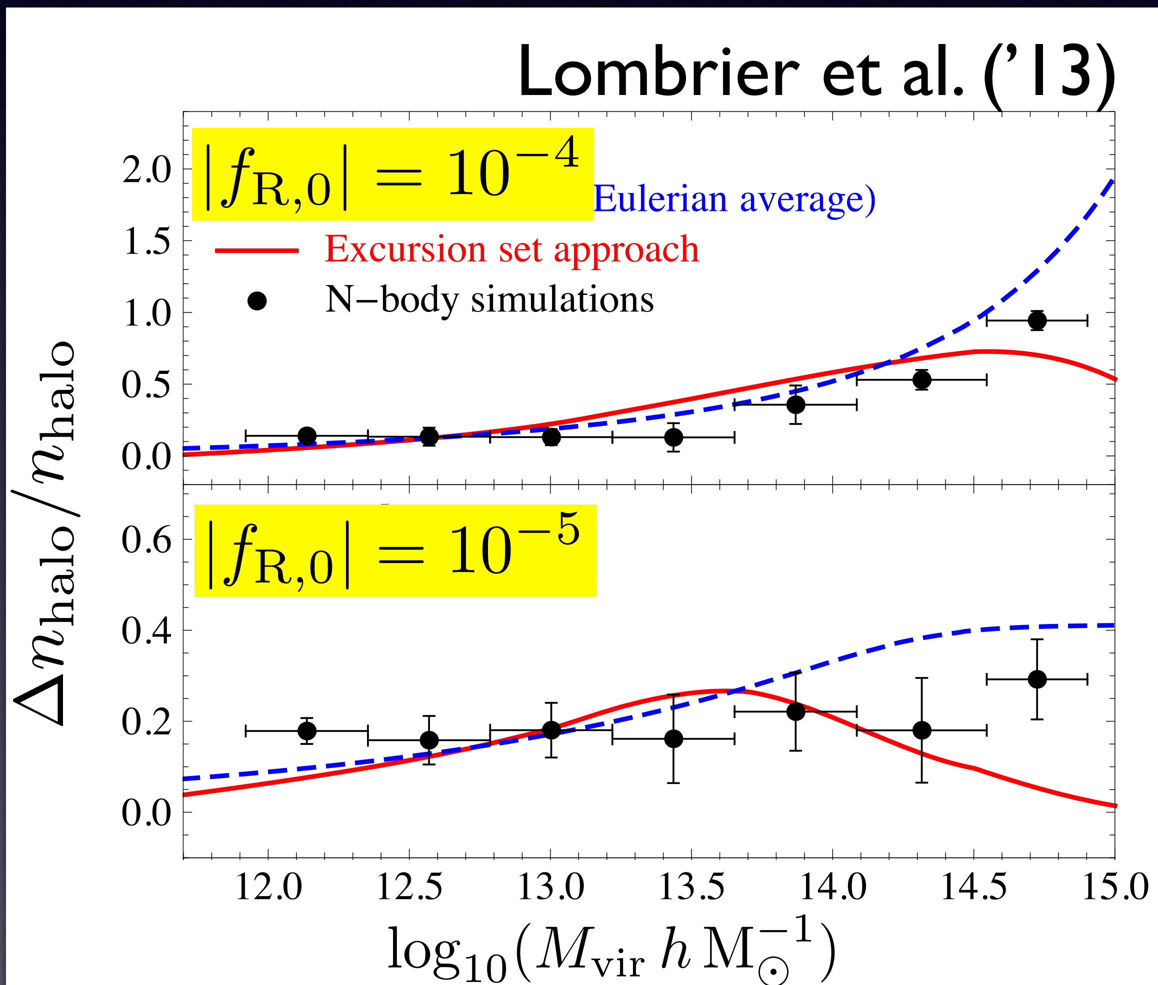




Cluster constraint on f(R) gravity

Abundance

Ineffective screening increases massive halos

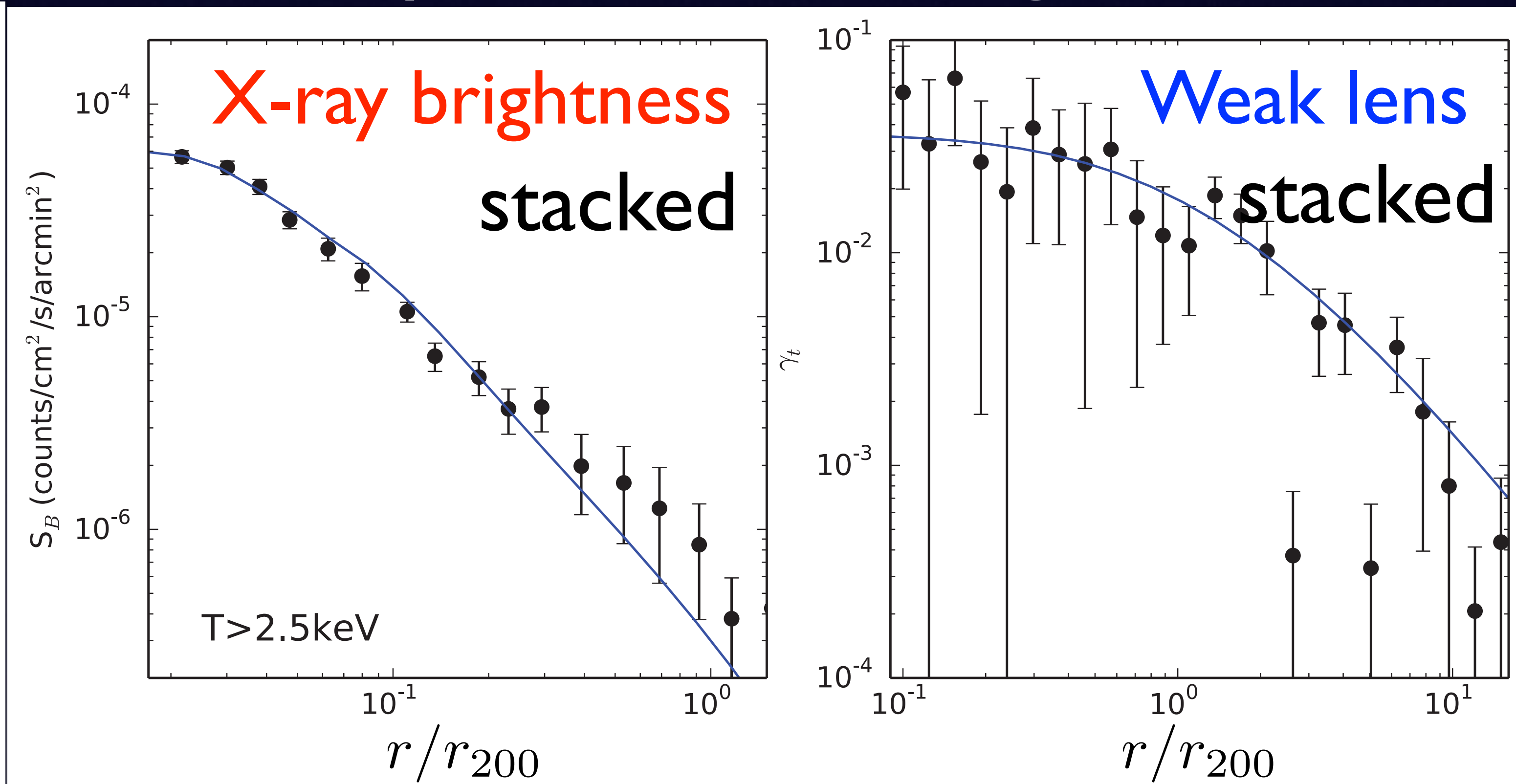


$$|f_{\mathrm{R},0}| < 2.6 \times 10^{-5}\,(2\sigma)$$

Cataneo et al. ('15)

X-ray & Lensing profiles

5th force changes relation btw. dynamical & lensing masses



$$|f_{\mathrm{R},0}| < 6 \times 10^{-5}\,(2\sigma)$$

Terukina et al. ('14); Wilcox et al. ('15)

Constraints on f(R): summary

Upper bound (2σ)

$$f(R) \simeq -16\pi G \rho_\Lambda + |f_{R,0}| \frac{R_0^2}{R}$$

Scale	Scale	$\log_{10}\lvert f_{R0}\rvert$
Solar system (Hu & Sawicki 2007)	pc	−6
Dwarf galaxies (Jain et al. 2013)	kpc	−6.3
Coma cluster (Terukina et al. 2014)	Mpc	−4.2
Cluster abundance (Cataneo et al. **2015**)	Mpc	−4.6
Cluster stack (Wilcox et al. **2015**)	Mpc	−4.2
Clustering ratio (Bel et al. **2015**)	20Mpc	−4.3
CMB (Raveri et al. 2014)	Gpc	−3.0
RSD (Song, AT, et al. '15)	**50-150 Mpc**	**-3.1**

Small scale

Large scale

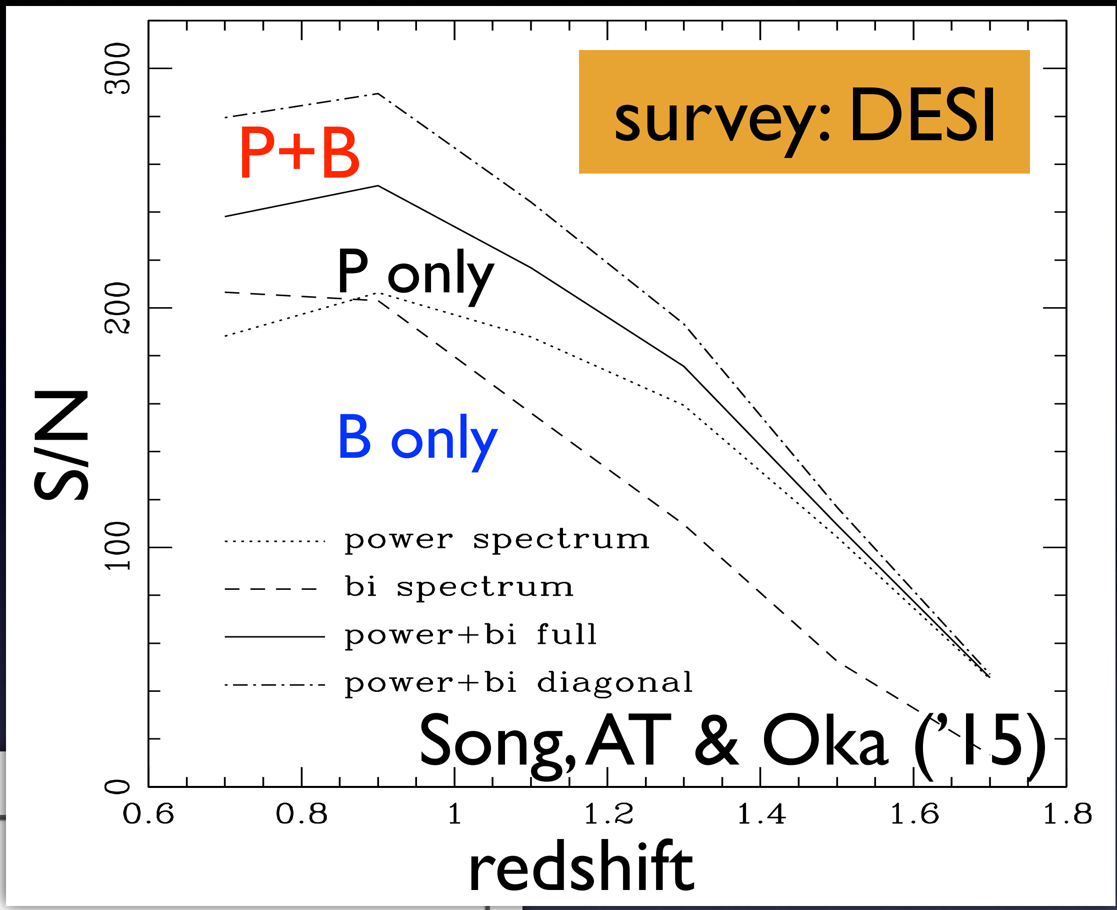
A broad parameter range is still allowed on large scales (>50Mpc)

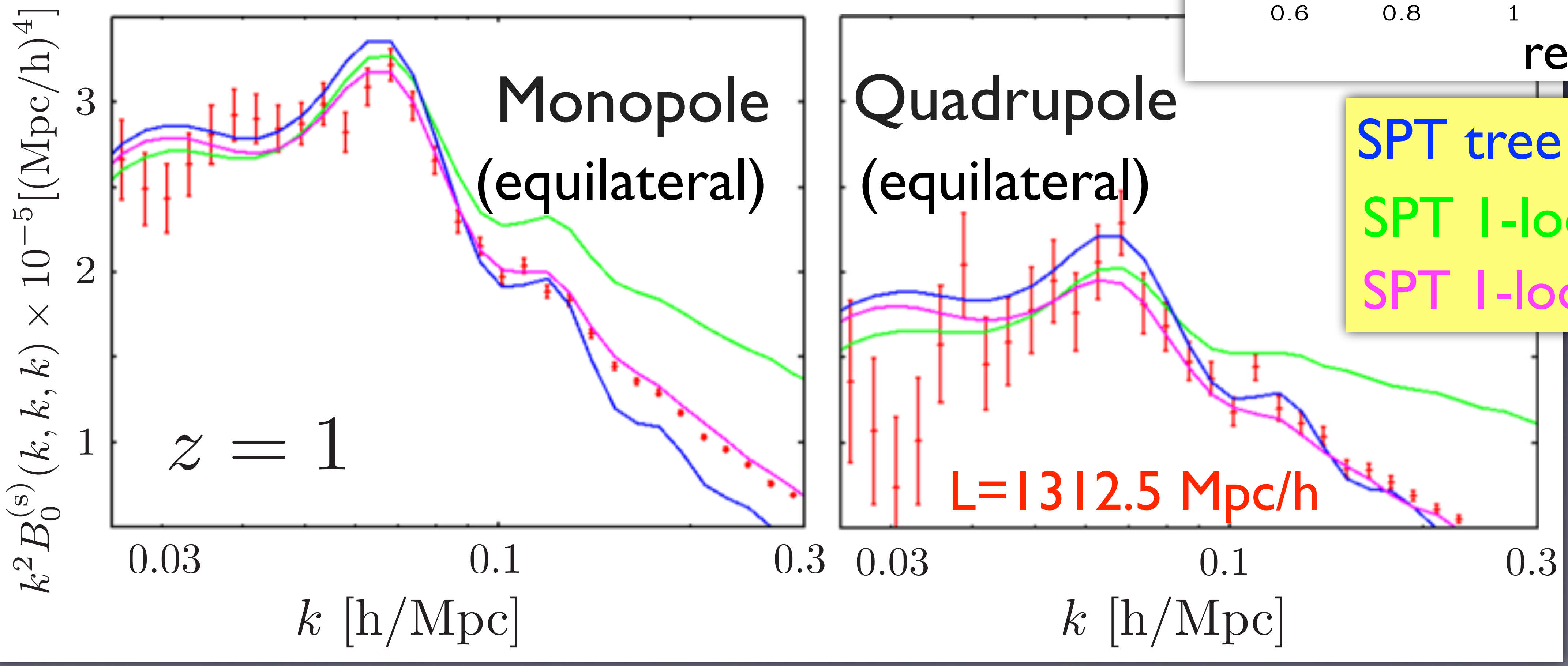
Wilcox et al. ('15), modified & updated

Narrowing constraints in future

Combination of bispectrum helps to tightly constrain modified gravity with RSD

(by more than factor of two)





Hashimoto, Rasera & AT (in prep.)

Summary

Testing modified gravity with large-scale structure observations

At linear regime

Model-independent test

Beyond linear regime

Test of specify modified gravity

→ crucial for consistent nonlinear modeling

weaker

constraints

stronger

Improving with future RSD: measurement of bispectrum

Cosmological test of gravity is still innovative area that deserves further investigation both theoretically & observationally