Large-scale redshift space distortions in modified gravity

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Outline

- Motivation
- Modified gravity models: f(R) and nDGP
- Simulations and galaxy catalogues
- Redshift space distortions

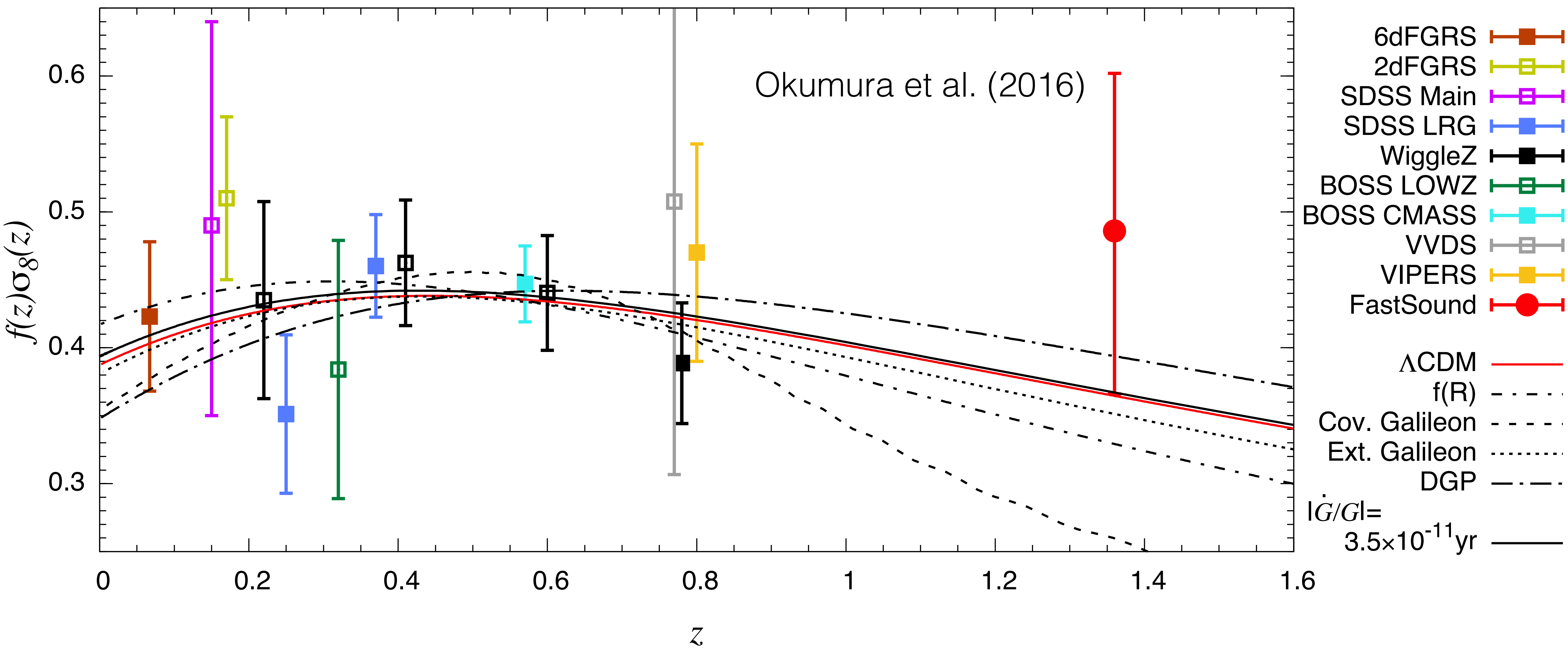
Based on: MNRAS, 485, 2194 (arXiv:1811.09197)

Motivation

- Future galaxy surveys, such as DESI and Euclid, will map the distribution of millions of galaxies to probe the evolution of dark energy and set constraints of models of modified gravity.

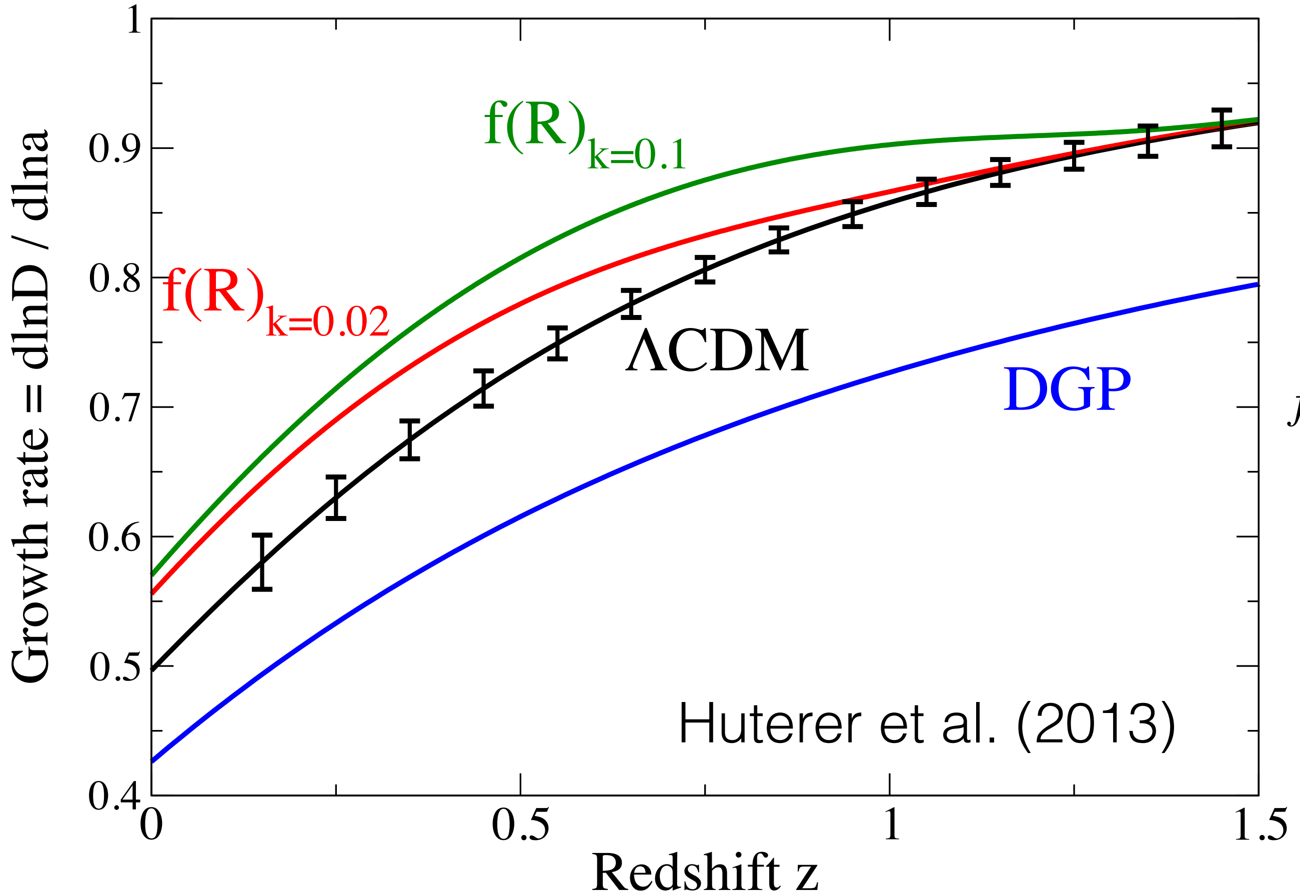
- Dark energy can be studied by two main cosmological observables: measurements of the expansion rate of the universe (e.g. Sn Ia) and measurements of the growth rate of structure of the universe (e.g. RSD)

Redshift space distortions: estimating the growth rate of structure

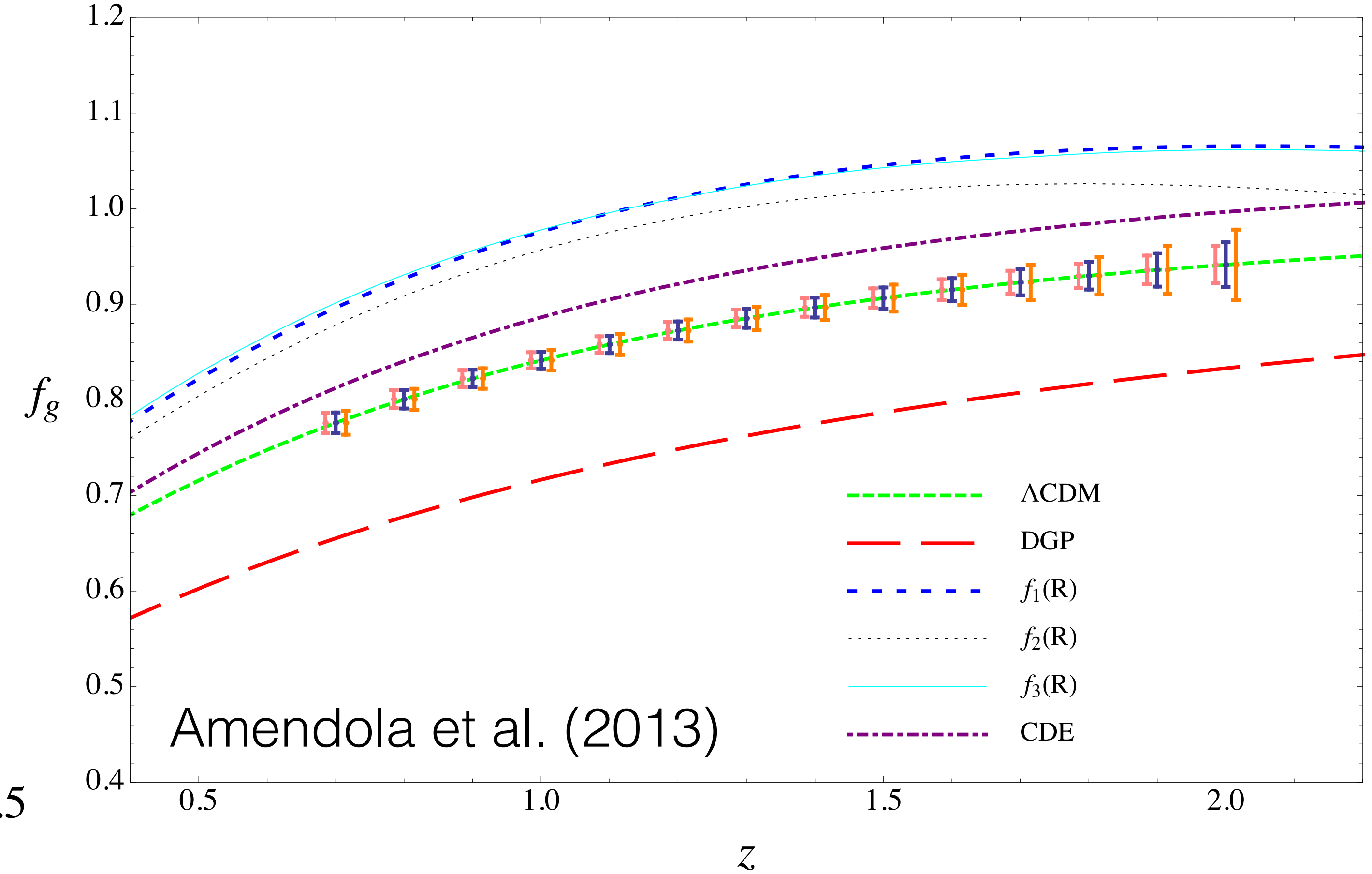


Redshift space distortions: estimating the growth rate of structure

DESI forecast



Euclid forecast



f(R) gravity

Add a function of the Ricci scalar, f(R), to the Einstein-Hilbert Action:

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}[R + f(R)] + \int d^4x\mathcal{L}_m$$

$$\nabla^2\phi = \frac{16\pi G}{3}\delta\rho - \frac{1}{6}\delta R(f_R),$$ Modified Poisson Eq.

$$\nabla^2\delta f_R = \frac{1}{3}[\delta R(f_R) - 8\pi G\delta\rho],$$ Constraint Eq.

Hu & Sawicki (2007)

$$f(R) = -m^2\frac{c_1(-R/m^2)^n}{c_2(-R/m^2)^n + 1}$$

Scalaron field:

$$f_R \equiv \frac{df(R)}{dR} = -n\frac{c_1}{c_2^2}\frac{(-R/m^2)^{(n+1)}}{[1 + (-R/m^2)^n]^2}$$ where $$\frac{c_1}{c_2^2} = -\frac{1}{n}\left[3\left(1 + 4\frac{\Omega_\Lambda}{\Omega_\mathrm{m}}\right)\right]^{n+1} f_{R0}$$

$n = 1, \quad |f_{R_0}| \leq 10^{-5}$ Solar system constraints

nDGP models

In this model, standard GR and the known matter fields are defined on a four-dimensional brane that is embedded in a five-dimensional bulk spacetime containing a five-dimensional generalisation of GR.

$$S = \int_{\rm brane} {\rm d}^4x\sqrt{-g}\left(\frac{R}{16\pi G}\right) + \int {\rm d}^5x\sqrt{-g^{(5)}}\left(\frac{R^{(5)}}{16\pi G^{(5)}}\right) + S_m(g_{\mu\nu},\psi_i)$$

with

$$r_c = \frac{1}{2}\frac{G^{(5)}}{G}$$

Expansion rate

$$H(a) = H_0\sqrt{\Omega_{\rm m0}a^{-3} + \Omega_{\rm DE}(a) + \Omega_{r_c}} - \sqrt{\Omega_{r_c}}$$

where

$$\Omega_{r_c} = \frac{1}{4H_0^2 r_c^2}$$

Structure formation

$$\nabla^2\Phi = 4\pi G a^2\delta\rho_m + \frac{1}{2}\nabla^2\varphi,$$

$$\nabla^2\varphi = -\frac{r_c^2}{3\beta a^2}\left[(\nabla^2\varphi)^2 - (\nabla_i\nabla_j\varphi)^2\right] + \frac{8\pi G a^2}{3\beta}\delta\rho_m,$$

where

$$\beta = 1 + 2Hr_c\left(1 + \frac{\dot{H}}{3H^2}\right)$$

Growth of structure in MG models

The linear growth for the matter fluctuations in the gravity models can be obtained by solving the equation of the linear growth factor, D

$$D'' + \left(2 - \frac{3}{2}\Omega_{\rm m}(a)\right) D' - \frac{3}{2}\frac{G_{\rm eff}}{G}\Omega_{\rm m}(a)D = 0$$

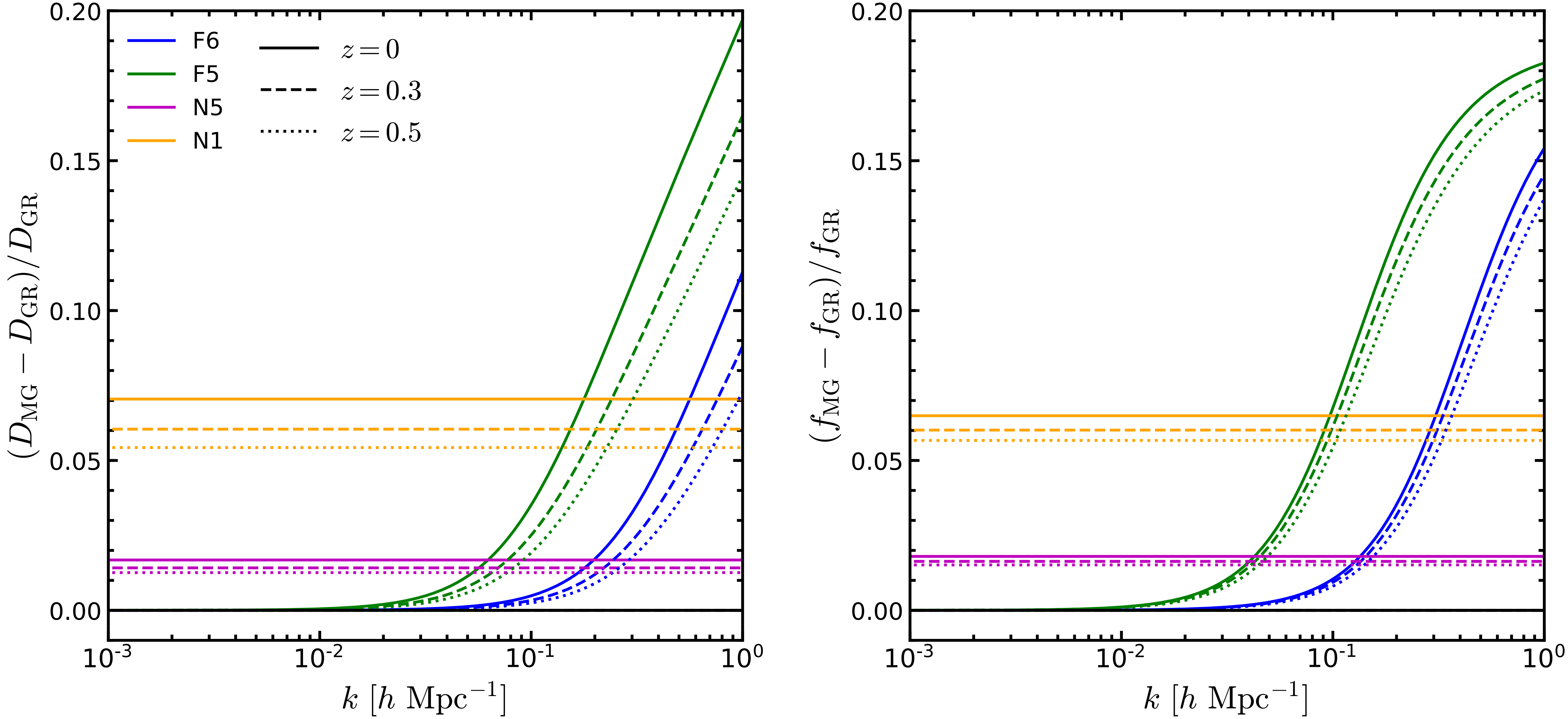
where ′ denotes a derivative with respect to ln(a) and $G_{\rm eff}$ takes values of

$$\frac{G_{\rm eff}}{G} = \begin{cases} 1 & \text{GR} \\ 1 + k^2/[3(k^2 + a^2 m_{f_R}^2)] & f(R) \\ 1 + 1/(3\beta) & \text{nDGP} \end{cases}$$

We define the linear growth rate, f, as

$$f \equiv \frac{{\rm d}\ln D}{{\rm d}\ln a}$$

Growth of structure in MG models



$$|f_{R0}| = 10^{-6}\ (\mathrm{F6}),\ |f_{R0}| = 10^{-5}\ (\mathrm{F5}),\ H_0 r_c = 5\ (\mathrm{N5}),\ H_0 r_c = 1\ (\mathrm{N1})$$

ELEPHANT (Extended LEnsing PHysics with ANalytical ray Tracing) Simulations

(Cautun et al. 2017, Hernández-Aguayo et al. 2018)

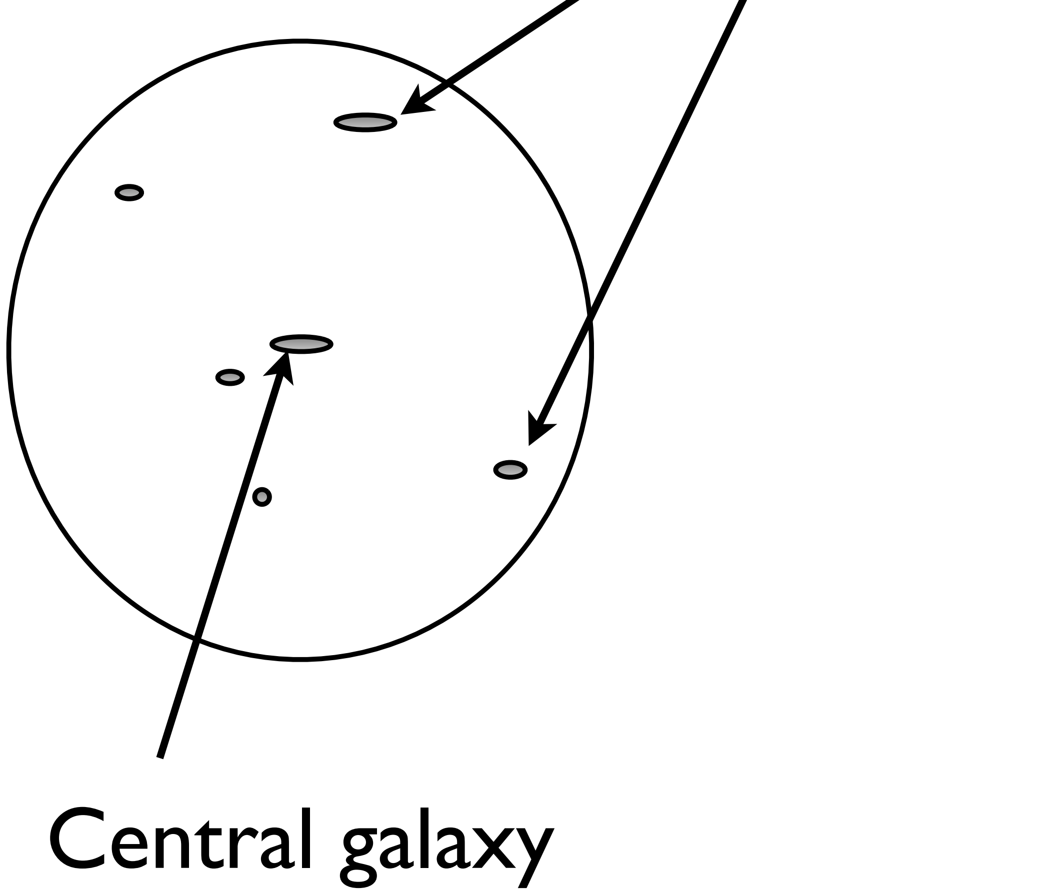
parameter	physical meaning	value
Ω_m	present fractional matter density	0.281
Ω_Λ	$1 - \Omega_m$	0.719
h	$H_0/(100 \text{ km s}^{-1}\text{Mpc}^{-1})$	0.697
n_s	primordial power spectral index	0.971
σ_8	r.m.s. linear density fluctuation	0.820
$\lvert f_{R0} \rvert$	Hu & Sawicki $f(R)$ parameter	0 (GR) 10^{-6} (F6), 10^{-5} (F5)
$H_0 r_c$	nDGP parameter	5.0 (N5), 1.0 (N1)
L_{box}	simulation box size	1024 h^{-1}Mpc
N_{p}	simulation particle number	1024^3
m_{p}	simulation particle mass	$7.78 \times 10^{10} h^{-1} M_\odot$
N_{dc}	domain grid cell number	1024^3
N_{ref}	refinement criterion	8

We use the outputs at z=0, 0.3 and 0.5

Halo occupation distribution

We assign a number of galaxies (central and satellites) to each halo

$$\rho_{\rm NFW} = \frac{\rho_{\rm s}}{(r/r_{\rm s})(1+r/r_{\rm s})^2}$$



Centrals are in the centre of their host dark matter halo. The average number of centrals that resides in a halo of mass M is denoted by:

$$\langle N_{\rm cen} \rangle = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{\log M - \log M_{\rm min}}{\sigma_{\log M}}\right)\right]$$

Satellites are orbiting inside a larger host halos. The average number of satellites that resides in a halo of mass M is denoted by:

$$\langle N_{\rm sat} \rangle = \langle N_{\rm cen} \rangle \left(\frac{M - M_0}{M_1}\right)^{\alpha}$$

The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: a large sample of mock galaxy catalogues *BOSS CMASS sample*

Marc Manera[1⋆], Roman Scoccimarro[2], Will J. Percival[1], Lado Samushia[1], Cameron

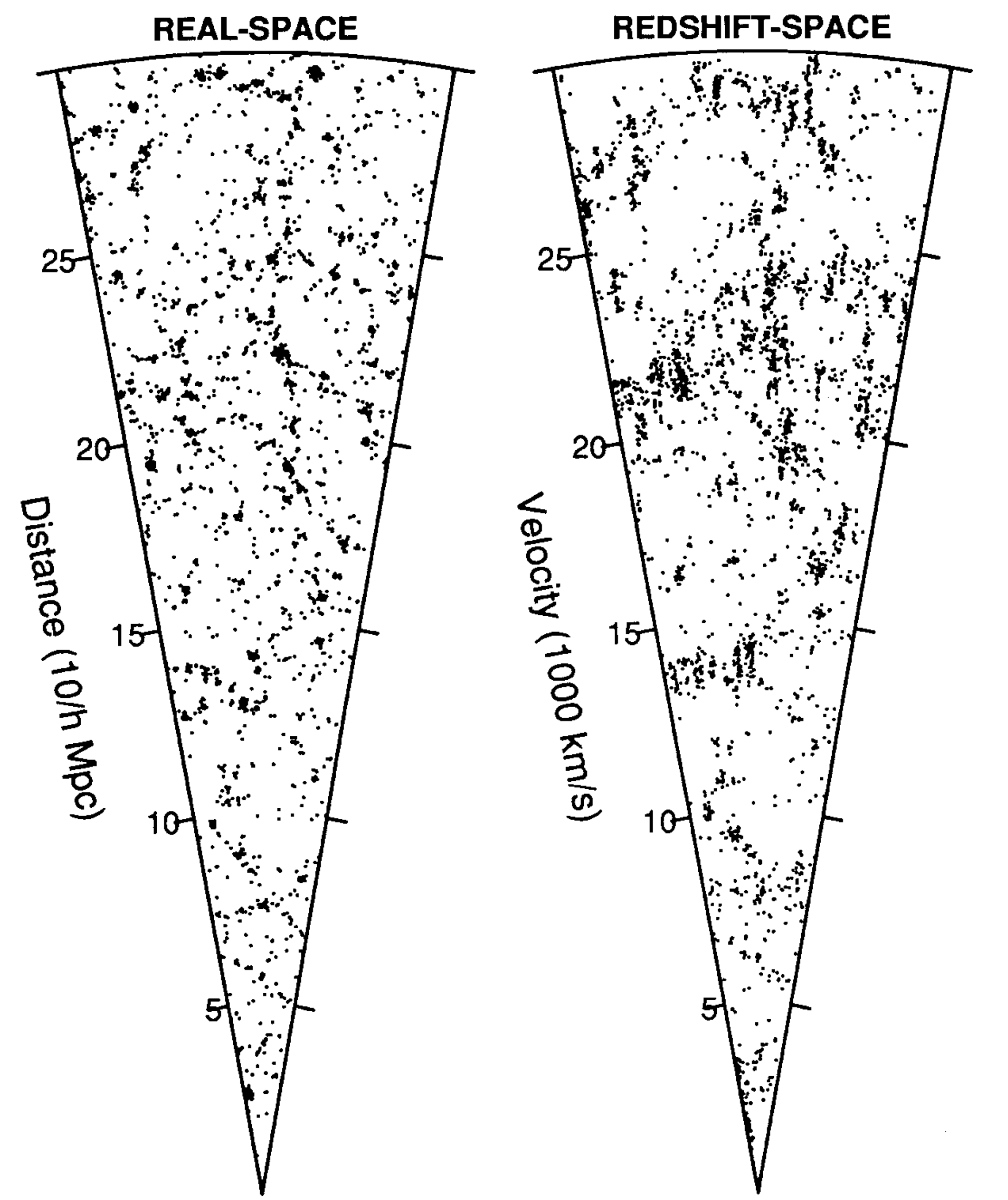
$$\log(M_{min}) = 13.09$$
$$\log(M_1) = 14.00$$
$$\log(M_0) = 13.077$$
$$\sigma_{\log M} = 0.596$$
$$\alpha = 1.0127.$$

We 'tuned' the HOD parameters such that the galaxy number densities and the real-space galaxy two-point correlation functions in the modified gravity models match those in GR to within 1 ~ 2%.

Redshift space distortions

Distortions produced by the peculiar velocity of galaxies that changes the line-of-sight position

$$\mathbf{s} = \mathbf{r} + \frac{(1+z)v_{\parallel}}{H(z)}\hat{e}_{\parallel}$$

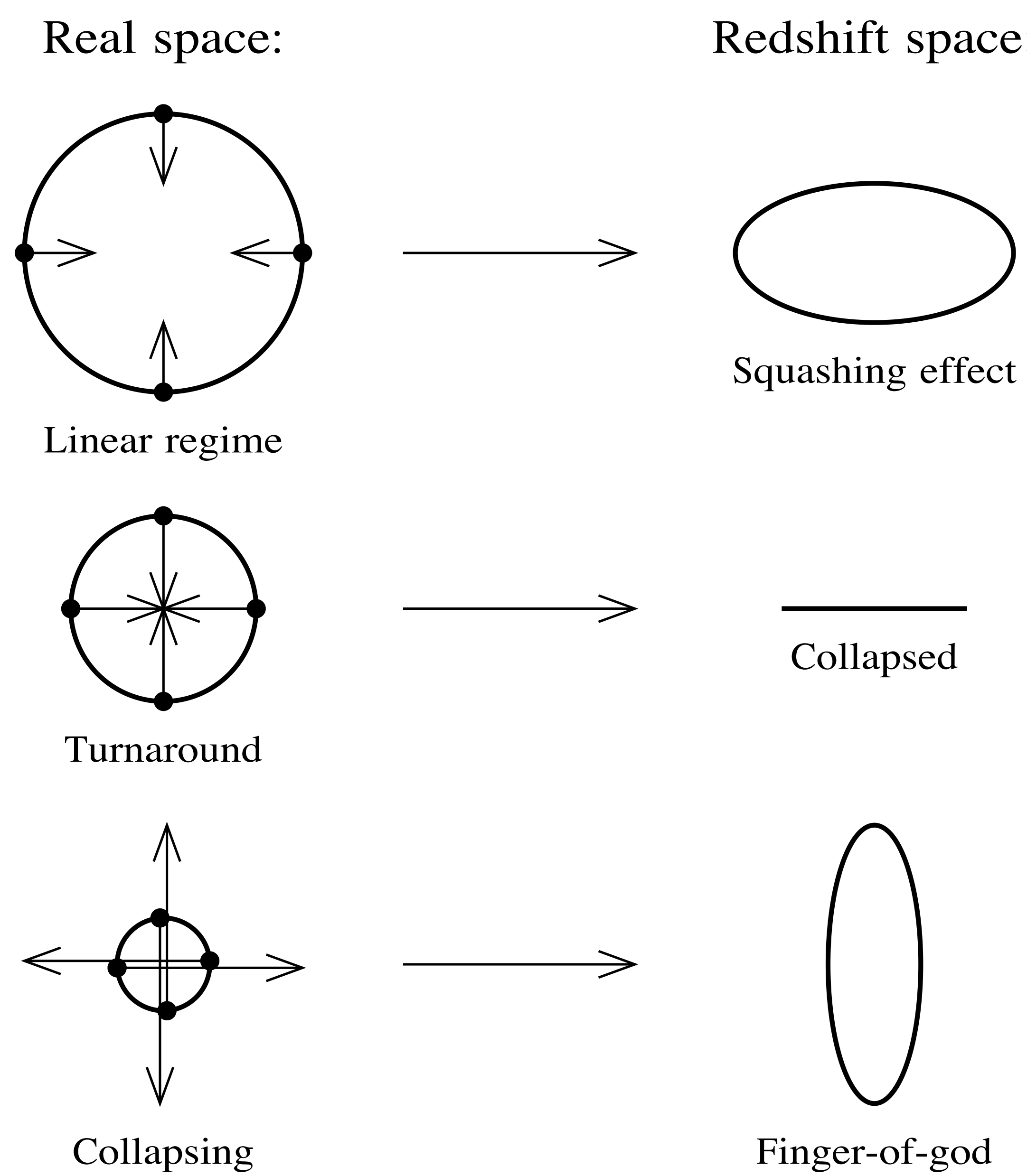


Praton et al (1997)

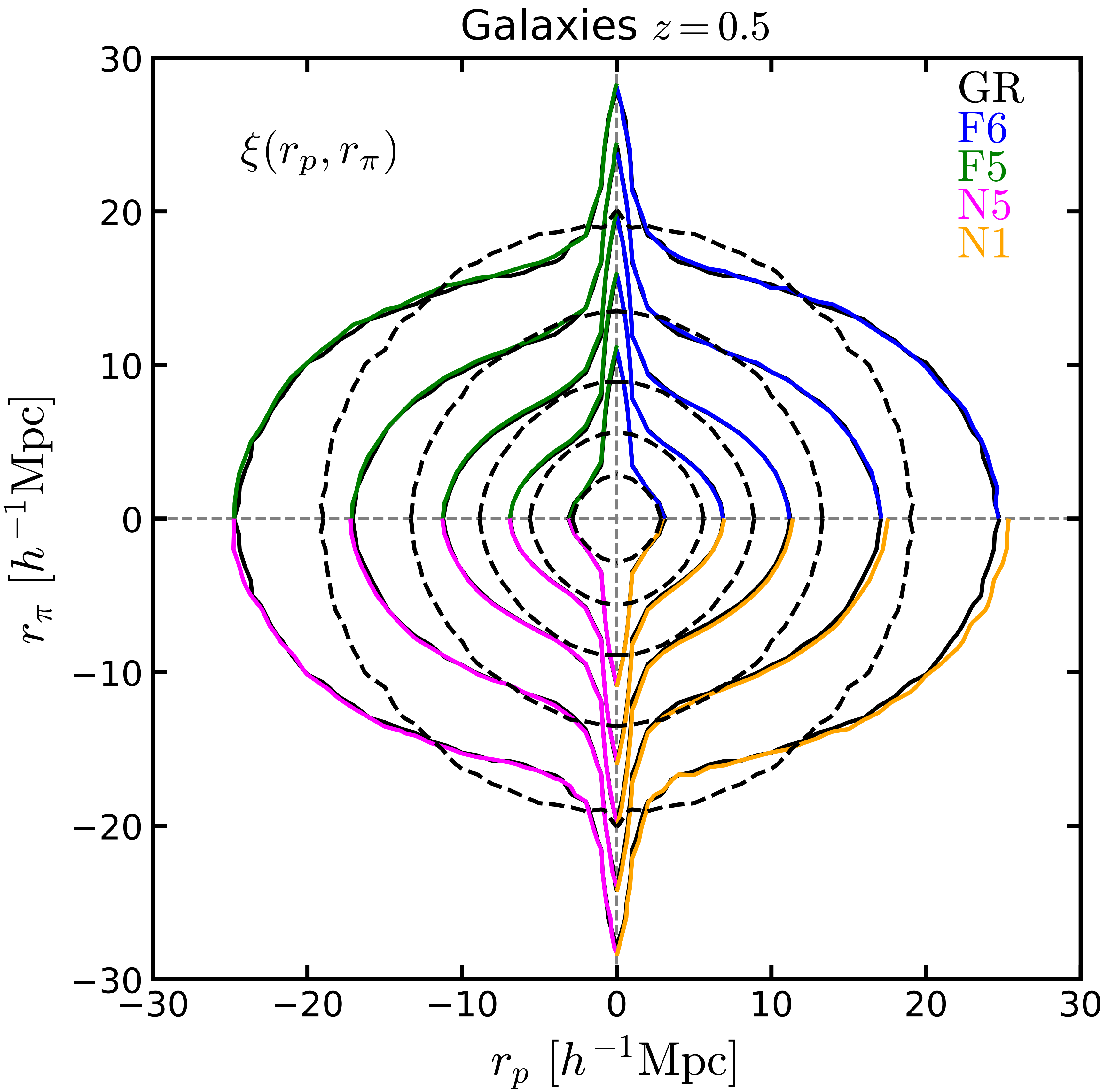
Redshift space distortions

- Kaiser effect on large scales due to the infall of galaxies

- Finger-of-God effect on small scale due to virialized random motion



RSDs: quantify anisotropic clustering



Modelling RSDs: linear theory

Kaiser (1987)

Hamilton (1992)

$$P_s(k,\mu) = (1+\beta\mu_k^2)^2 P_r(k) \longrightarrow \xi(s,\mu) = [1+\beta(\partial/\partial z)^2(\nabla^2)^{-1}]^2\xi(r)$$

$$\beta \equiv \frac{f}{b}$$ (distortion parameter)

$$f = \frac{\mathrm{d}\ln D}{\mathrm{d}\ln a}$$ (linear growth rate)

$$b = \sqrt{\frac{\xi_{\mathrm{gg}}}{\xi_{\mathrm{mm}}}}$$ (linear bias)

The correlation function reduces to:

$$\xi(s,\mu) = \xi_0(s)P_0(\mu) + \xi_2(s)P_2(\mu) + \xi_4(s)P_4(\mu)$$

Where:

$$\xi_0(s) = \left(1 + \frac{2\beta}{3} + \frac{\beta^2}{5}\right)\xi(r)\,,$$

$$\xi_2(s) = \left(\frac{4\beta}{3} + \frac{4\beta^2}{7}\right)[\xi(r) - \bar{\xi}(r)]\,,$$

$$\xi_4(s) = \frac{8\beta^2}{35}\left[\xi(r) + \frac{5}{2}\bar{\xi}(r) - \frac{7}{2}\bar{\bar{\xi}}(r)\right]\,,$$

Modelling RSDs: linear theory

$$R(s) \equiv \frac{\xi_0(s)}{\xi(r)} = 1 + \frac{2\beta}{3} + \frac{\beta^2}{5}$$

$$Q(s) \equiv \frac{\xi_2(s)}{\xi_0(s) - \bar{\xi}_0(s)} = \frac{(4/3)\beta + (4/7)\beta^2}{1 + (2/3)\beta + (1/5)\beta^2}$$

Modelling RSDs: linear theory

$$R(s) \equiv \frac{\xi_0(s)}{\xi(r)} = 1 + \frac{2\beta}{3} + \frac{\beta^2}{5}$$

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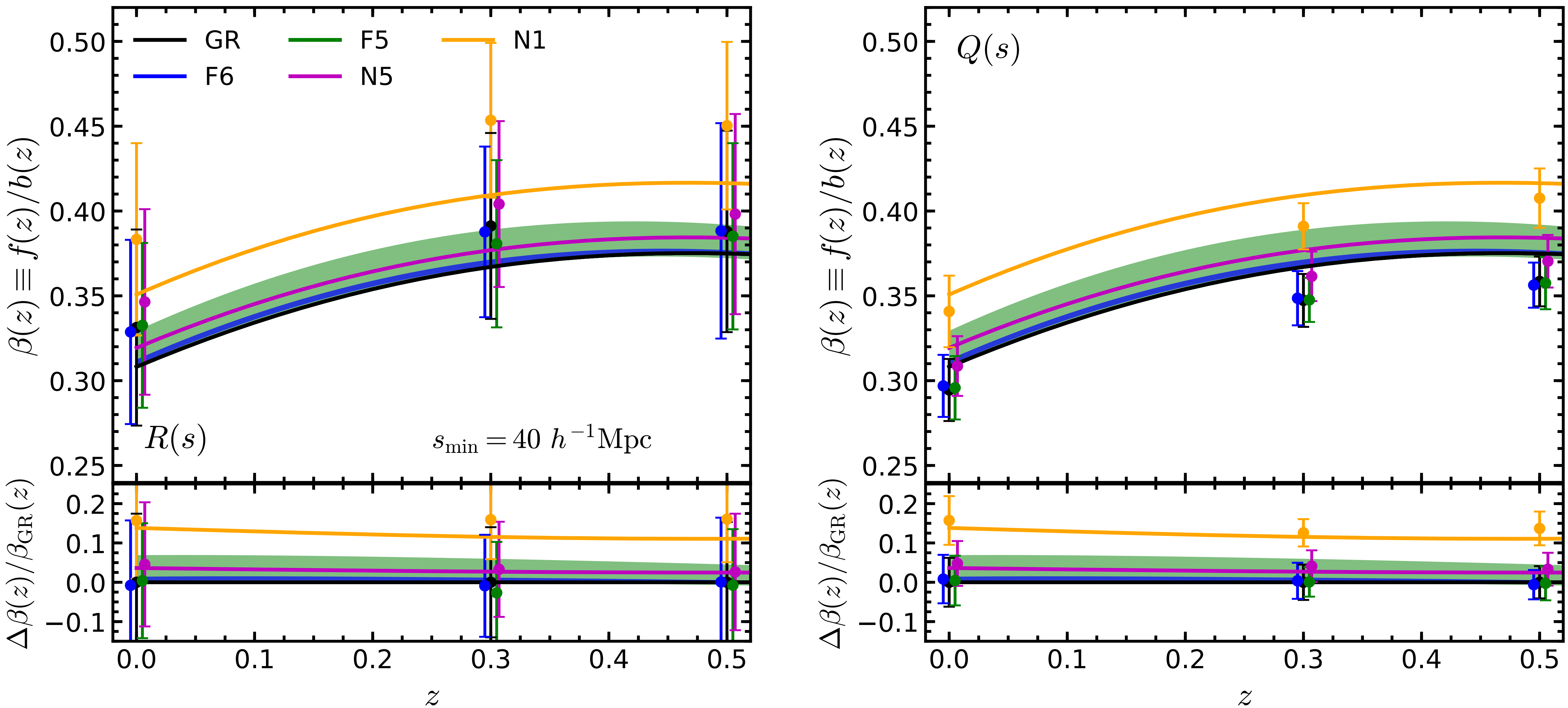

$s_{\rm max} = 150\ h^{-1}{\rm Mpc}$

Modelling RSDs: nonlinear model

Crocce & Scoccimarro (2006), Sánchez et al (2017)

Power spectrum:

$$P(k,\mu) = P_{\rm novir}(k,\mu)D_{\rm FoG}(k,\mu)$$

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Power spectrum:

$$P(k,\mu) = P_{\rm novir}(k,\mu) D_{\rm FoG}(k,\mu)$$

Non-virial power spectrum

$$P_{\rm novir}(k,\mu) = P^{(1)}_{\rm novir}(k,\mu) + (k\mu f) P^{(2)}_{\rm novir}(k,\mu) + (k\mu f)^2 P^{(3)}_{\rm novir}(k,\mu)$$

Modelling RSDs: nonlinear model

Crocce & Scoccimarro (2006), Sánchez et al (2017)

Power spectrum:

$$P(k,\mu) = P_{\rm novir}(k,\mu) D_{\rm FoG}(k,\mu)$$

Nonlinear power spectrum

$$P_{\rm novir}(k,\mu) = P^{(1)}_{\rm novir}(k,\mu) + (k\mu f) P^{(2)}_{\rm novir}(k,\mu) + (k\mu f)^2 P^{(3)}_{\rm novir}(k,\mu)$$

where:

$$P^{(1)}_{\rm novir}(k,\mu) = P_{\rm gg}(k) + 2f\mu^2 P_{\rm g\theta}(k) + f^2\mu^4 P_{\theta\theta}(k)\,,$$

$$P^{(2)}_{\rm novir}(k,\mu) = \int \frac{{\rm d}^3p}{(2\pi)^3} \frac{p_z}{p} \left[B_\sigma(\mathbf{p}, \mathbf{k}-\mathbf{p}, -\mathbf{k}) - B_\sigma(\mathbf{p}, \mathbf{k}, -\mathbf{k}-\mathbf{p})\right]$$

$$P^{(3)}_{\rm novir}(k,\mu) = \int \frac{{\rm d}^3p}{(2\pi)^3} F(\mathbf{p}) F(\mathbf{k}-\mathbf{p})\,.$$

Modelling RSDs: nonlinear model

Crocce & Scoccimarro (2006), Sánchez et al (2017)

Power spectrum:

$$P(k,\mu) = P_{\rm novir}(k,\mu) D_{\rm FoG}(k,\mu)$$

Finger-of-God effect

$$D_{\rm FoG}(k,\mu) = \frac{1}{\sqrt{1+f^2k^2\mu^2 a_{\rm vir}^2}} \exp\left(\frac{-f^2k^2\mu^2\sigma_v^2}{1+f^2k^2\mu^2 a_{\rm vir}^2}\right)$$

Modelling RSDs: nonlinear model

Crocce & Scoccimarro (2006), Sánchez et al (2017)

Power spectrum:

$$P(k,\mu) = P_{\rm novir}(k,\mu) D_{\rm FoG}(k,\mu)$$

Fourier transform

$$\xi(s,\mu) = \frac{1}{(2\pi)^3}\int_0^\infty P(k,\mu)\, \exp(i\,\mathbf{k}\cdot\mathbf{s})\, {\rm d}^3 k$$

Modelling RSDs: nonlinear model

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Power spectrum:

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Fourier transform

$$\xi(s,\mu) = \frac{1}{(2\pi)^3} \int_0^\infty P(k,\mu)\, \exp(i\,\mathbf{k}\cdot\mathbf{s})\, \mathrm{d}^3k$$

$$\xi_l(s) = \frac{2l+1}{2} \int_{-1}^{1} \xi(s,\mu) P_l(\mu)\, \mathrm{d}\mu$$

Multipole moments

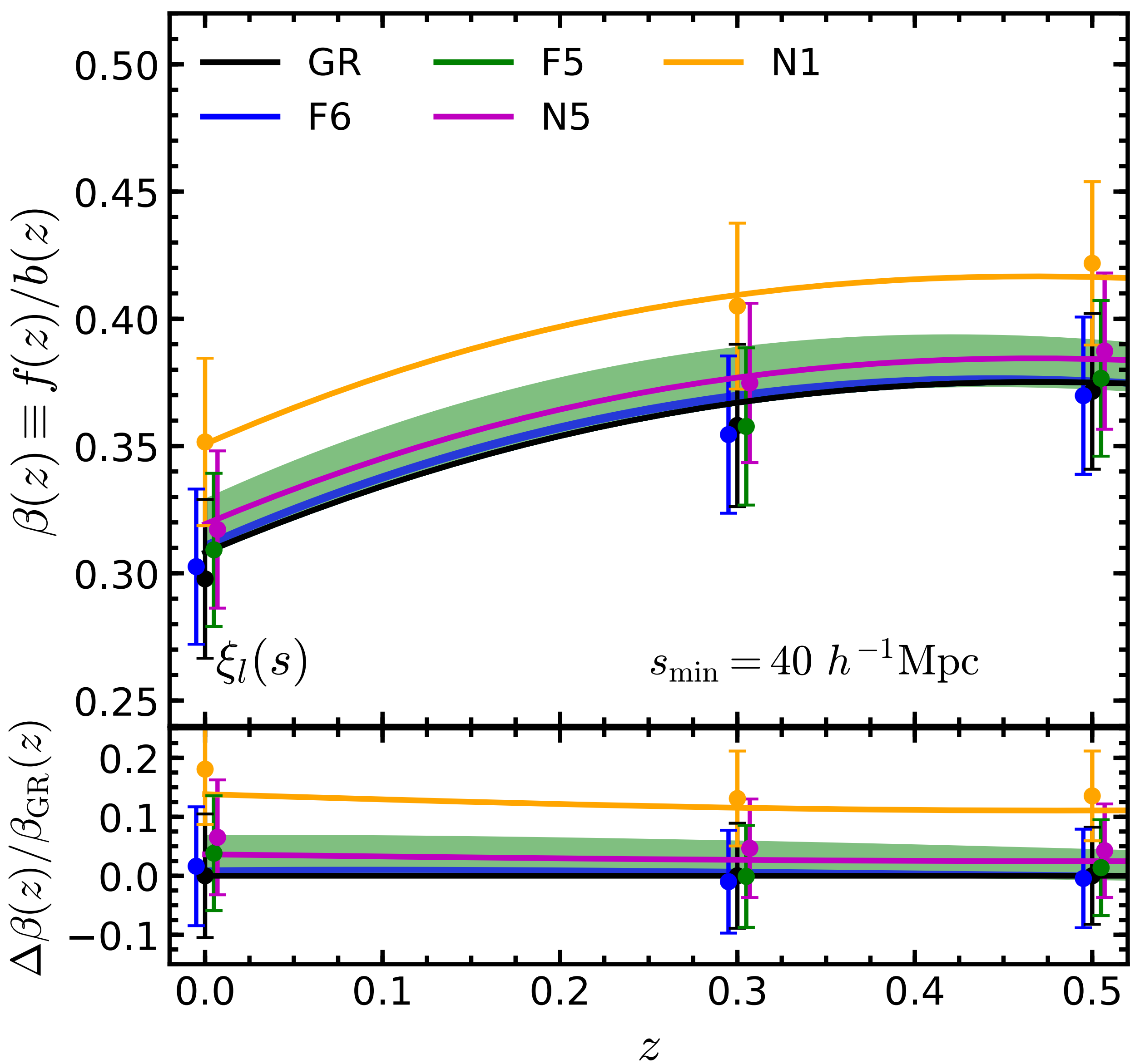
$$\xi_w(s) = \frac{1}{\mu_2 - \mu_1} \int_{\mu_1}^{\mu_2} \xi(s,\mu)\, \mathrm{d}\mu$$

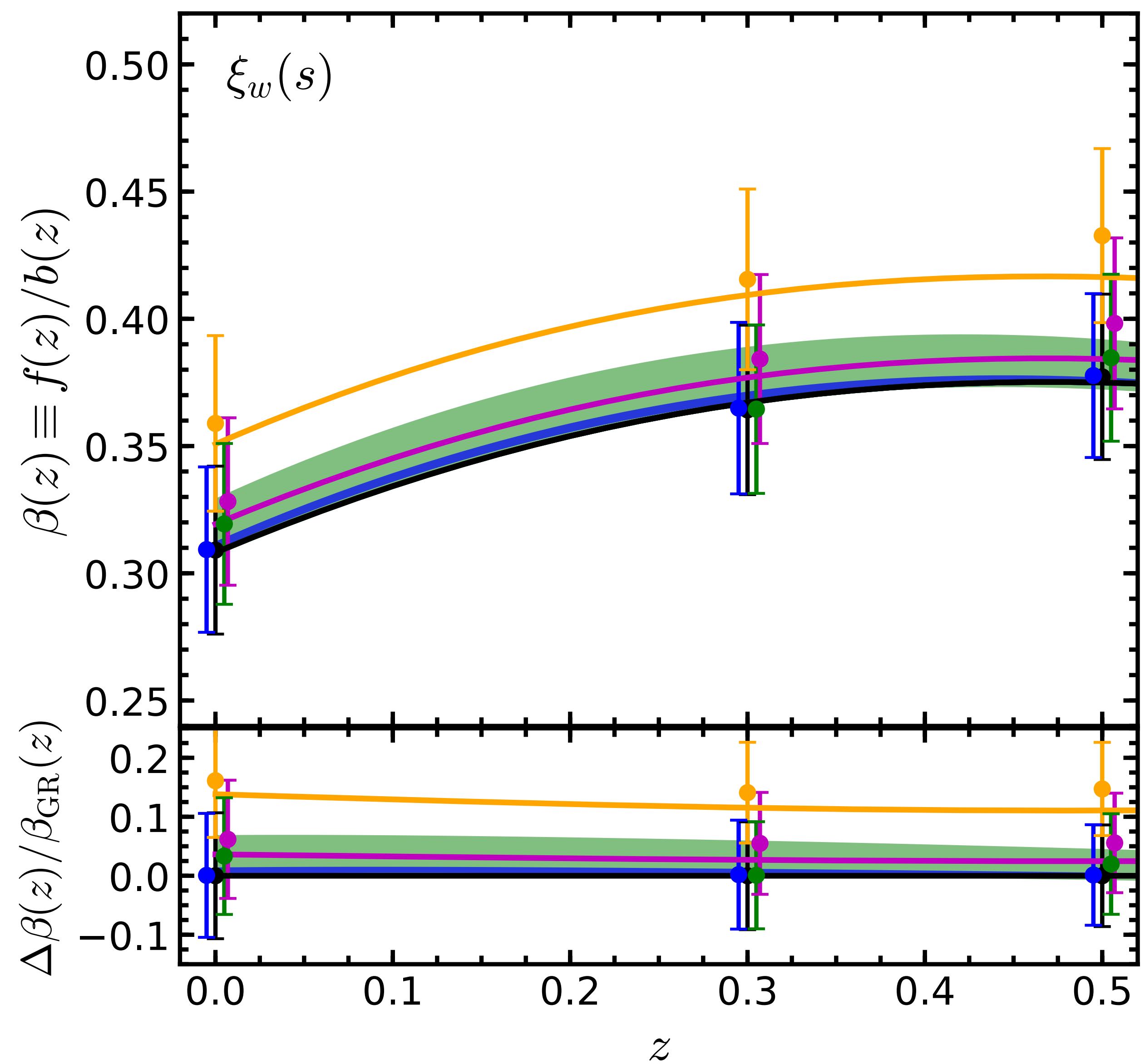
Clustering wedges

Modelling RSDs: nonlinear model

$$\xi_l(s) = \frac{2l+1}{2}\int_{-1}^{1} \xi(s,\mu) P_l(\mu)\ \mathrm{d}\mu$$

$$\xi_w(s) = \frac{1}{\mu_2-\mu_1}\int_{\mu_1}^{\mu_2} \xi(s,\mu)\ \mathrm{d}\mu$$





$s_{\rm max} = 150\ h^{-1}{\rm Mpc}$

Summary

- Measurements of redshift space distortions can help us to distinguish between gravity models.

- We found that the linear model fails to recover the true value of the distortion parameter.

- The fact that the nonlinear model produces reasonable results for modified gravity give us a means to measure a signature of modified gravity in the large-scale structure of the Universe.

- Despite the capability of distinguish between gravity models, our results suggest that the impact of RSD on f(R) gravity models is small enough to be differentiated from GR.