UNIVERSITY OF CAMBRIDGE

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Simulating cosmic structure formation in modified gravity models

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code comparison project collaborators: Hans A. Winther, Fabian Schmidt, Alexandre Barreira et al.

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Modified gravity models - Motivation

- need to drive accelerated expansion (large scales / low densities)

vacuum energy?

dynamical dark energy?

modified gravity?

- for modified gravity:
  - ➡ need to satisfy solar system constraints (small scales / dense environments)
- some freedom to modify gravity on intermediate galaxy, cluster, LSS scales (GR not that well tested there)

Which model? Let's go for f(R)-gravity first.

- Einstein-Hilbert action replaced by

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

➡ varying with respect to the metric yields

$$G_{\mu\nu} + f_R R_{\mu\nu} - \left(\frac{f}{2} - \Box f_R \right) g_{\mu\nu} - \nabla_\mu \nabla_\nu f_R = 8\pi G T_{\mu\nu}$$

modified Einstein equation

with $f_R \equiv \mathrm{d}f/\mathrm{d}R$ scalar degree of freedom

➡ modified Friedmann equations

f(R)-gravity

- in the quasi-static limit perturbations in a FRW universe satisfy

$$\nabla^2 f_R = \frac{1}{3c^2}\left(\delta R - 8\pi G \delta\rho\right)$$

- the gravitational potential is given by

$$\nabla^2 \phi = \frac{16\pi G}{3}\delta\rho - \frac{1}{6}\delta R$$

Chameleon f(R)-gravity

$$\nabla^2 f_R = \frac{1}{3c^2}\left(\delta R - 8\pi G \delta\rho\right) \qquad \nabla^2 \phi = \frac{16\pi G}{3}\delta\rho - \frac{1}{6}\delta R$$

- High curvature regime

$$\delta R \approx 8\pi G \delta\rho \qquad \Rightarrow \qquad \nabla^2\phi \approx 4\pi G\delta\rho$$

standard GR restored

- Low curvature regime

$$\delta R \ll 8\pi G \delta\rho \qquad \Rightarrow \qquad \nabla^2\phi \approx 16/3\pi G\delta\rho$$

gravity enhanced by 4/3

➡ need f(R) for which solar system lives in high curvature regime

The Hu & Sawicki '07 model

- f(R) with Chameleon mechanism

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

- a flat LCDM expansion history is reproduced if

$$\frac{c_1}{c_2} = 6 \frac{\Omega_\Lambda}{\Omega_m} \qquad m^2 \equiv H_0^2 \Omega_{\rm m}$$

- typically $c_2 (R/m^2)^n \gg 1$

$$\rightarrow \quad f_R \approx -n \frac{c_1}{c_2^2} \left(\frac{m^2}{R}\right)^{n+1}$$

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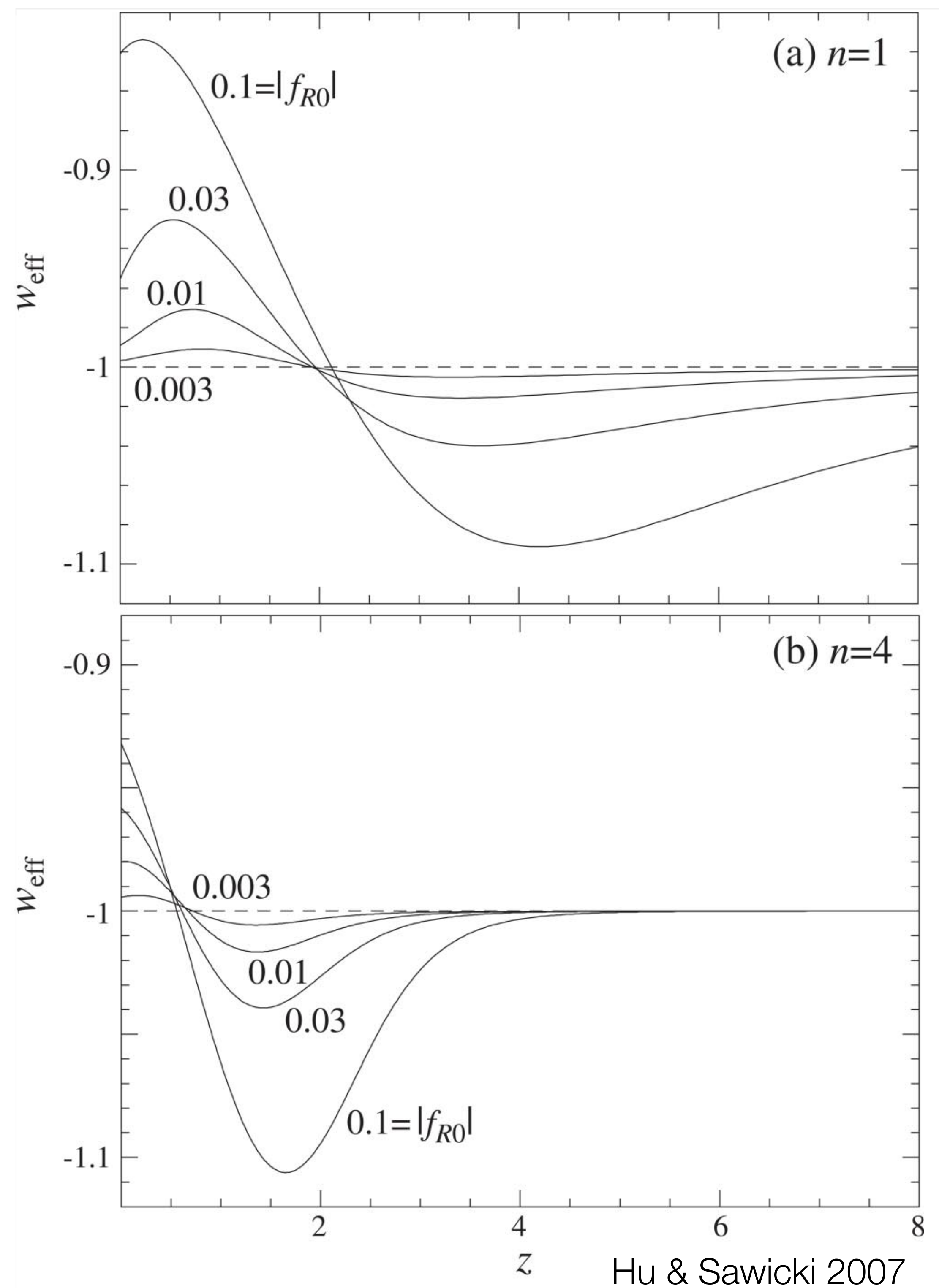

Hu & Sawicki 2007

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The Hu & Sawicki '07 model

- as a first application of our code, we study the case n=1

$$\bar{f}_R(a) = \bar{f}_{R0}\left(\frac{\bar{R}_0}{\bar{R}(a)}\right)^2 \qquad \delta R = \bar{R}(a)\left(\sqrt{\frac{\bar{f}_R(a)}{f_R}} - 1\right)$$

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→

$$\nabla^2 f_R = \frac{1}{3c^2}\left[\bar{R}(a)\left(\sqrt{\frac{\bar{f}_R(a)}{f_R}} - 1\right) - 8\pi G\delta\rho\right]$$

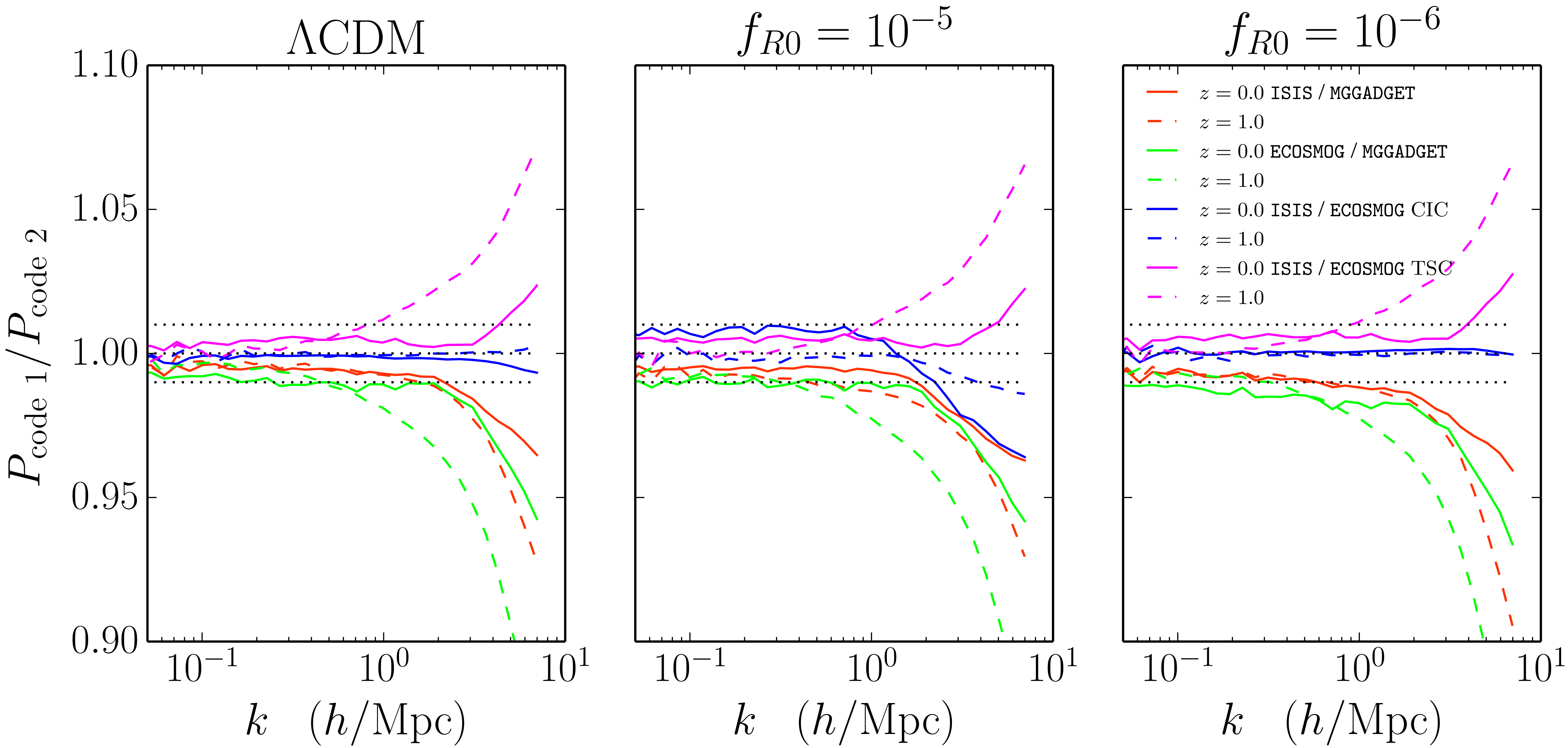
needs to be solved numerically

The MG-Gadget code

- wrote the Modified Gravity-Gadget (or MG-Gadget) simulation code (EP, Baldi, Springel 2013)
- based on the P-Gadget3 code
- the code is
  - has adaptive resolution (multigrid accelerated relaxation on adaptive mesh)
  - MPI parallel to allow large runs
  - allows including baryonic physics at the same time

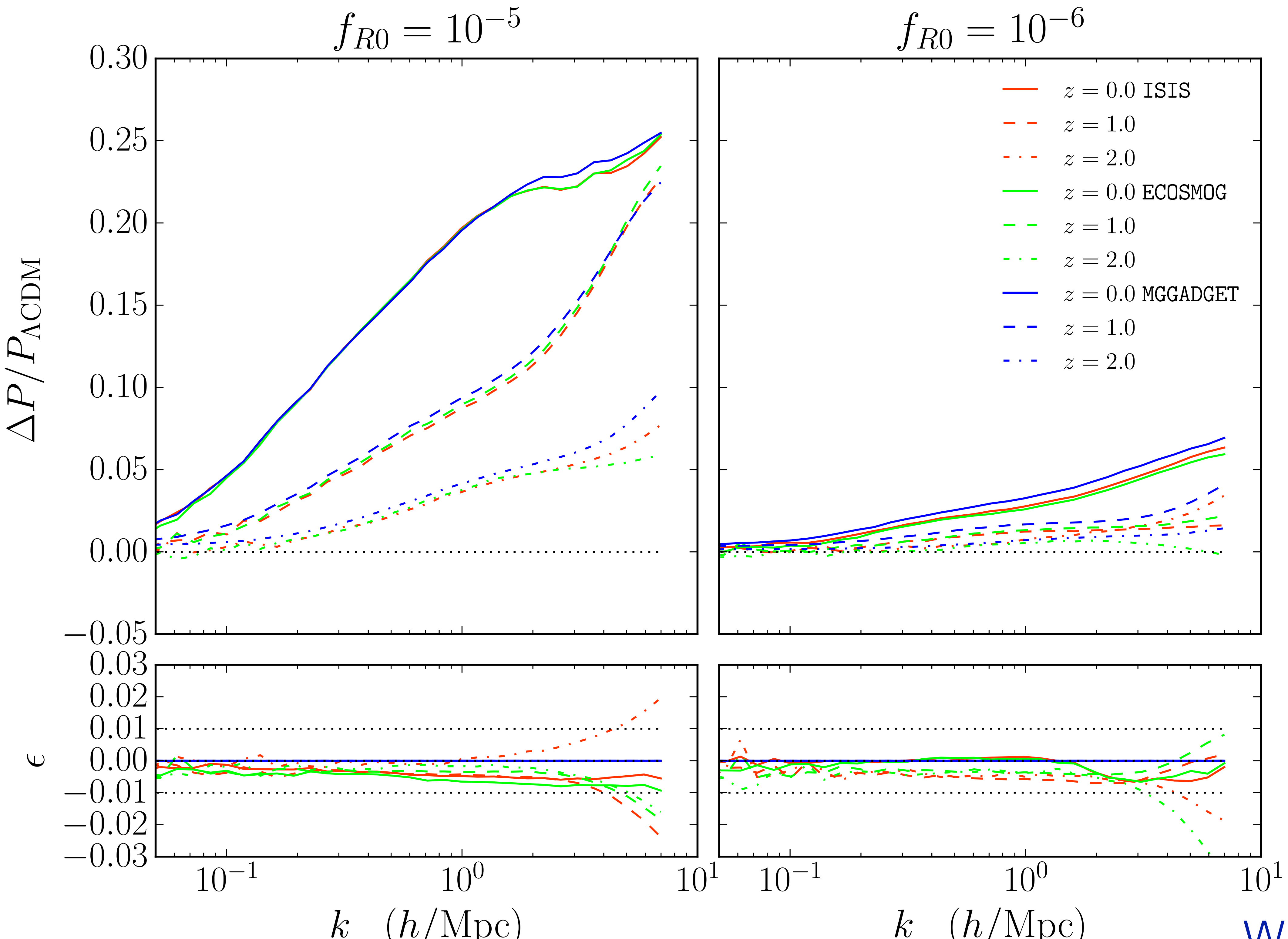
A first modified gravity code comparison

**comparison of the matter power spectrum
in different modified gravity codes**



Winther et al. 2015

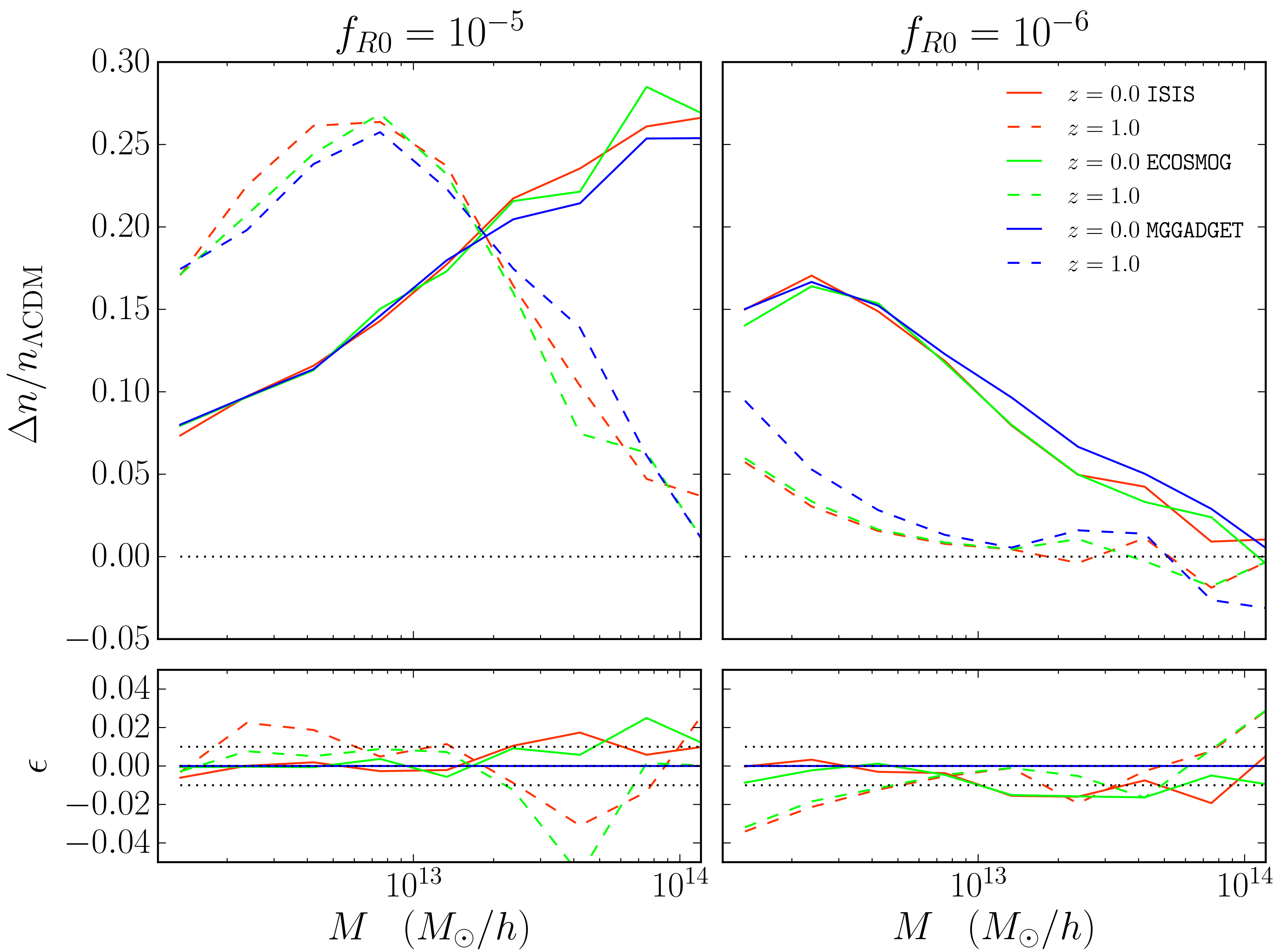
A first modified gravity code comparison



the modified gravity effect on the matter power spectrum

Winther et al. 2015

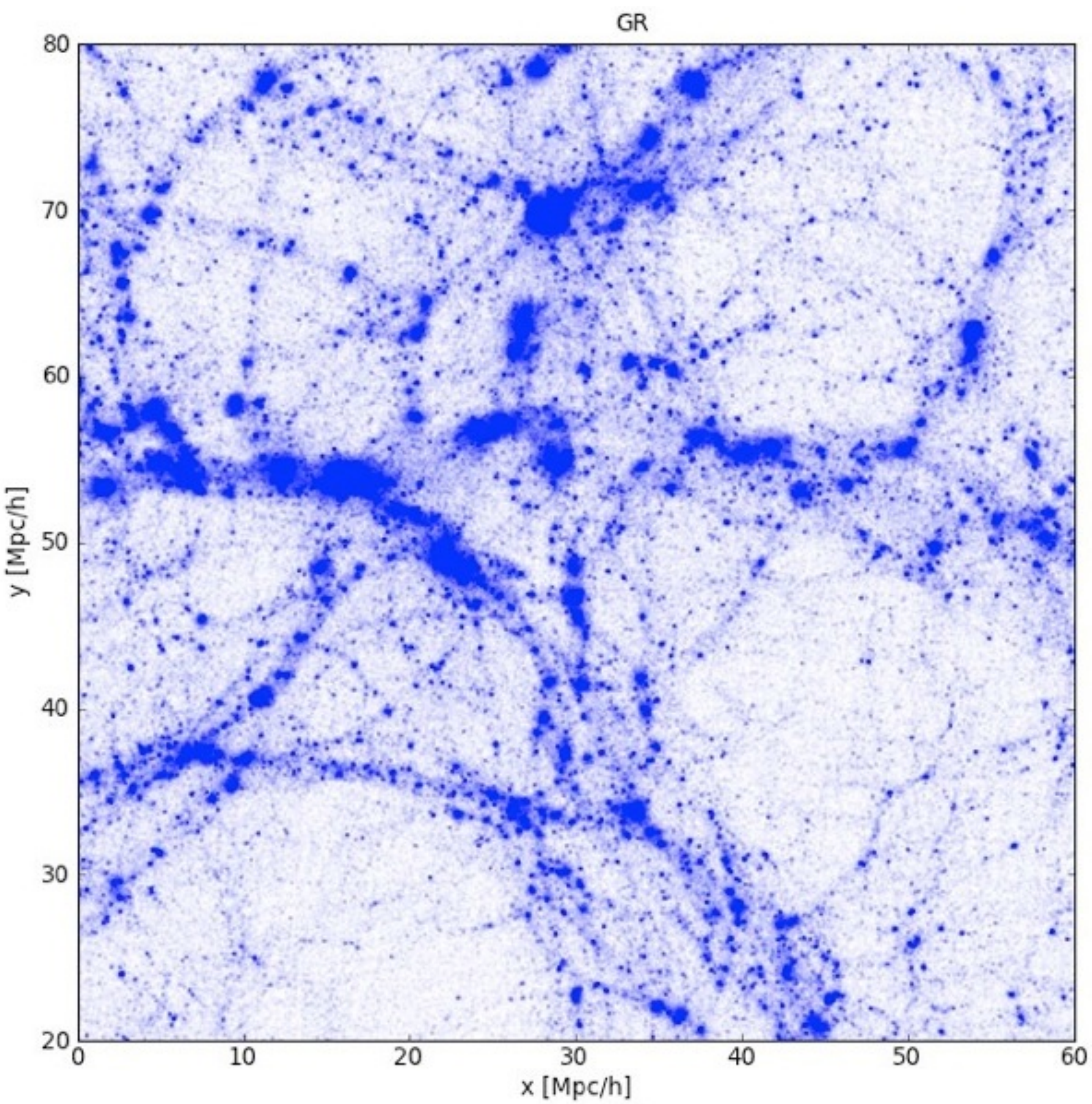
A first modified gravity code comparison

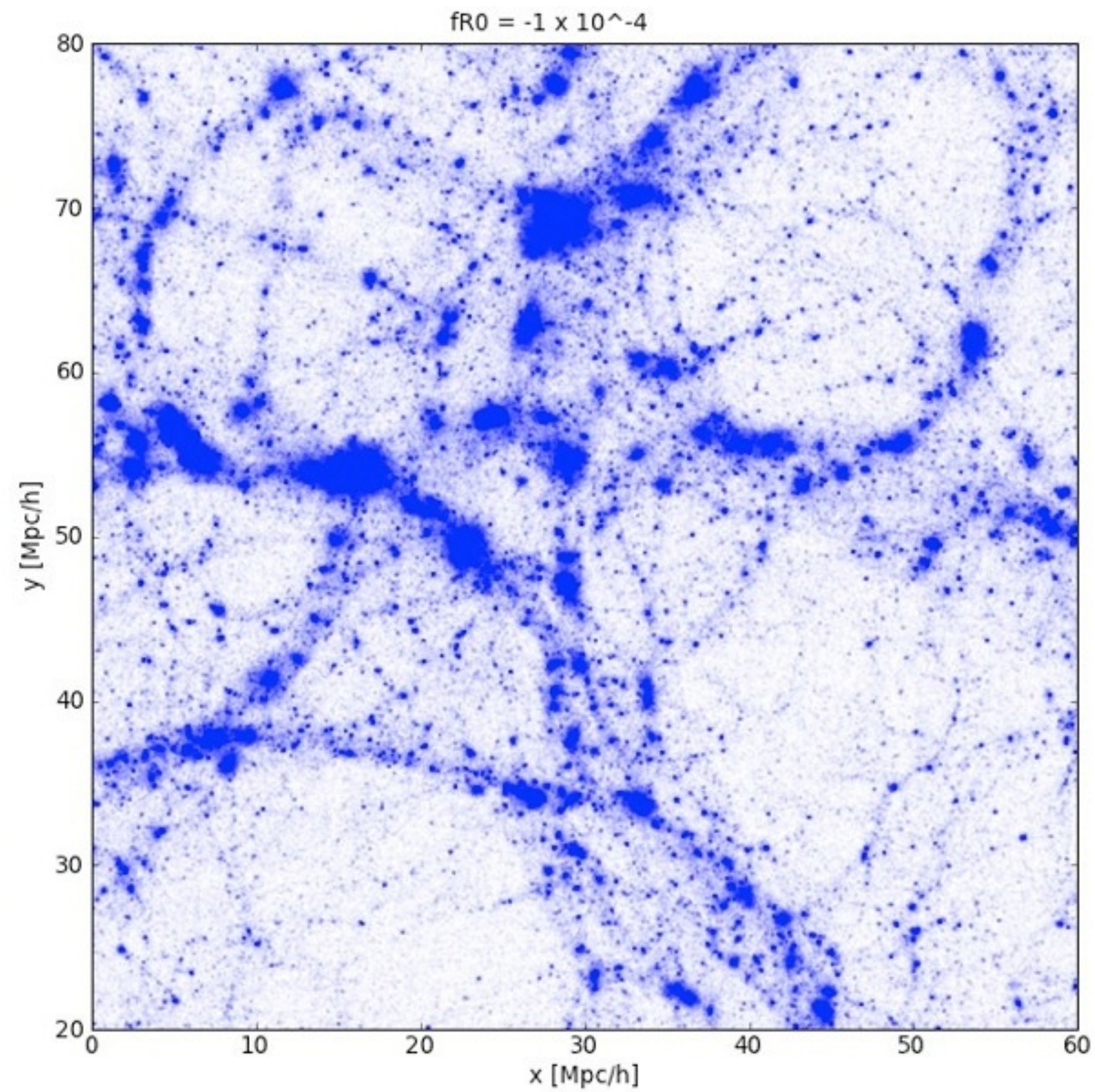


the modified gravity effect on the halo mass function

Winther et al. 2015

How modified gravity changes the matter density field





GR

$$\bar{f}_{R0} = -1 \times 10^{-4}$$

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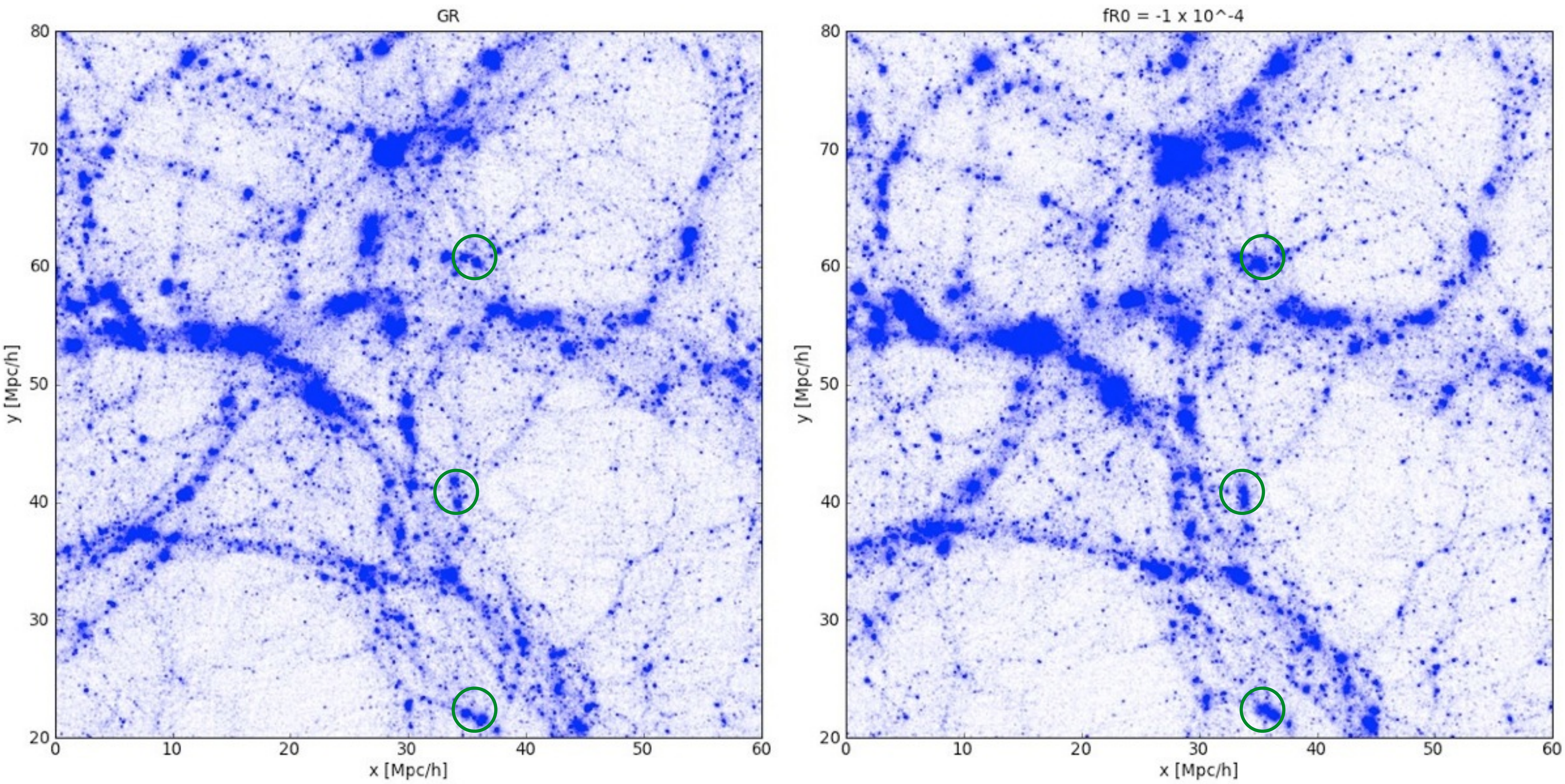
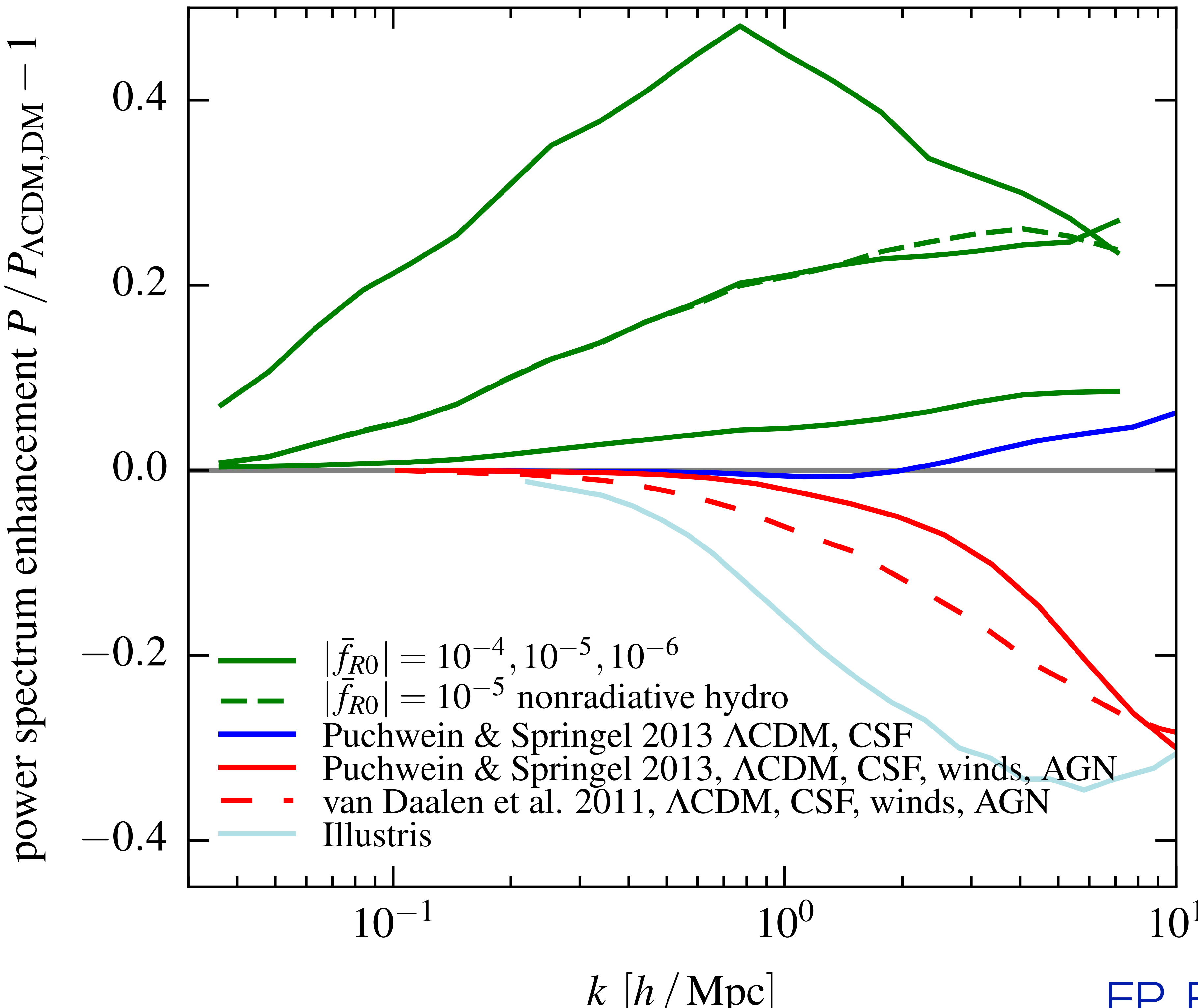


GR $\qquad$ $\bar{f}_{R0} = -1 \times 10^{-4}$

Degeneracies between modified gravity & baryonic physics effects



EP, Baldi, Springel 2013

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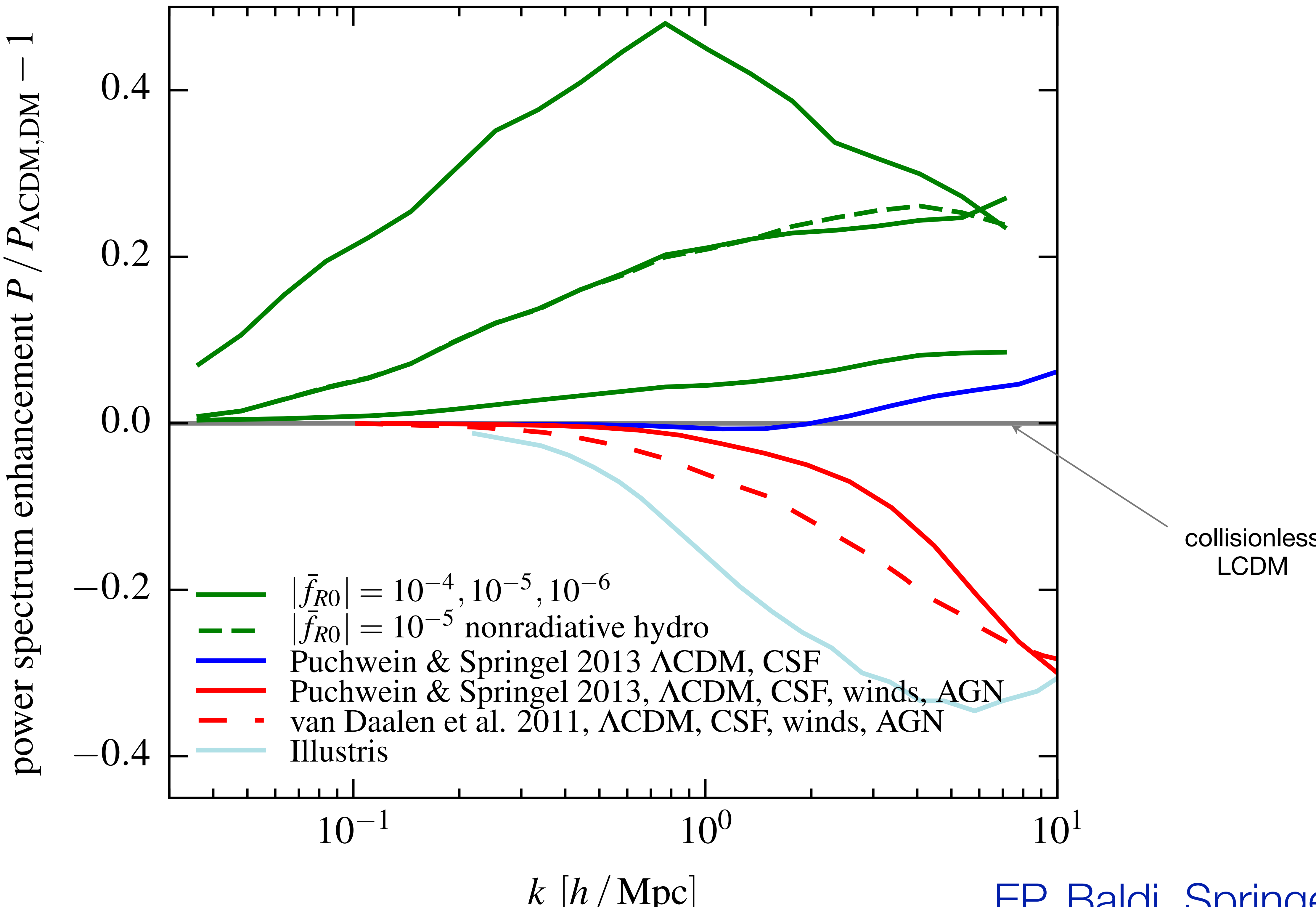

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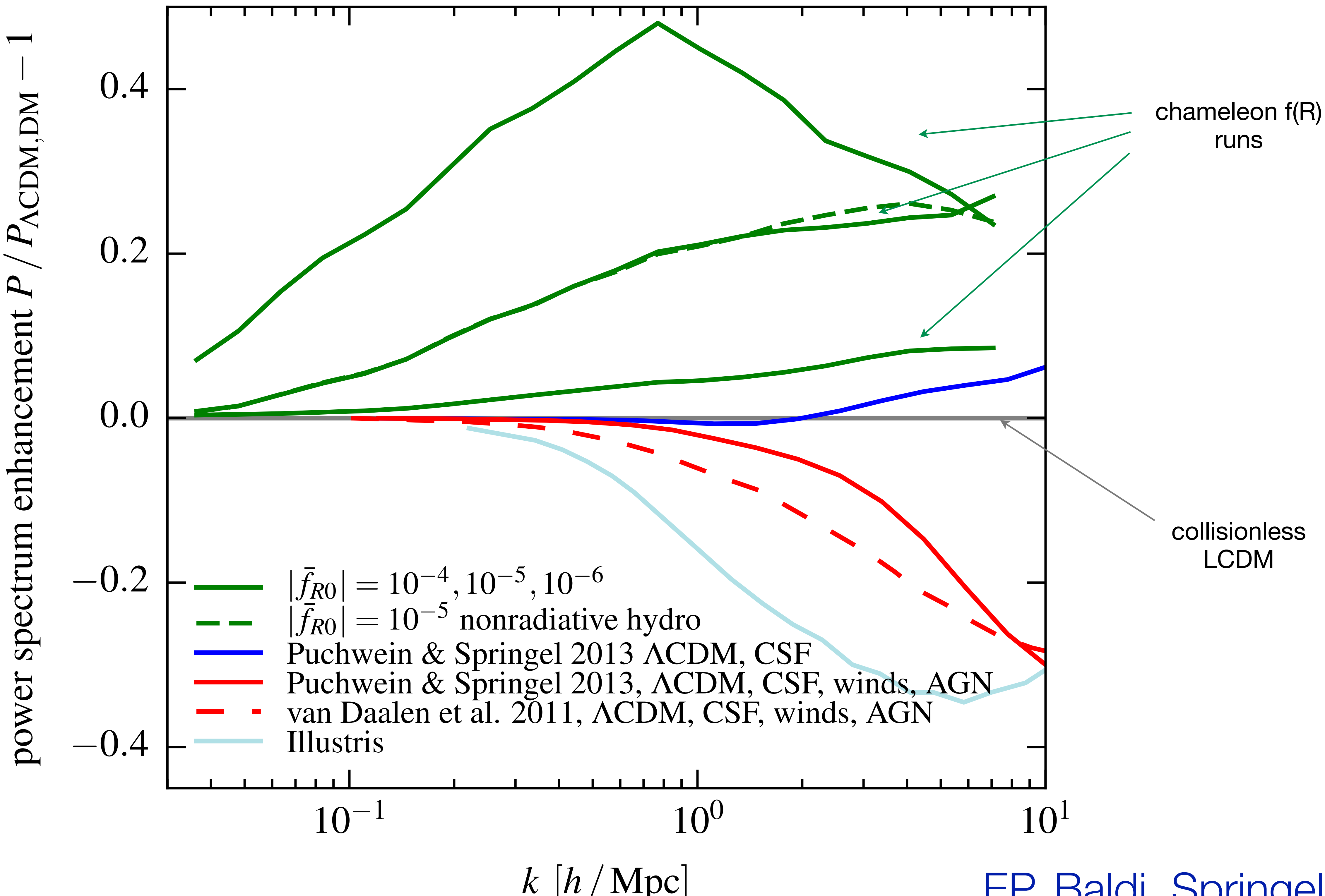

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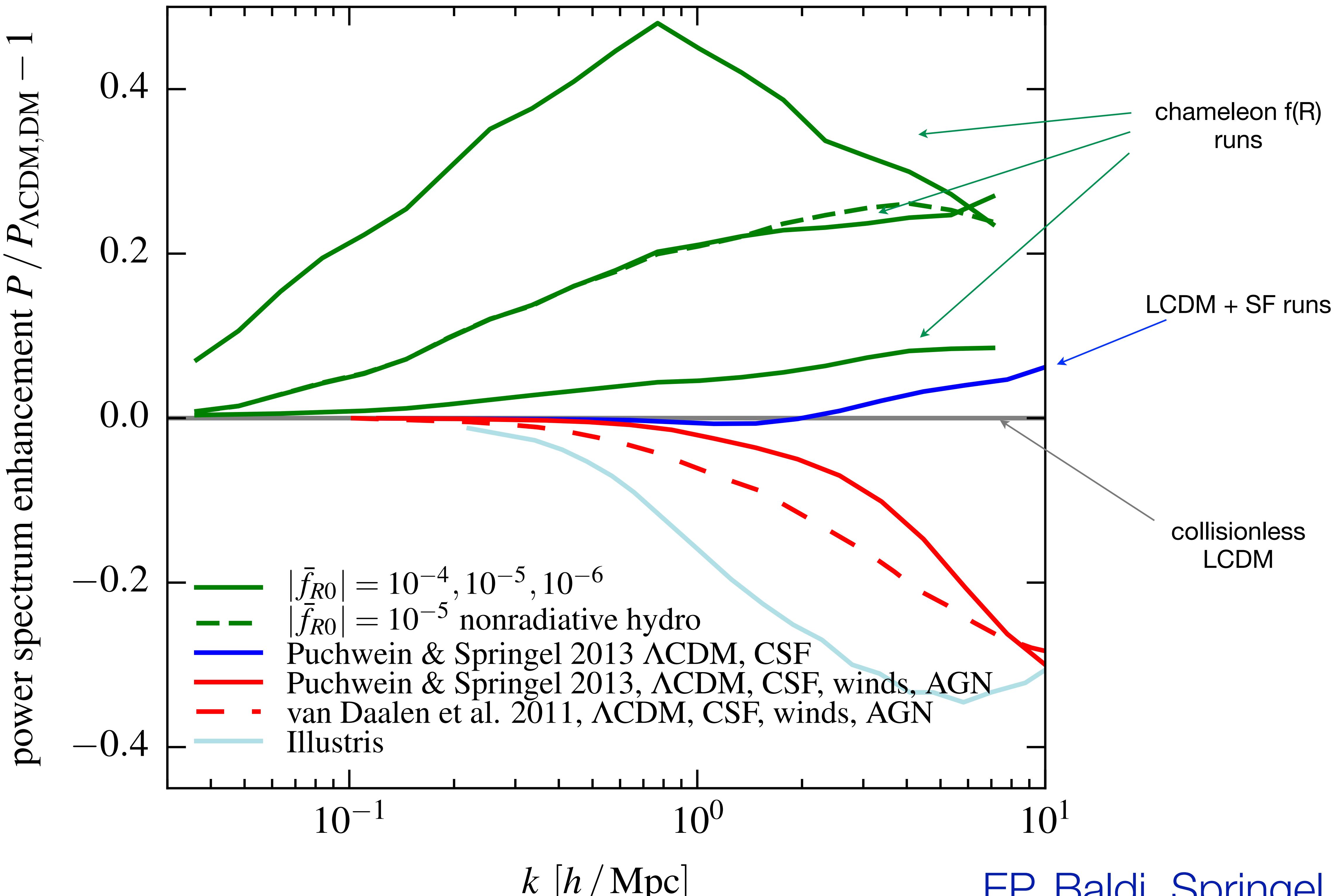

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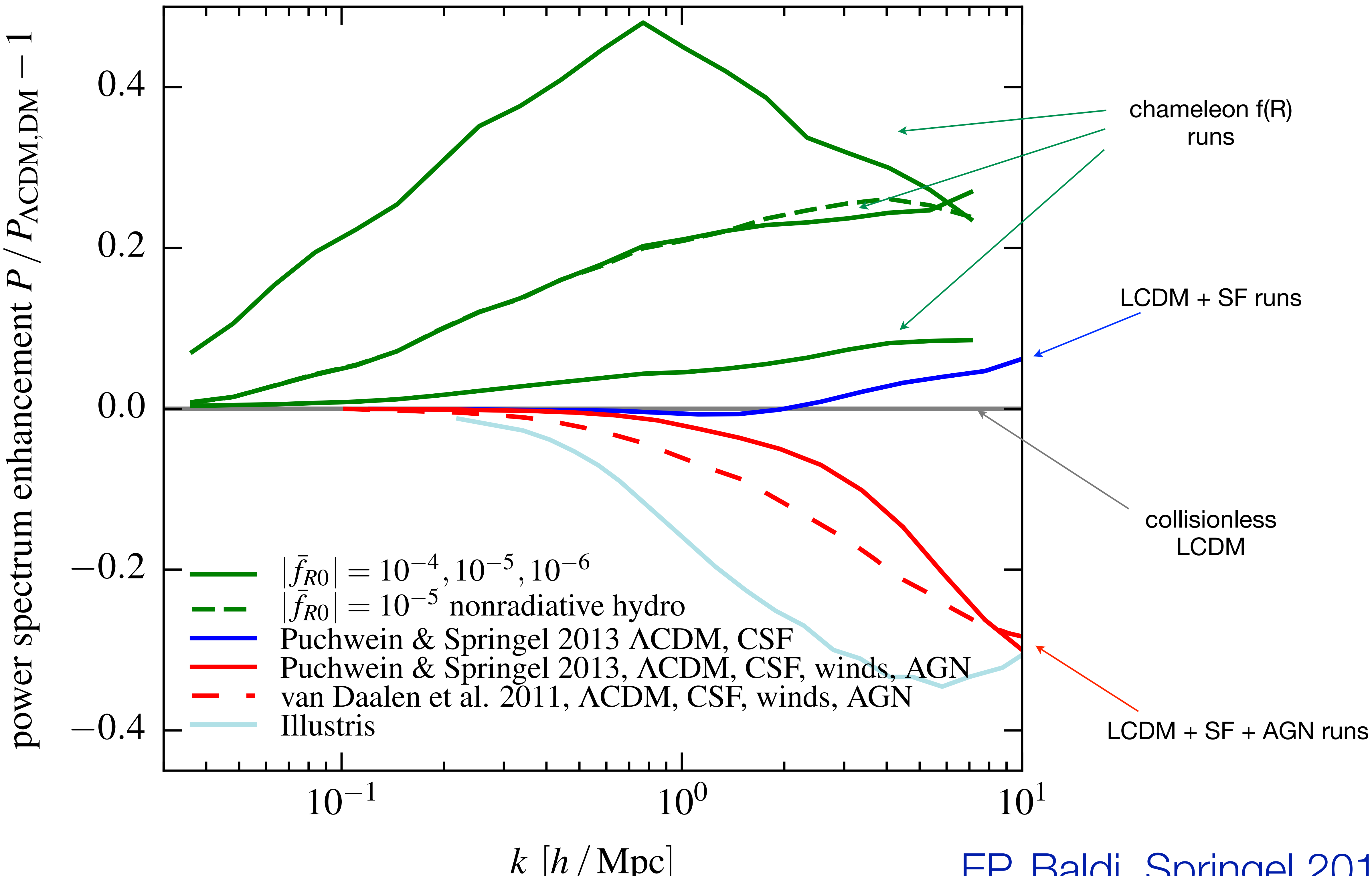
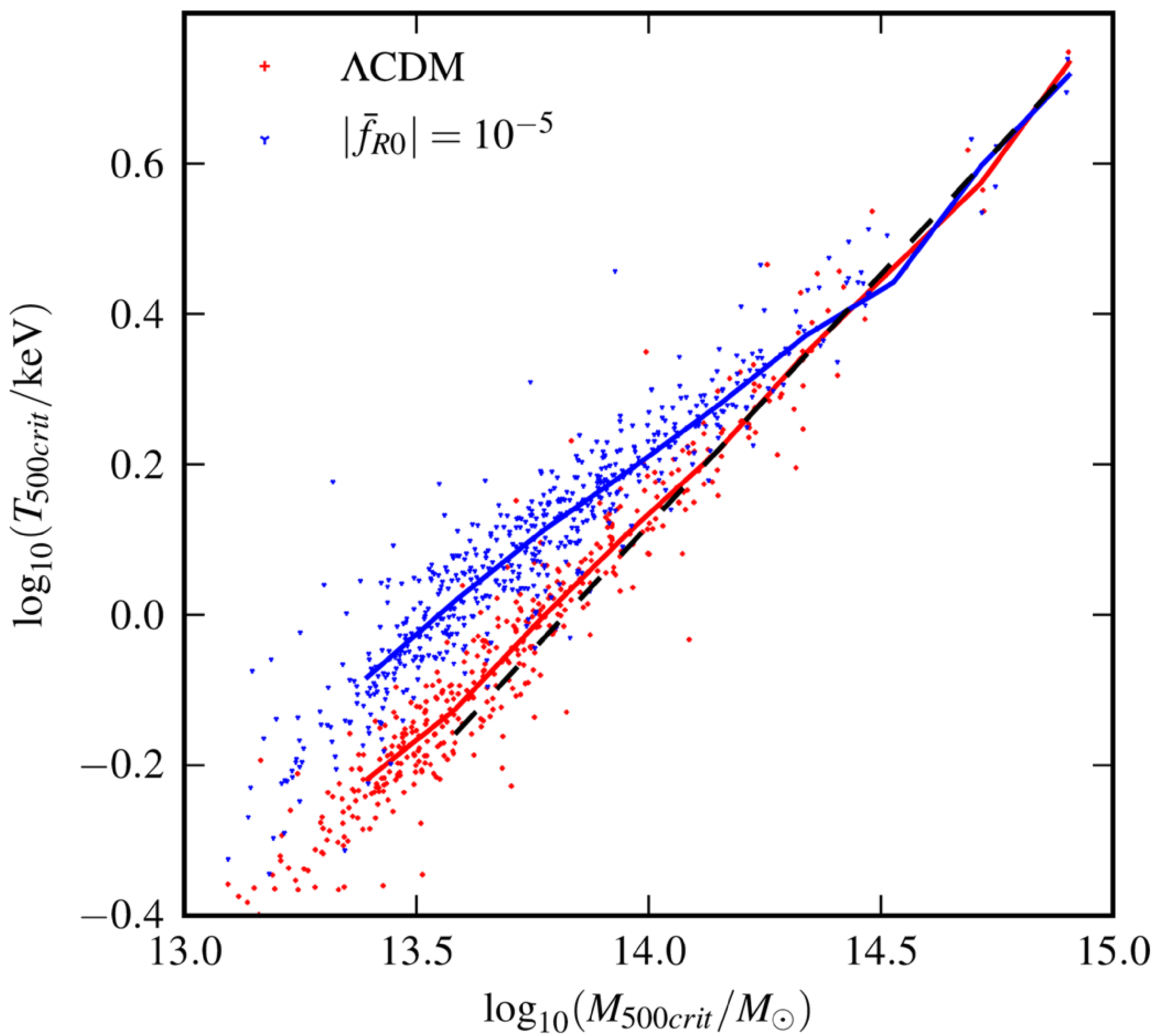


EP, Baldi, Springel 2013

Halo gas properties in chameleon-f(R) gravity

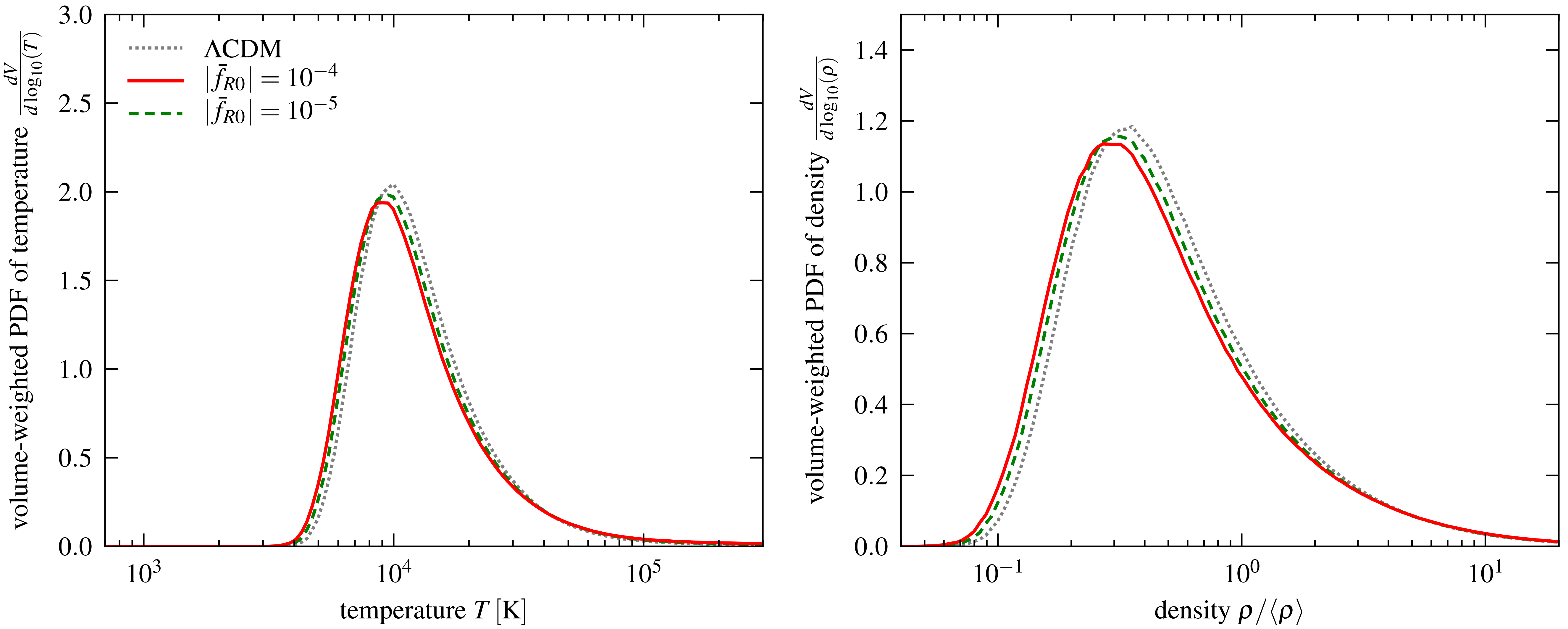
group & cluster M-T relation in non-radiative runs



Arnold, EP, Springel 2014

f(R) hydro runs

modified gravity effects on the intergalactic medium in radiative runs

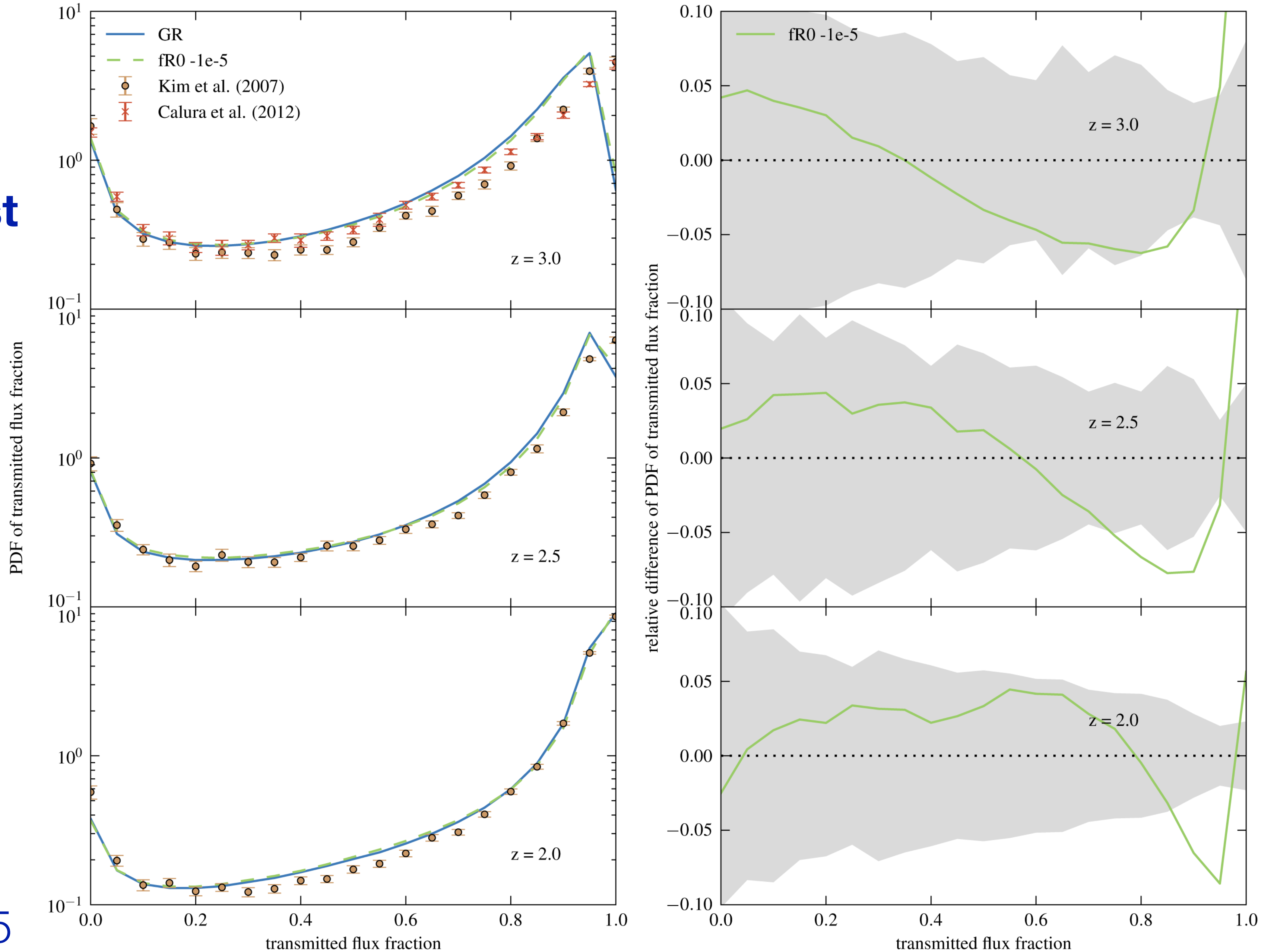


-> visible in the Lyman-α forest?

EP, Baldi, Springel 2013

The Lyman-α forest in chameleon-f(R)

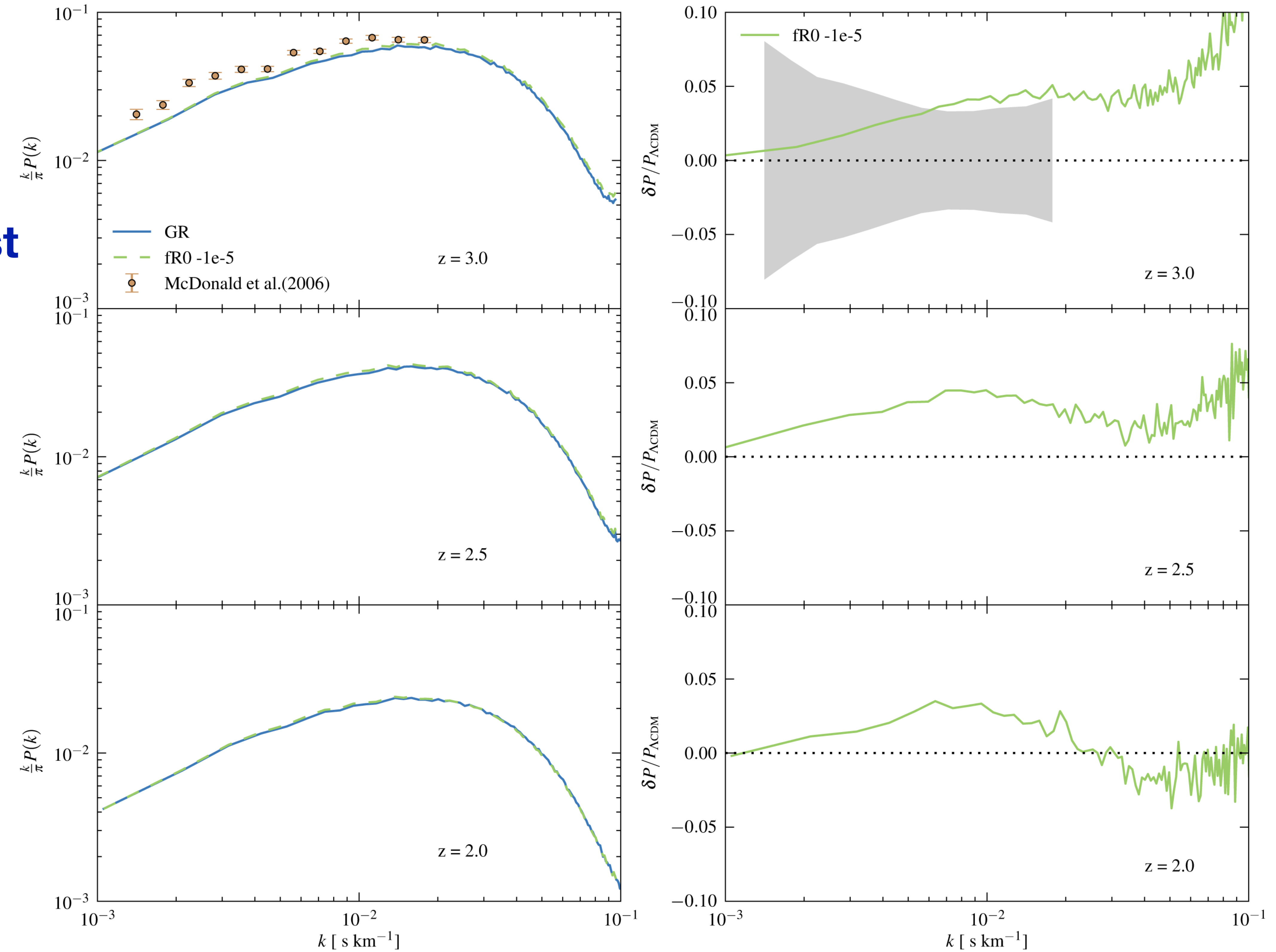
Lyman-α forest flux PDF



Arnold, EP, Springel 2015

The Lyman-α forest in chameleon-f(R)

Lyman-α forest flux power spectrum



Arnold, EP, Springel 2015

Summary & Conclusions

- good agreement between different modified gravity codes
- degeneracies between modified gravity effects and uncertainties in the baryonic physics (e.g. AGN feedback)
  - ➡ simulations that include both can help to find least affected signatures & give better predictions for observational tracers
- first modified gravity non-radiative and radiative hydrodynamical simulations
- modified gravity effects in the Lyman-α forest are small
  - ➡ challenging to constrain modifications of gravity with it