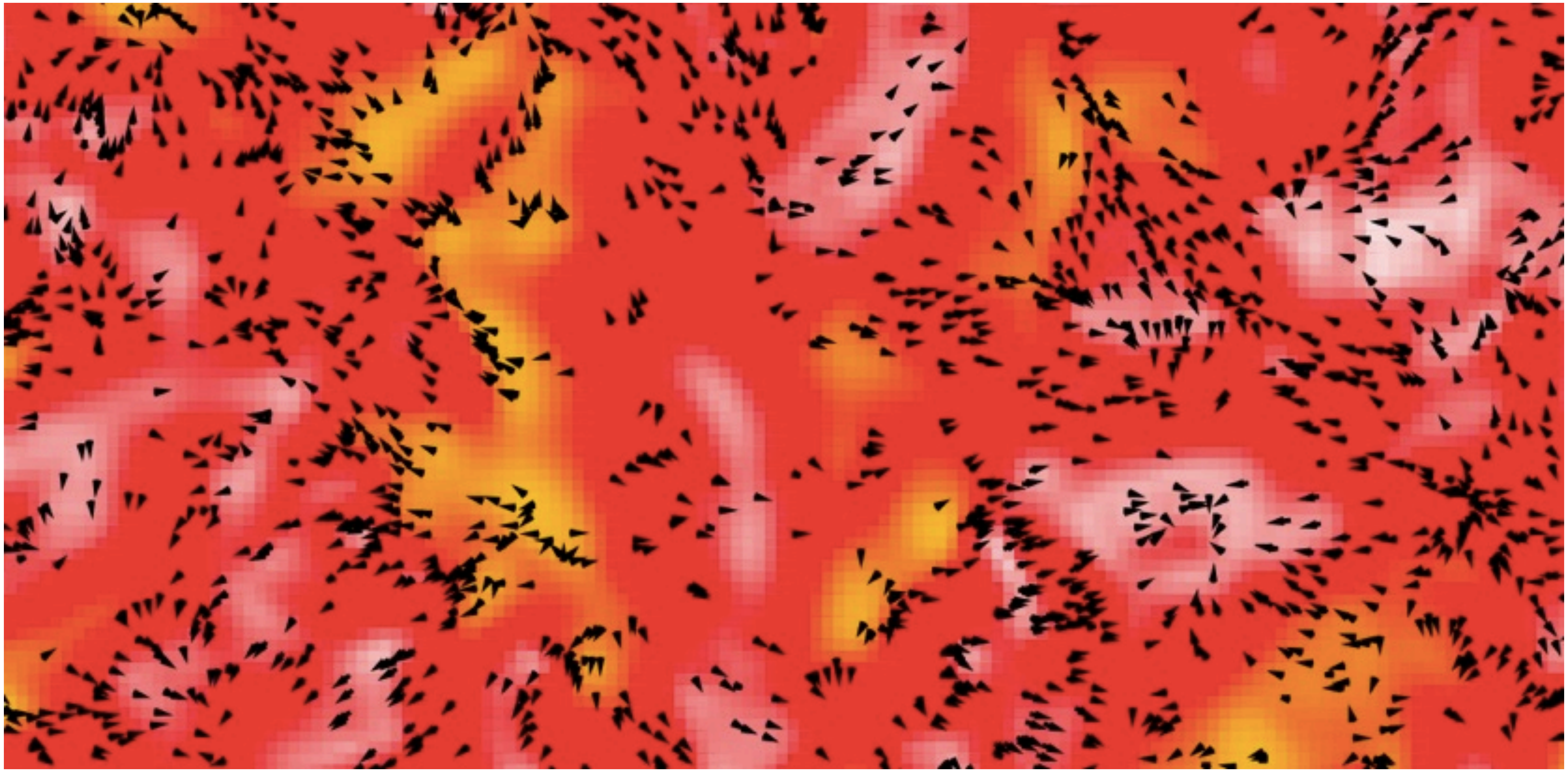

Remapping cosmological simulations from standard to modified gravity

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with: John Peacock, Lucas Lombriser, Baojiu Li

Introduction

Aim - take a particle or halo distribution from one simulation and manipulate it so that it approximates that of a different model

- Angulo & White 2010
- Why? - extremely rapid (~ minutes)
  - Covariance matrices
  - Galaxy formation
  - Mock catalogues
  - Clustering

} Functions of cosmology or model

f(R) gravity

$$S = \int \mathrm{d}^4x \sqrt{|g|} \left[\frac{R + f(R)}{16\pi G} + \mathcal{L}_{\mathrm{m}}(\psi_i, g_{ab}) \right]$$

- Change Einstein-Hilbert action from 'R' to 'R+f(R)'

δS=0

$$R_{ab} - \frac{1}{2} g_{ab} \left[R + f(R) \right] + (g_{ab} \Box - \nabla_a \nabla_b + R_{ab}) f'(R) = -8\pi G T_{ab}$$

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extra terms

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extra terms

- Maps to a subset of scalar-tensor theories

$$1 + f'(R) = \phi$$

$$-f'(R)R + f(R) = -V(\phi)$$

$$S = \int d^4x \sqrt{|g|} \left[\frac{\phi R - V(\phi)}{16\pi G} + \mathcal{L}_m(\psi_i, g_{ab}) \right]$$

Hu + ... '07

$$f(R) = -\bar{R}_0 \frac{c_1 (R/\bar{R}_0)^n}{c_2 (R/\bar{R}_0)^n + 1}$$

- Functional form designed to produce accelerated expansion as well as modify gravity

$$f(R) \simeq -\bar{R}_0 \frac{c_1}{c_2} + \bar{R}_0 \frac{c_1}{c_2^2} \left(\frac{\bar{R}_0}{R} \right)^n$$

$$f(R) = -2\Lambda - \bar{R}_0 \frac{f_{R0}}{n} \left(\frac{\bar{R}_0}{R} \right)^n$$

- $|f_{R0}|$ small
- expansion ΛCDM

‘Newtonian’ limit

$$\mathrm{d}s^2 = (1+2\Psi)\,\mathrm{d}t^2 - a^2(t)(1-2\Phi)\,\mathrm{d}\mathbf{x}^2$$

two potentials

$$\nabla^2\Psi = \frac{16\pi G}{3}\bar{\rho}_{\mathrm{m}}\delta - \frac{1}{6}\delta R \qquad \nabla^2\Phi = \frac{8\pi G}{3}\bar{\rho}_{\mathrm{m}}\delta + \frac{1}{6}\delta R$$

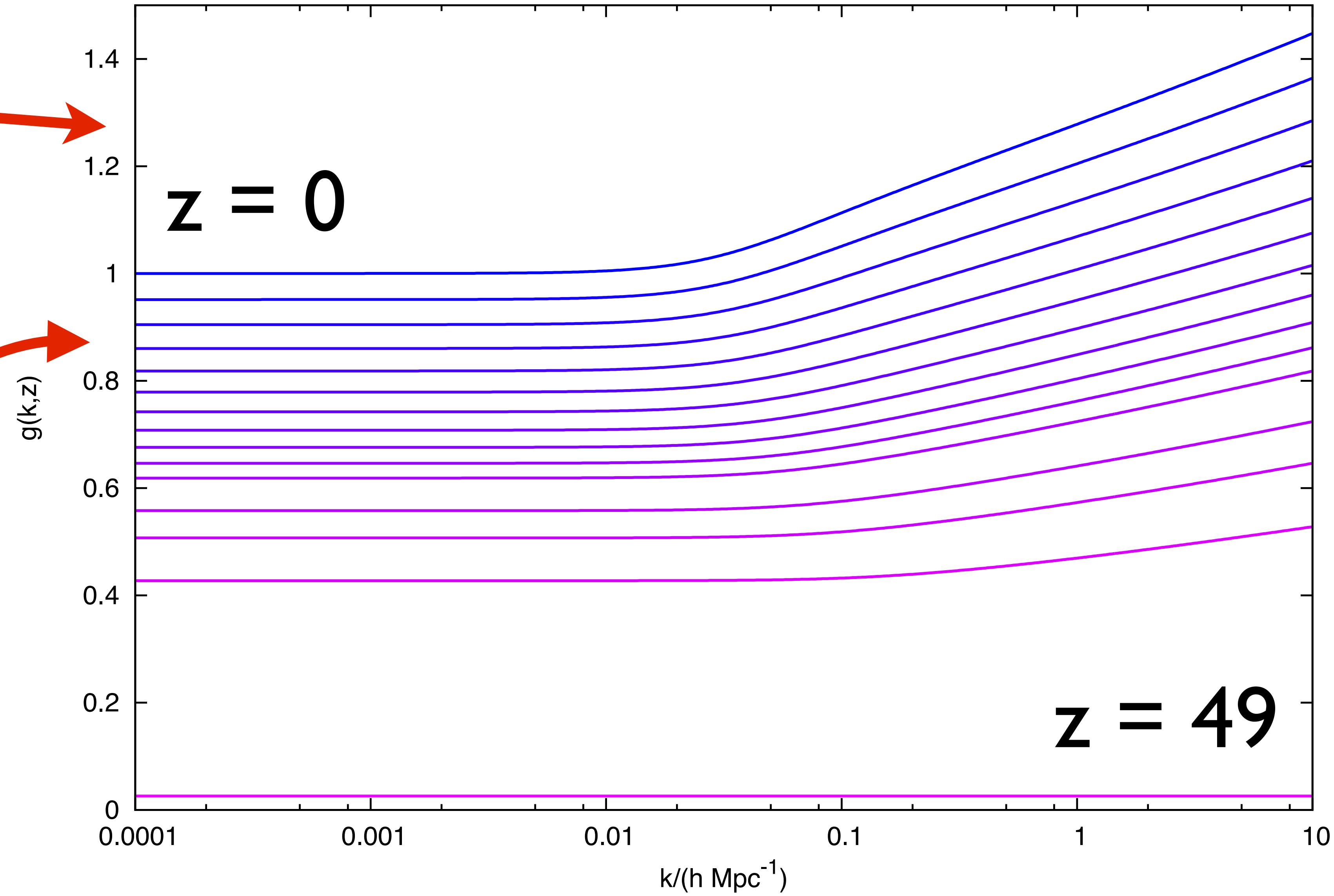
field equation for δf_R (or $\delta\phi$)

$$\nabla^2\delta f_R = \frac{1}{3}\delta R - \frac{8\pi G}{3}\bar{\rho}_{\mathrm{m}}\delta$$

Linear perturbations

$|f_{R0}| = 10^{-4}$

scale dependent perturbation growth

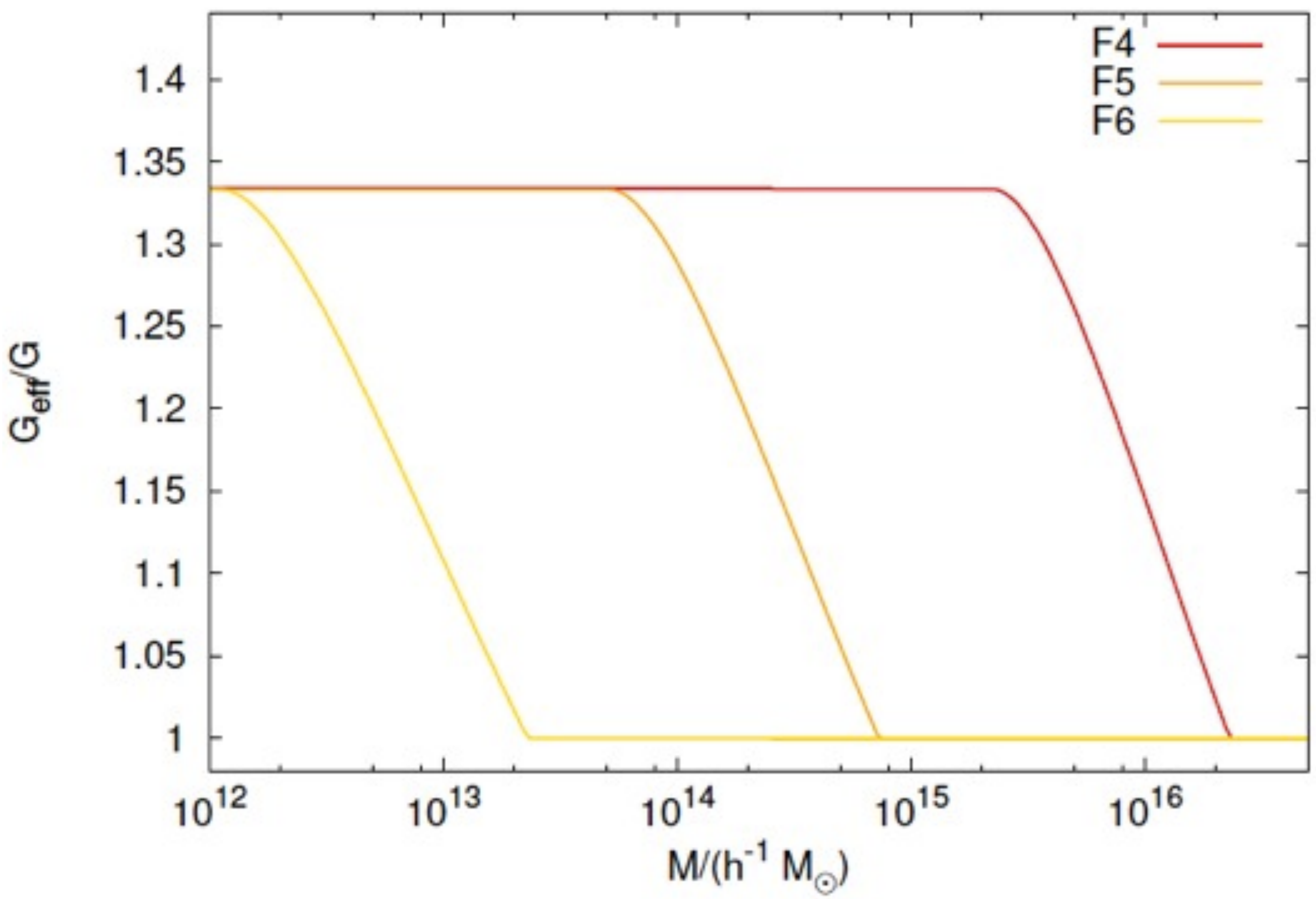


$$-\frac{k^2}{a^2}\Psi_k = 4\pi G\bar{\rho}_{\rm m}\delta_k\left[\frac{4}{3} - \frac{1}{3}\left(\frac{1}{1+\lambda^2 k^2/a^2}\right)\right]$$

Compton scale ~ f''(R)

Chameleon mechanism

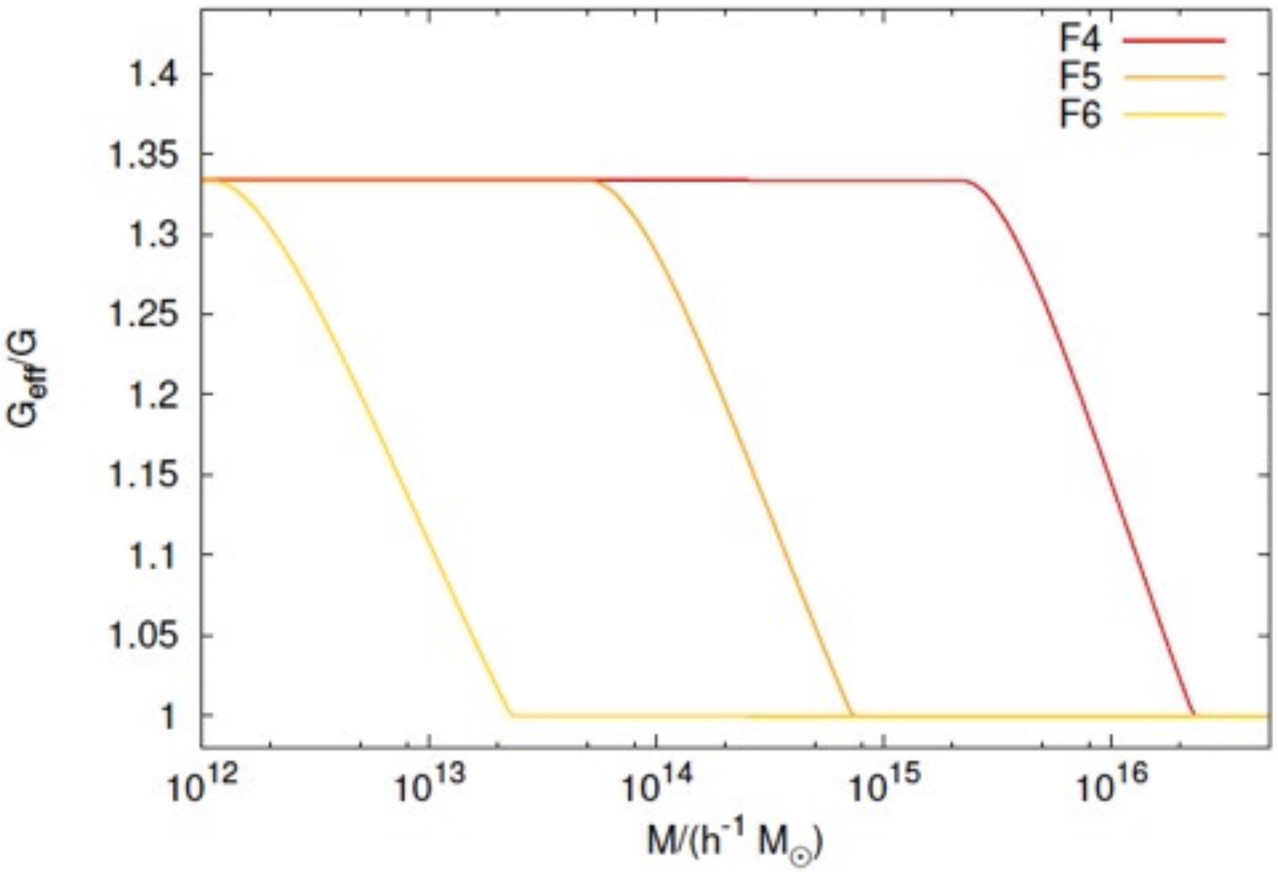
- Gravity restored to standard in some haloes
- Depends on halo mass (environment)
- Non-linear

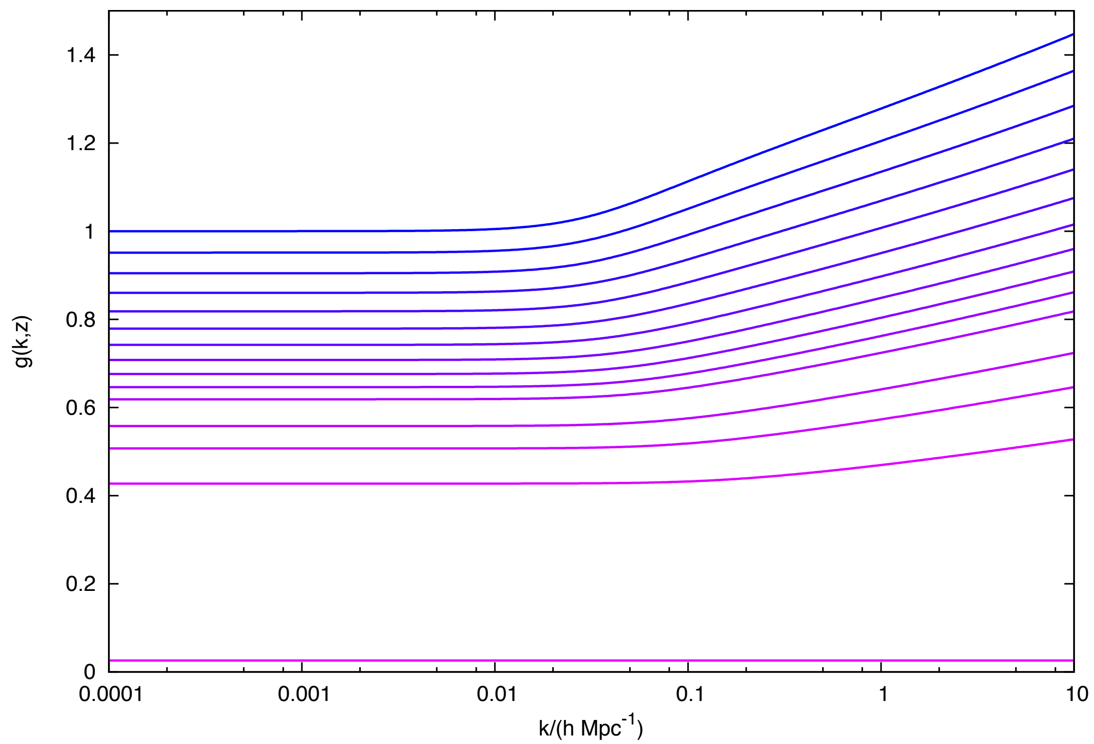


$$\left.\begin{aligned}\nabla^2 \delta f_R &= \frac{1}{3}\delta R - \frac{8\pi G}{3}\bar{\rho}_{\rm m}\delta \\ \nabla^2 \Psi &= \frac{16\pi G}{3}\bar{\rho}_{\rm m}\delta - \frac{1}{6}\delta R\end{aligned}\right\} \quad \nabla^2\Psi = 4\pi G\bar{\rho}_{\rm m}\delta$$

f(R) summary

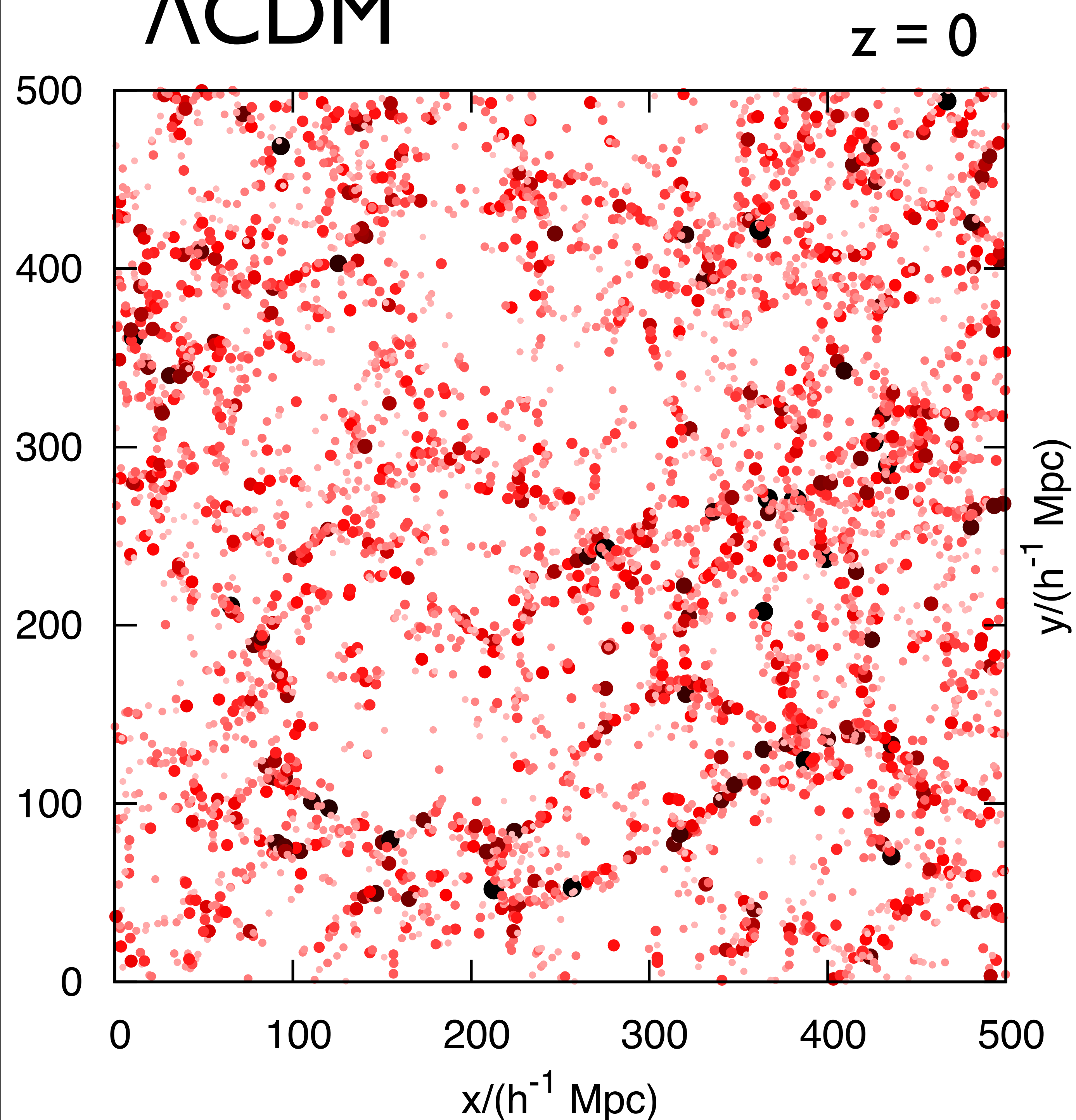
- Fairly generic example of a modified gravity theory
- Scale dependent growth
- Screening mechanism
- ΛCDM growth history



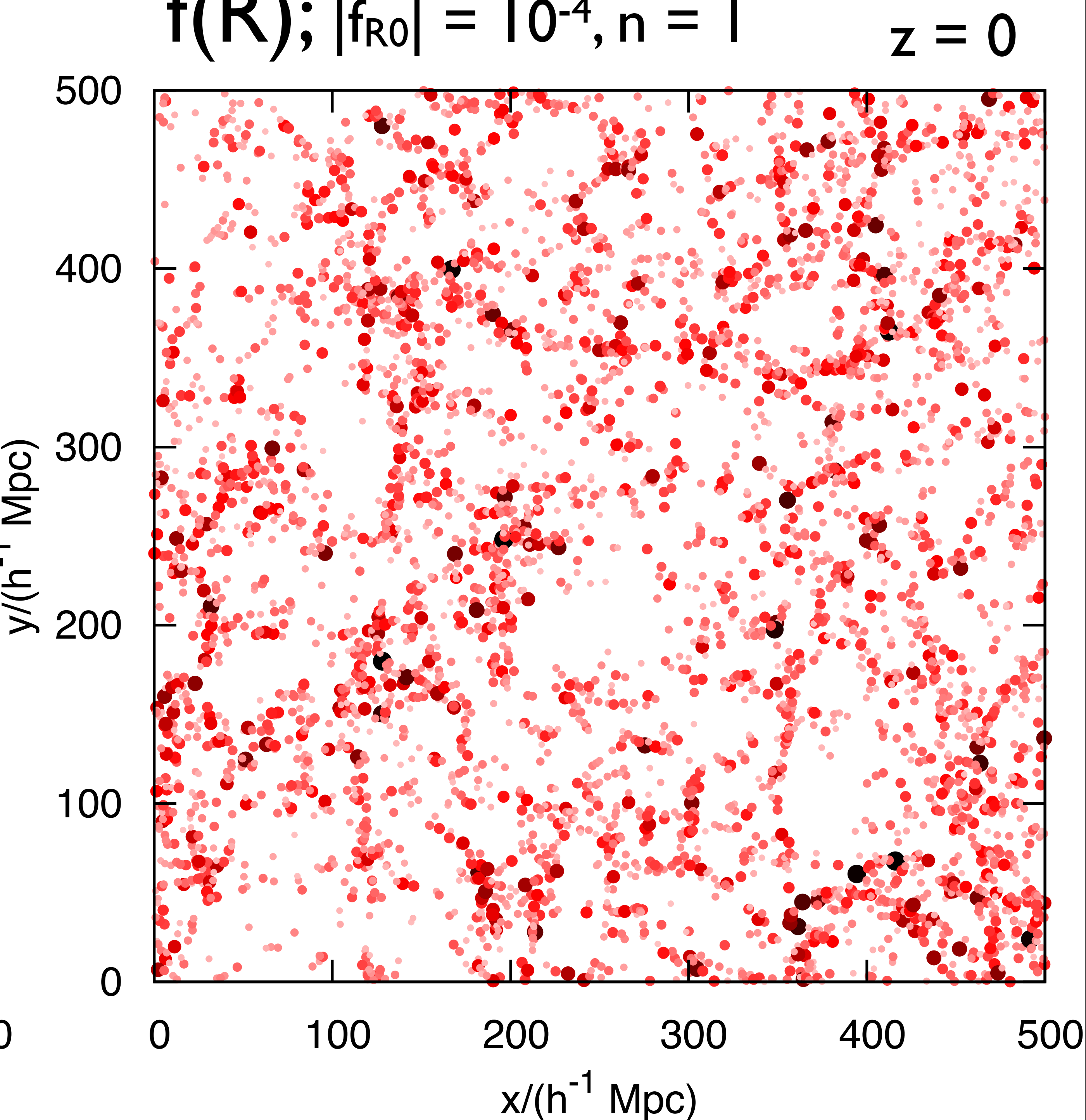


- Fairly widely simulated
- ~ O(x10 time) ΛCDM

ΛCDM



f(R); $|f_{R0}| = 10^{-4}$, n = 1



500 x 500 x 50 h^{-3} Mpc^3 slice

Haloes above 1.35 x 10^{13} h^{-1} $M_{\odot}$

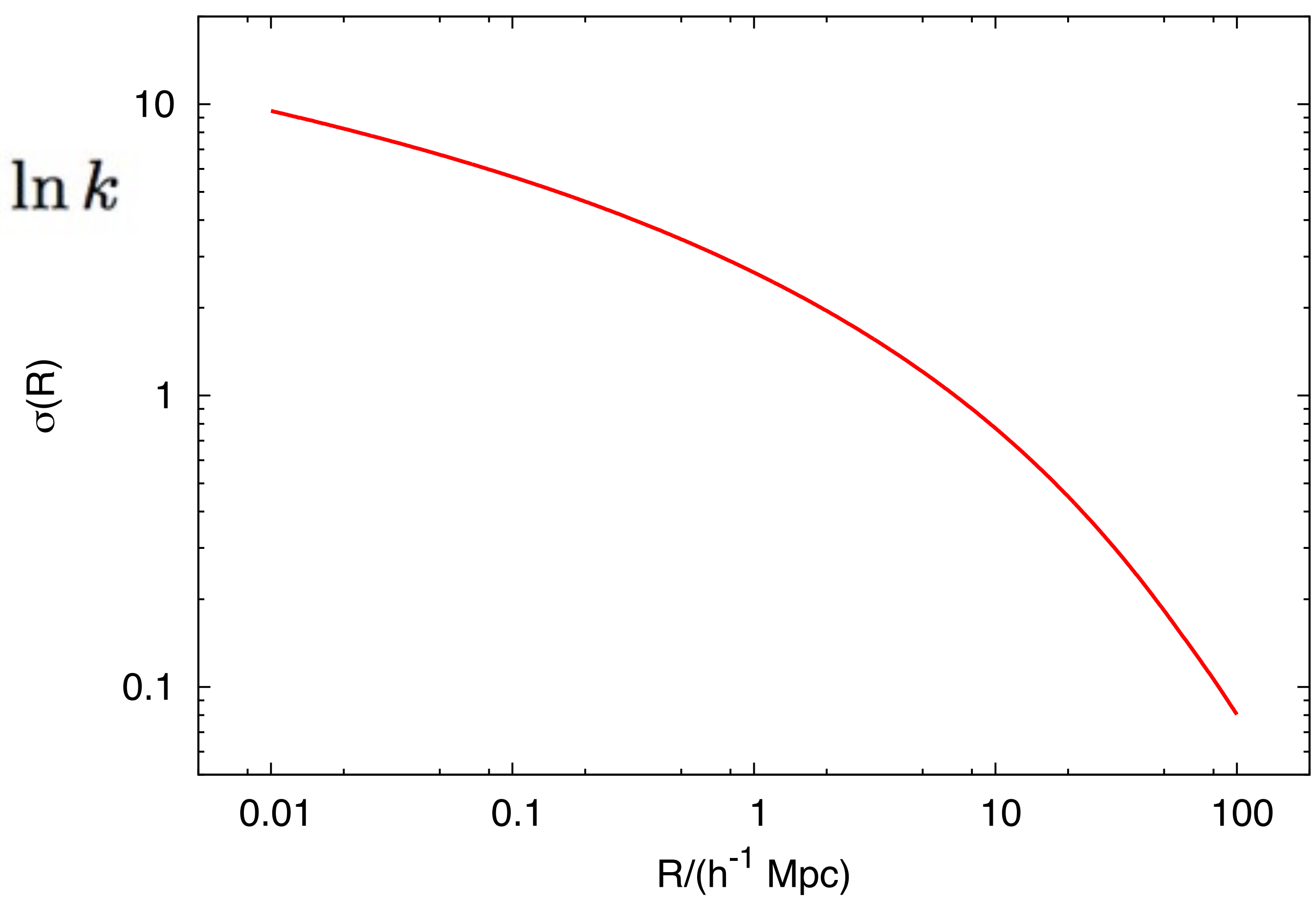
Mass functions

- Theoretically this depends only on the variance at a given scale in the cosmological model - it is 'universal' in this variable
- It is possible to rescale in redshift and box size so as to match the theoretical difference in mass functions as closely as possible

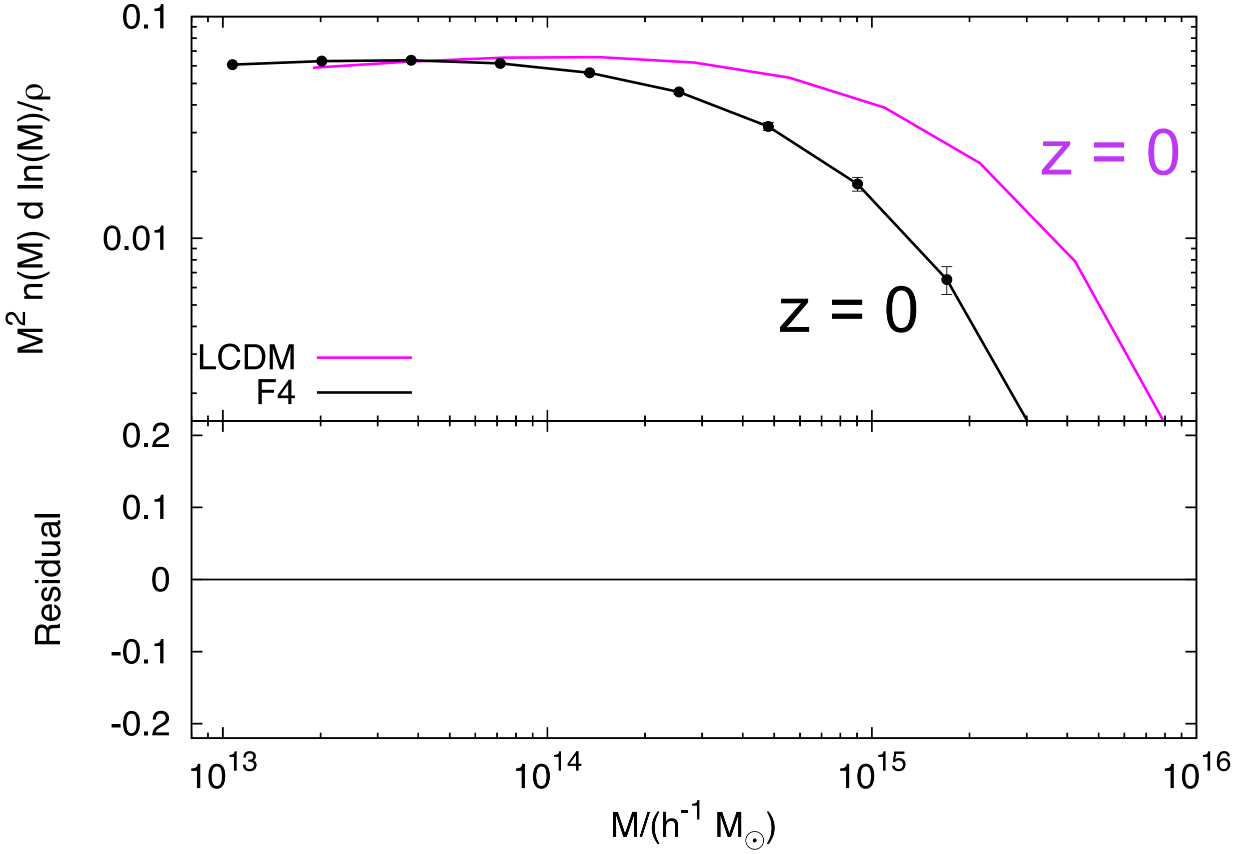
$$\sigma^2(R,z) = \int_0^\infty \Delta^2_{\text{lin}}(k,z) T^2(kR)\, \mathrm{d}\ln k$$

Linear matter power spectrum
in f(R) the growth of this is scale dependent

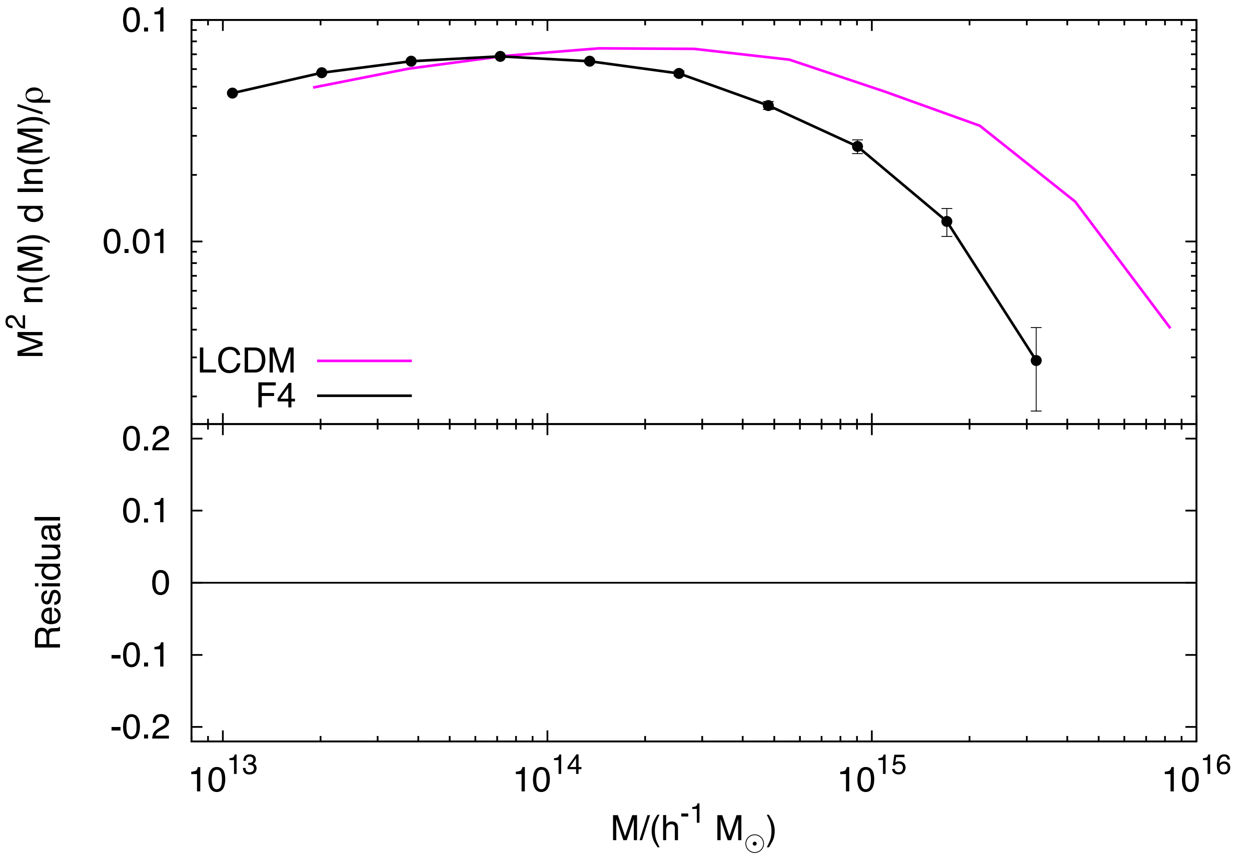
Filter of size 'R'



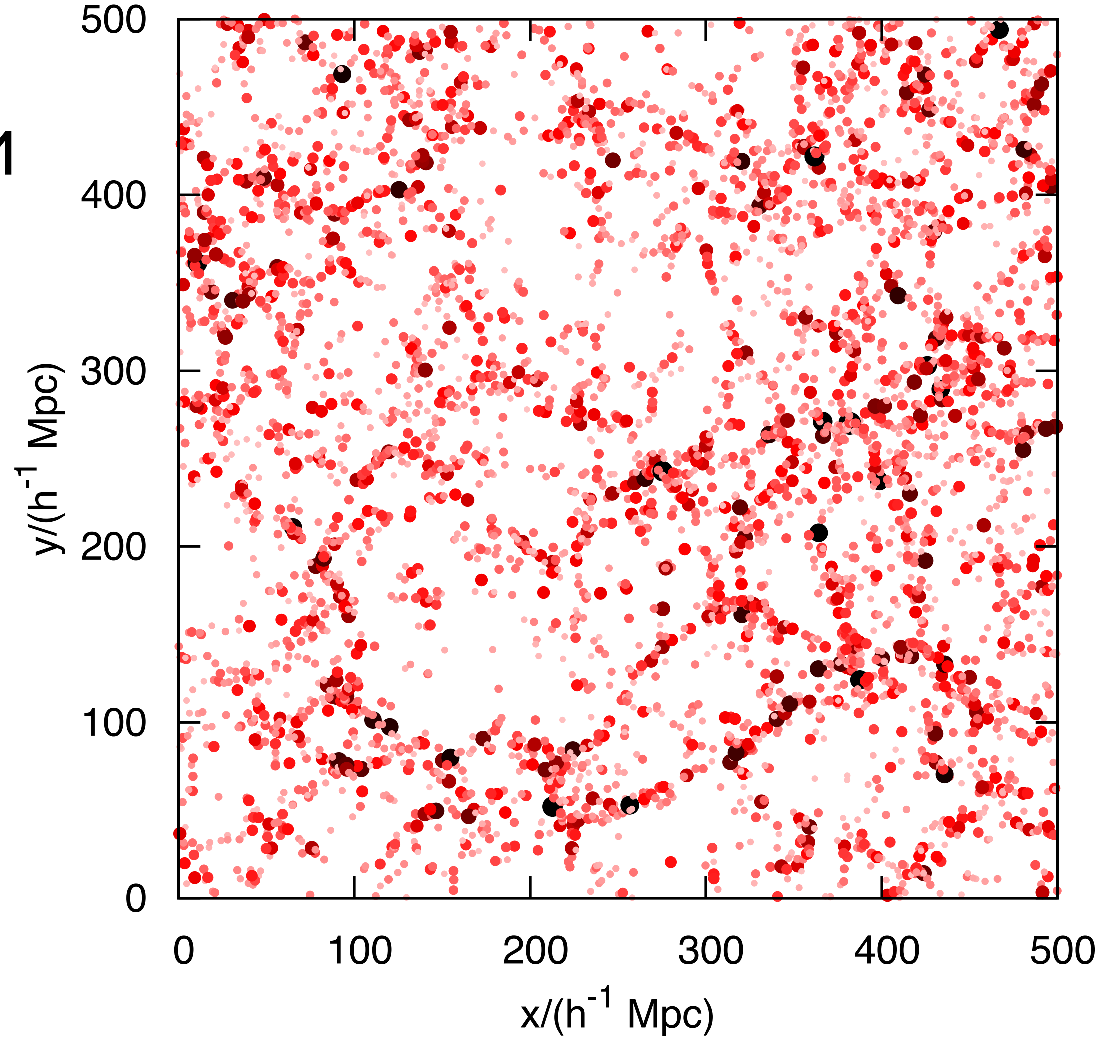
Theory



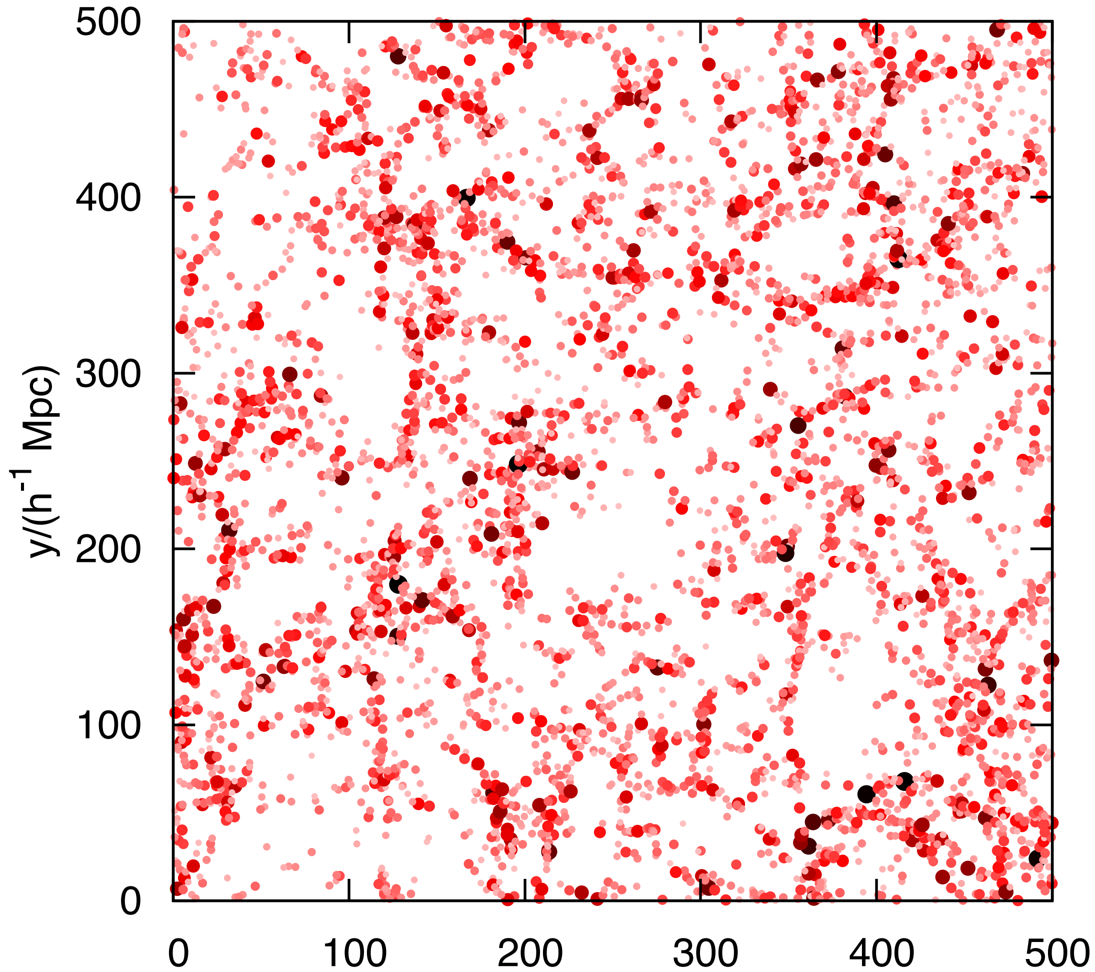
Simulated



ΛCDM



f(R)



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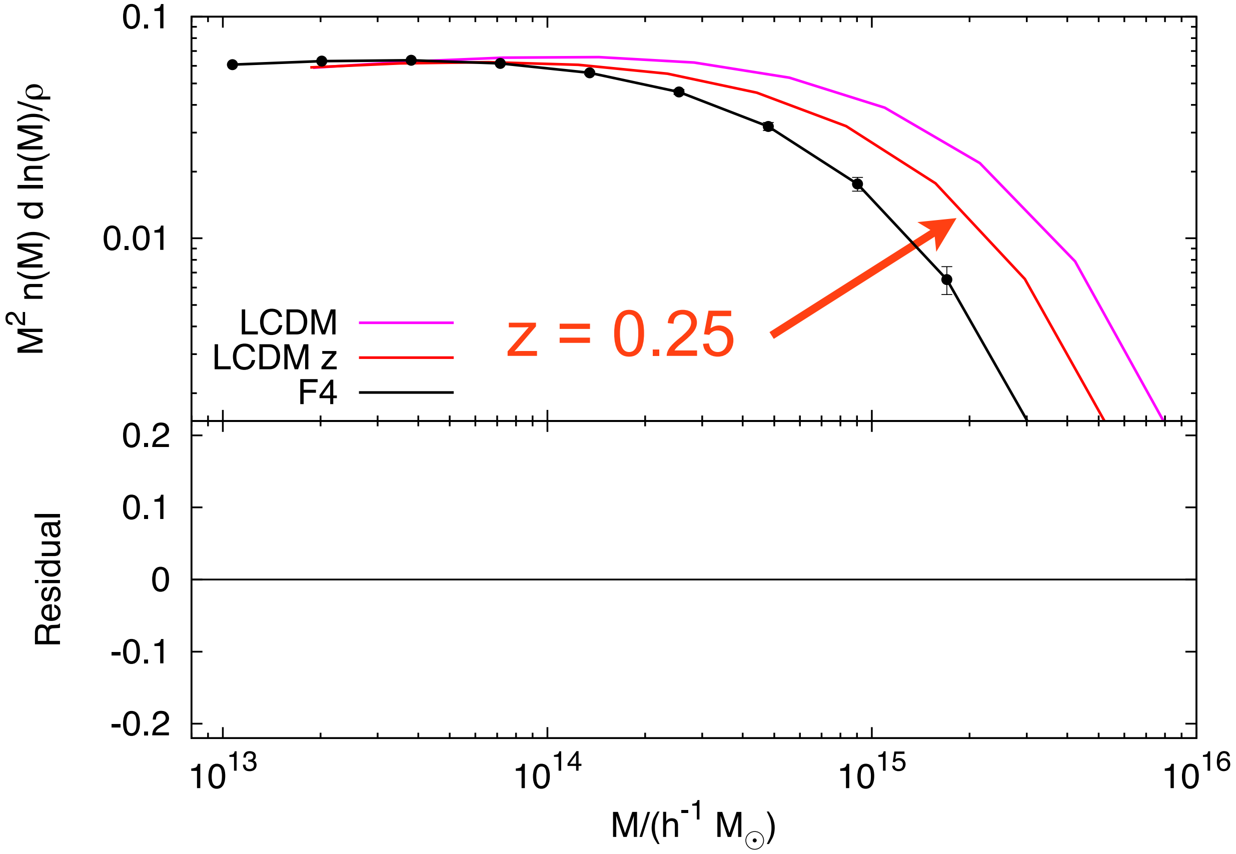

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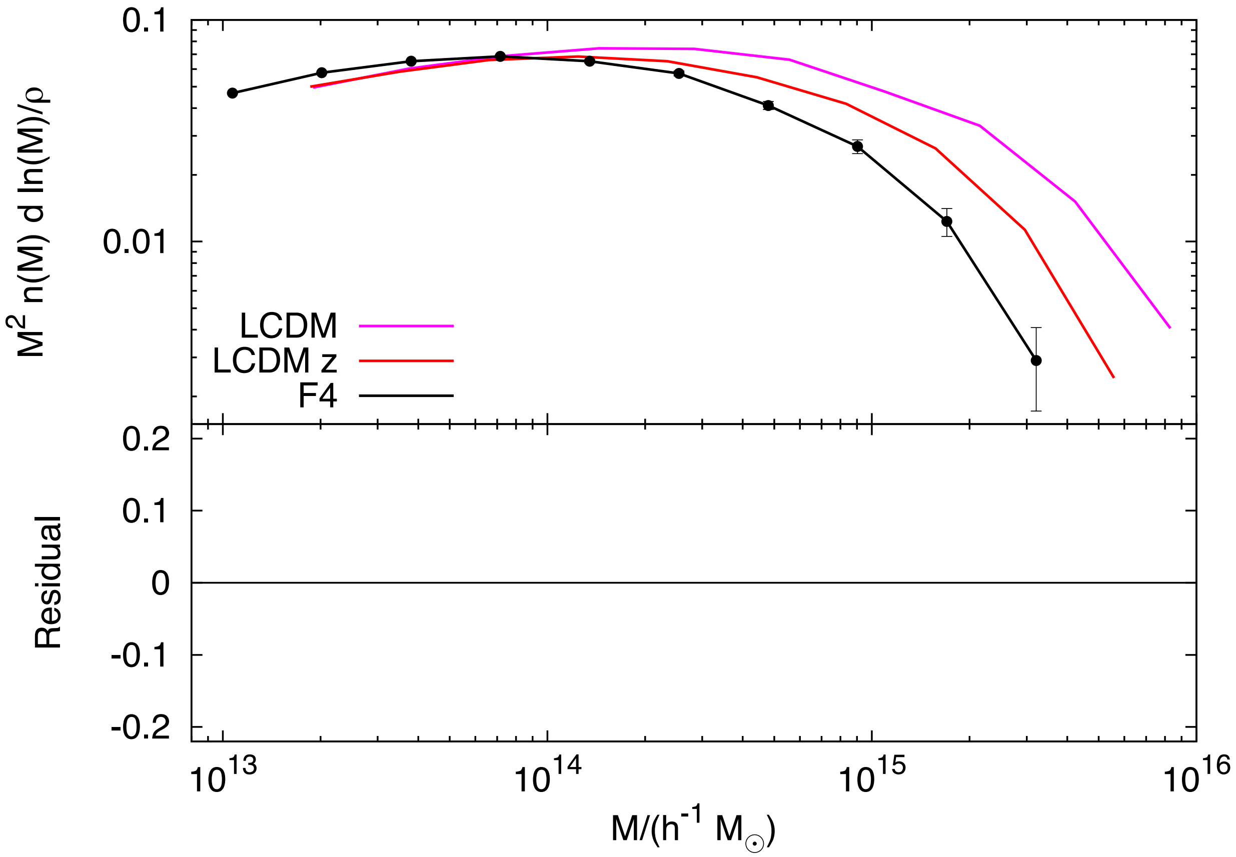
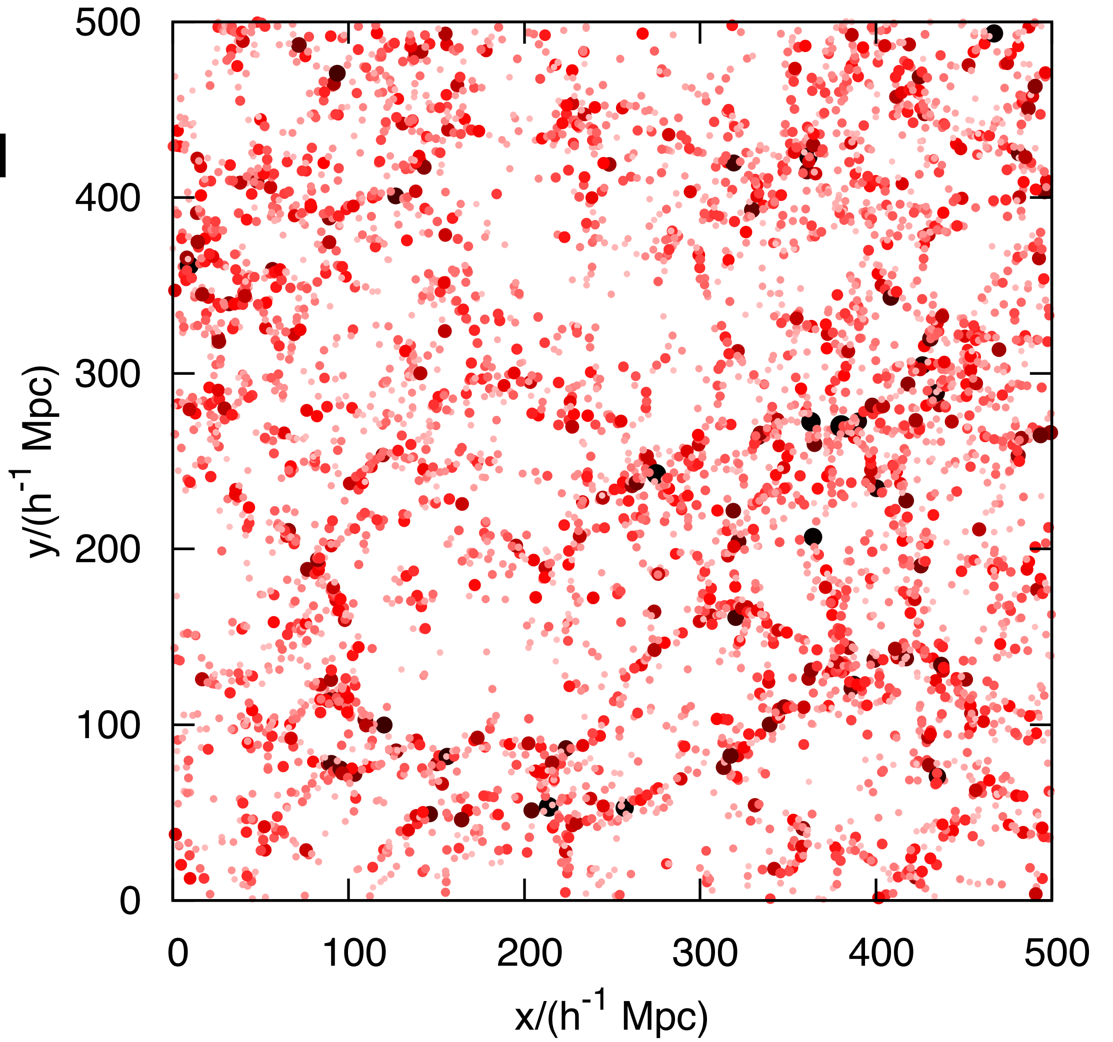
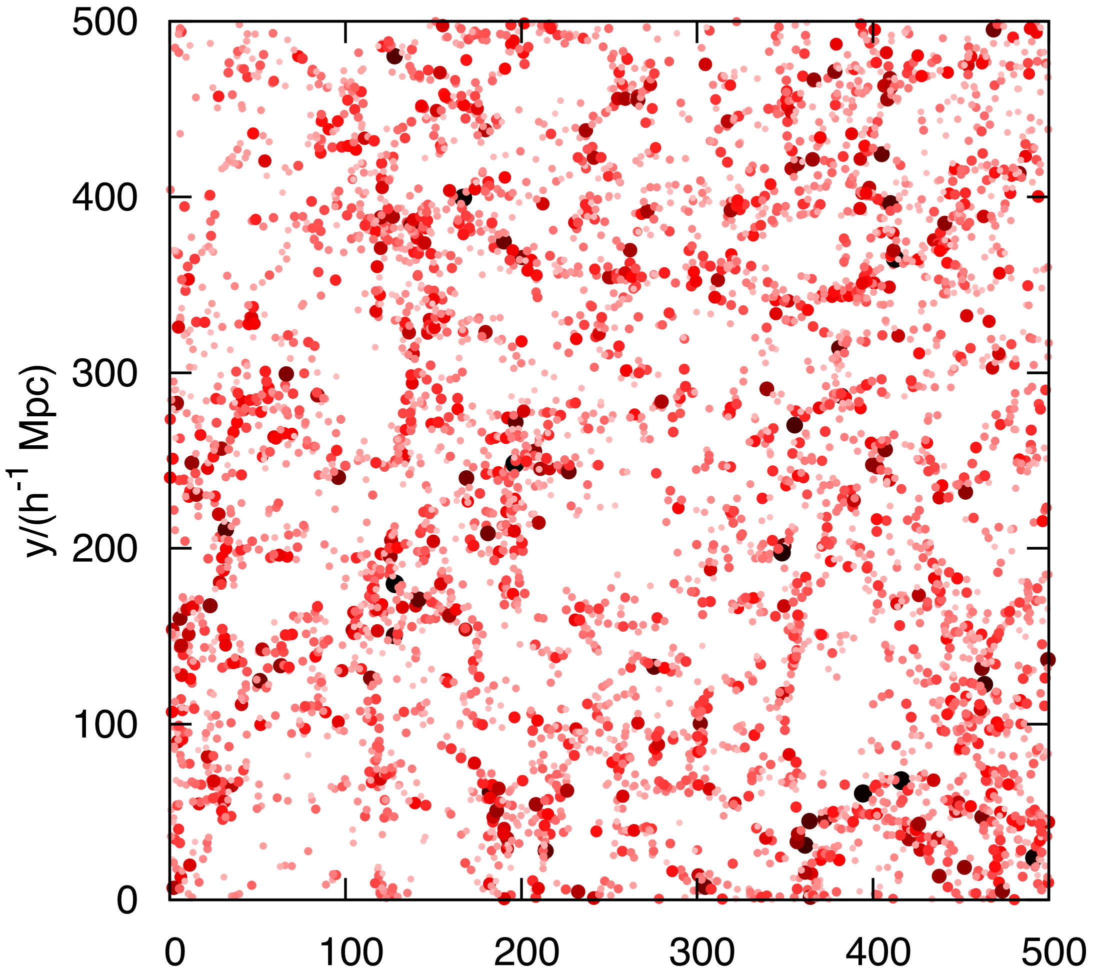


ΛCDM



f(R)



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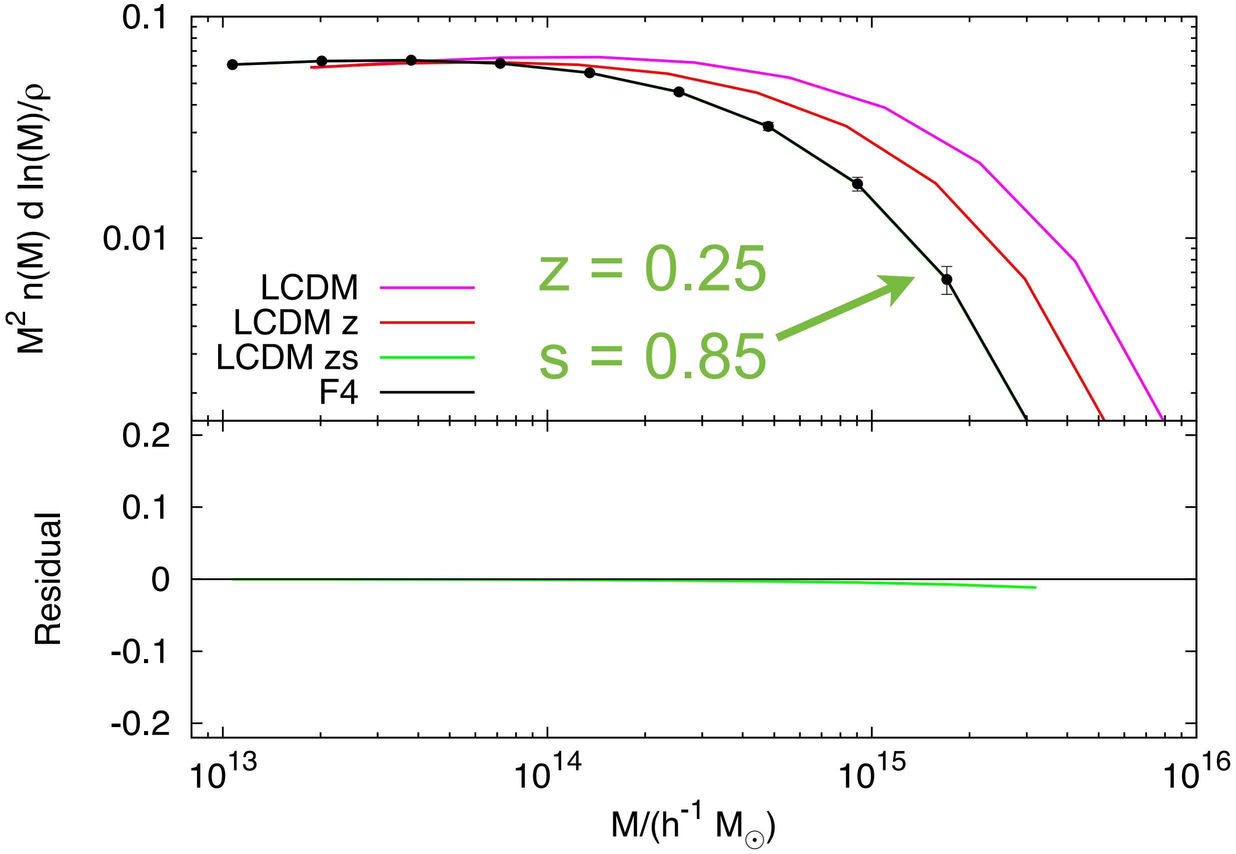

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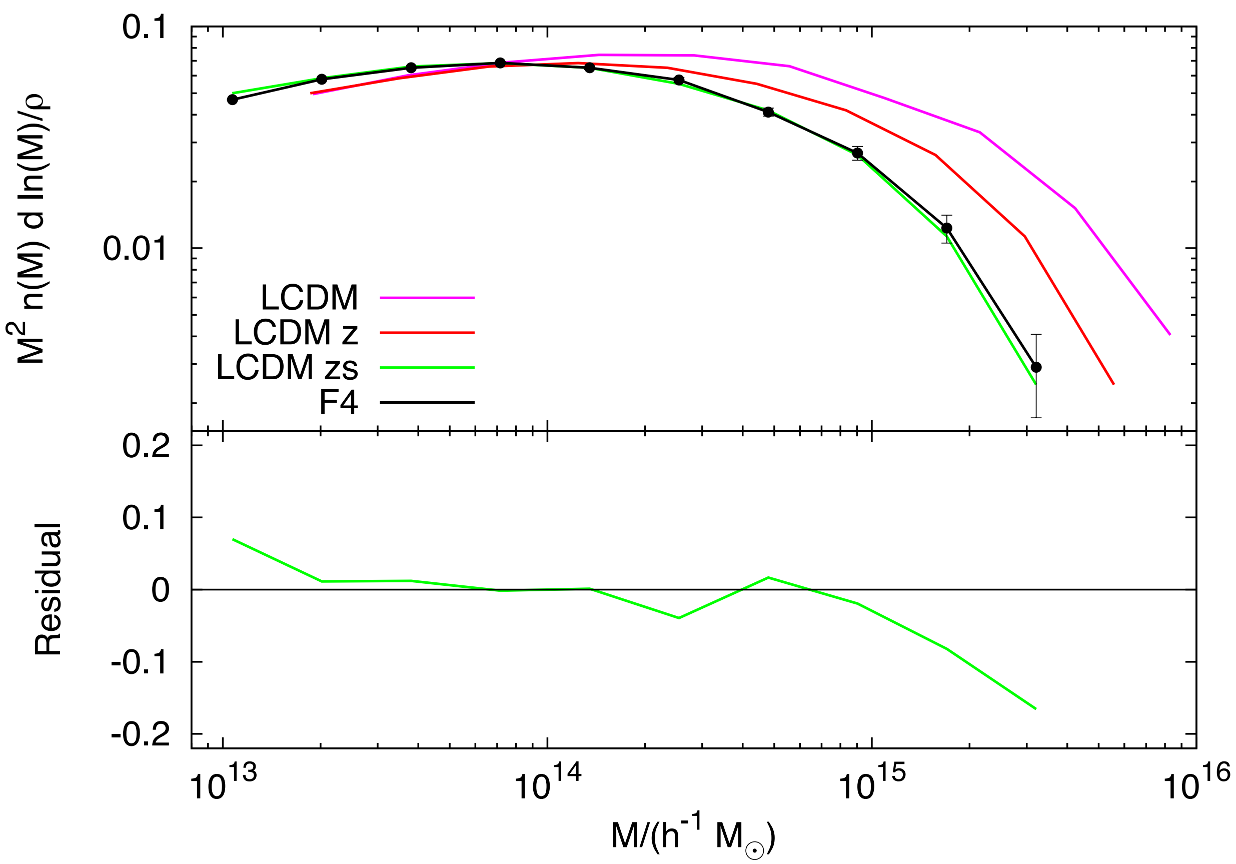
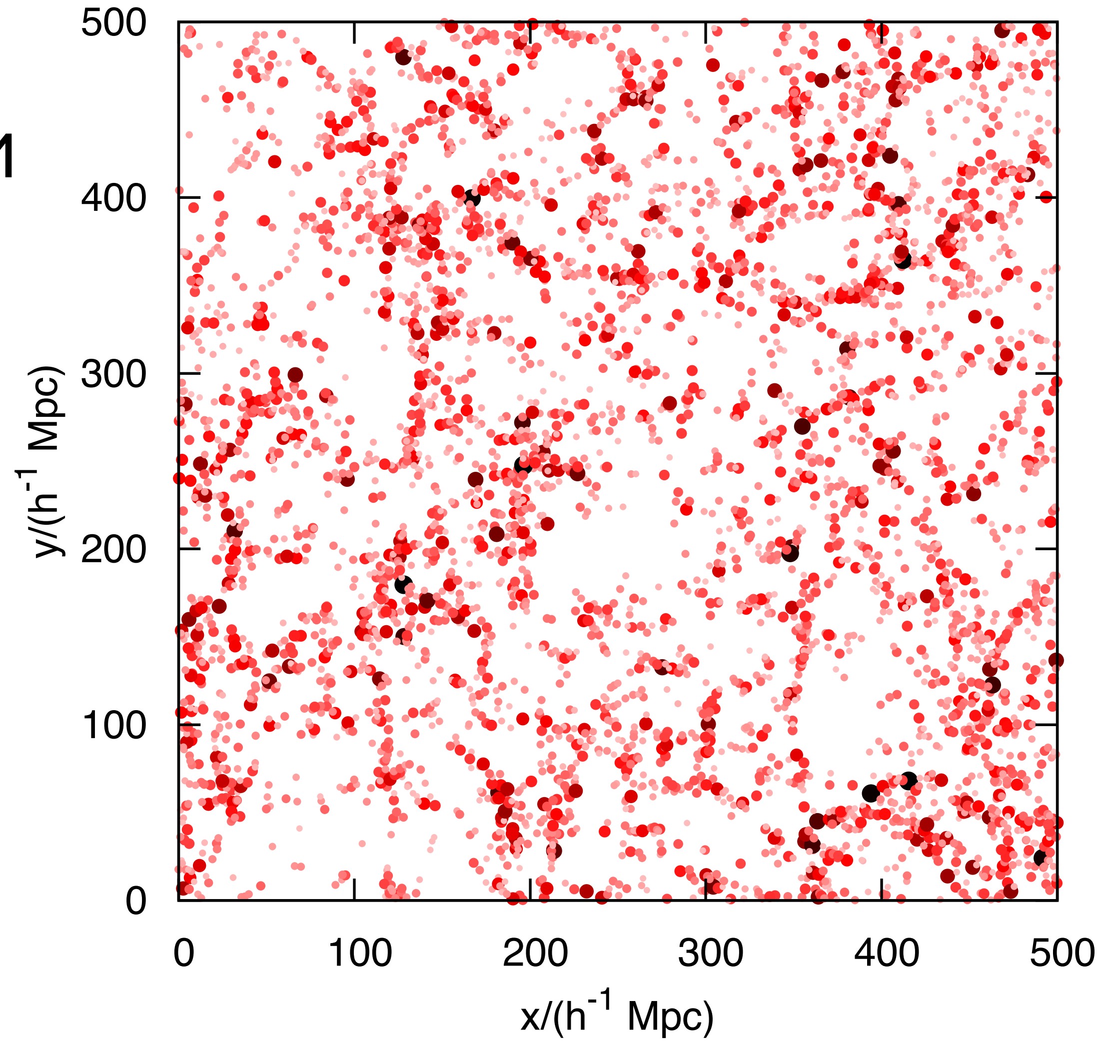
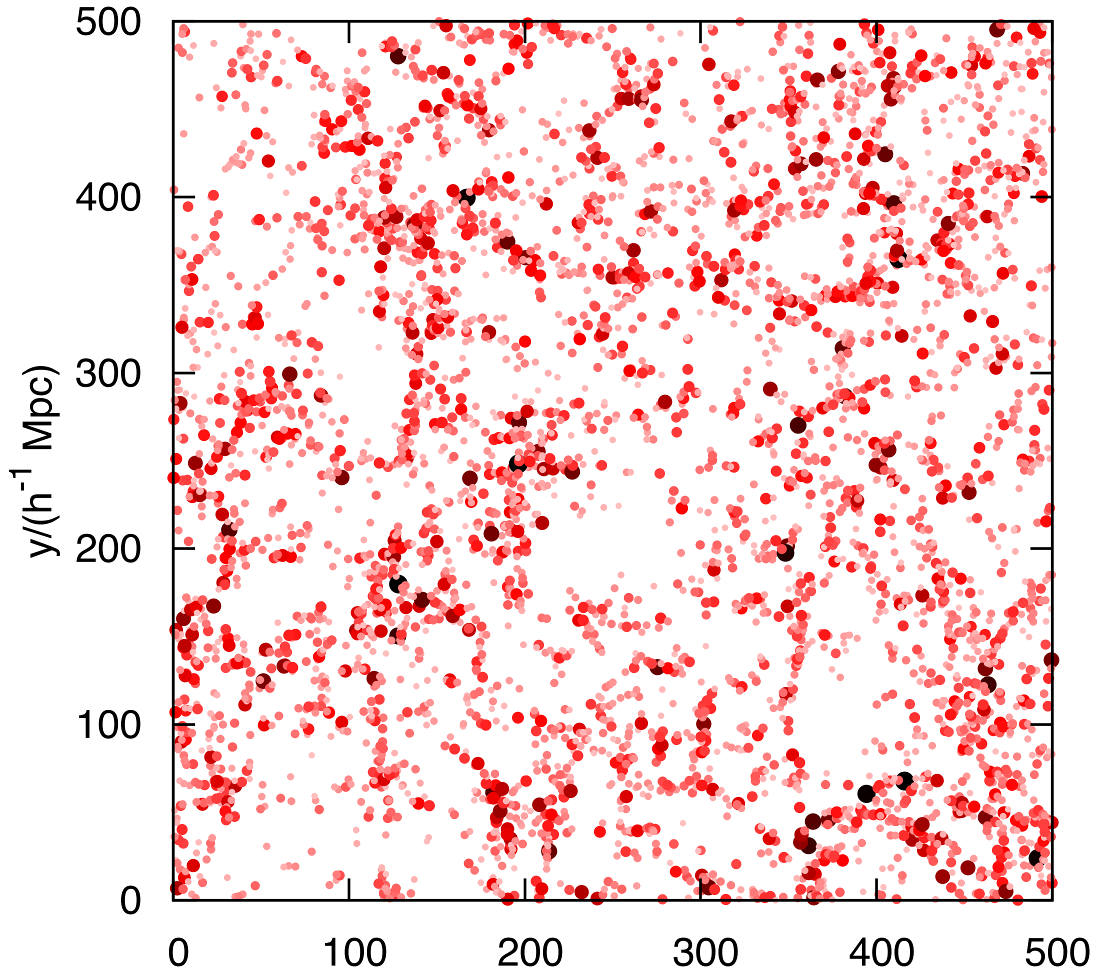


ΛCDM



f(R)



Clustering

- There remains a difference in matter clustering after this rescaling process

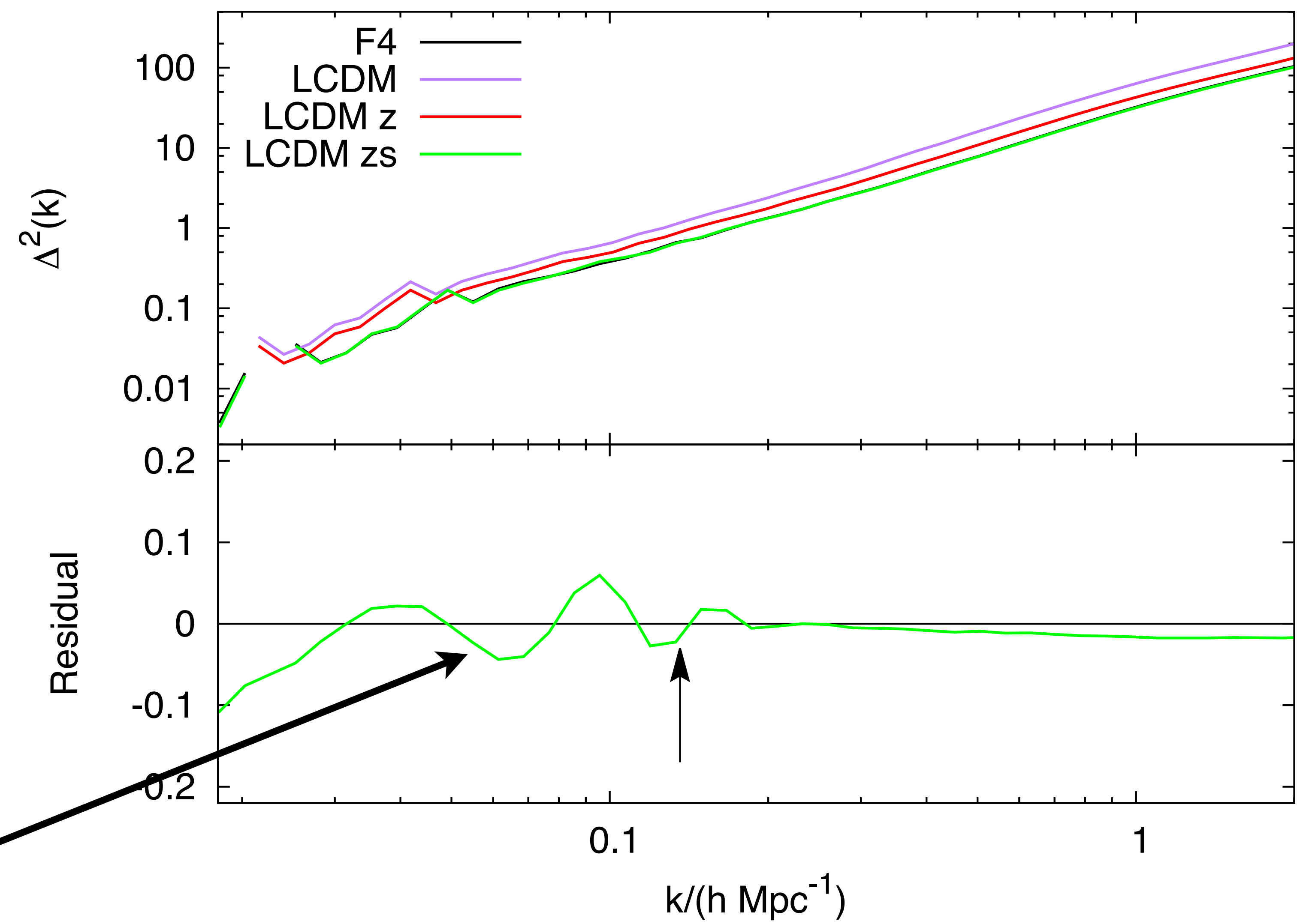
$$\mathbf{x} = \mathbf{q} + \mathbf{f}$$

$$\delta = -\nabla \cdot \mathbf{f}$$

$$\mathbf{f_k} = -i\frac{\delta_\mathbf{k}}{k^2}\mathbf{k}$$

$$\mathbf{x}' = s\left[\mathbf{x} + \left(\sqrt{\frac{\Delta'^2(k',z')}{\Delta^2(k,z)}} - 1\right)\mathbf{f}\right]$$

δf



Correct this!

Reconstruction

- Aim to reconstruct displacement fields
- Use density fields in simulation

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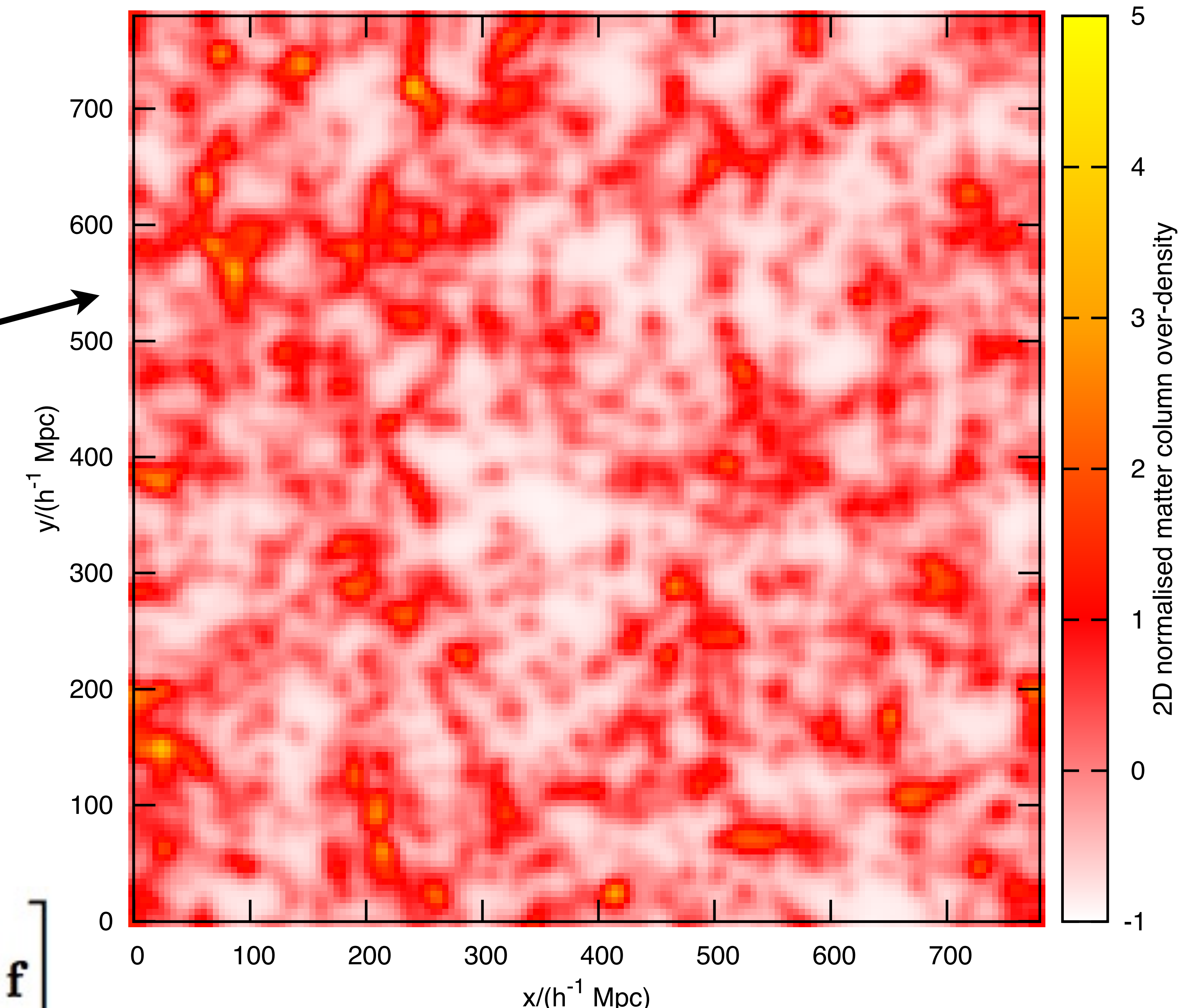

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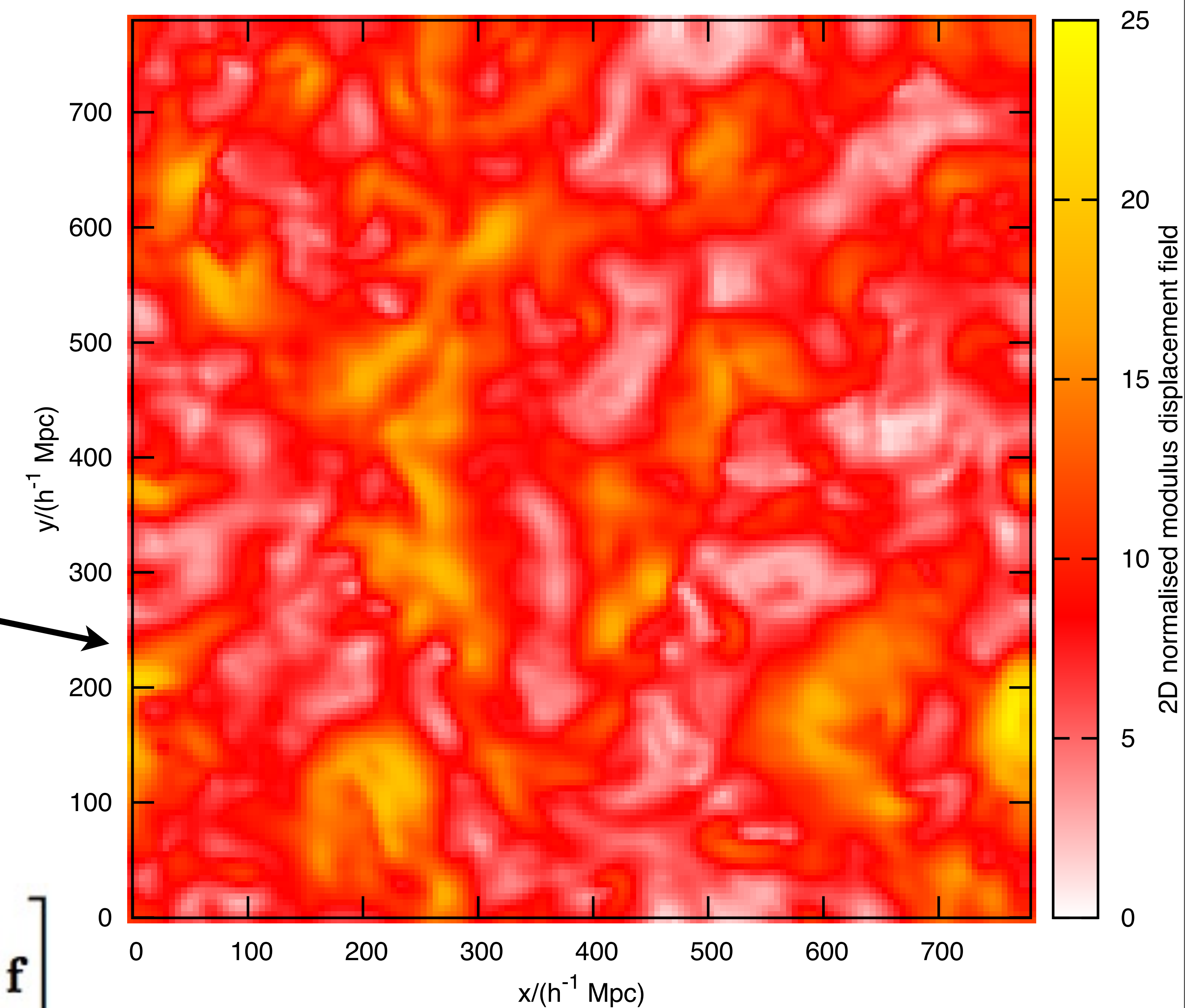

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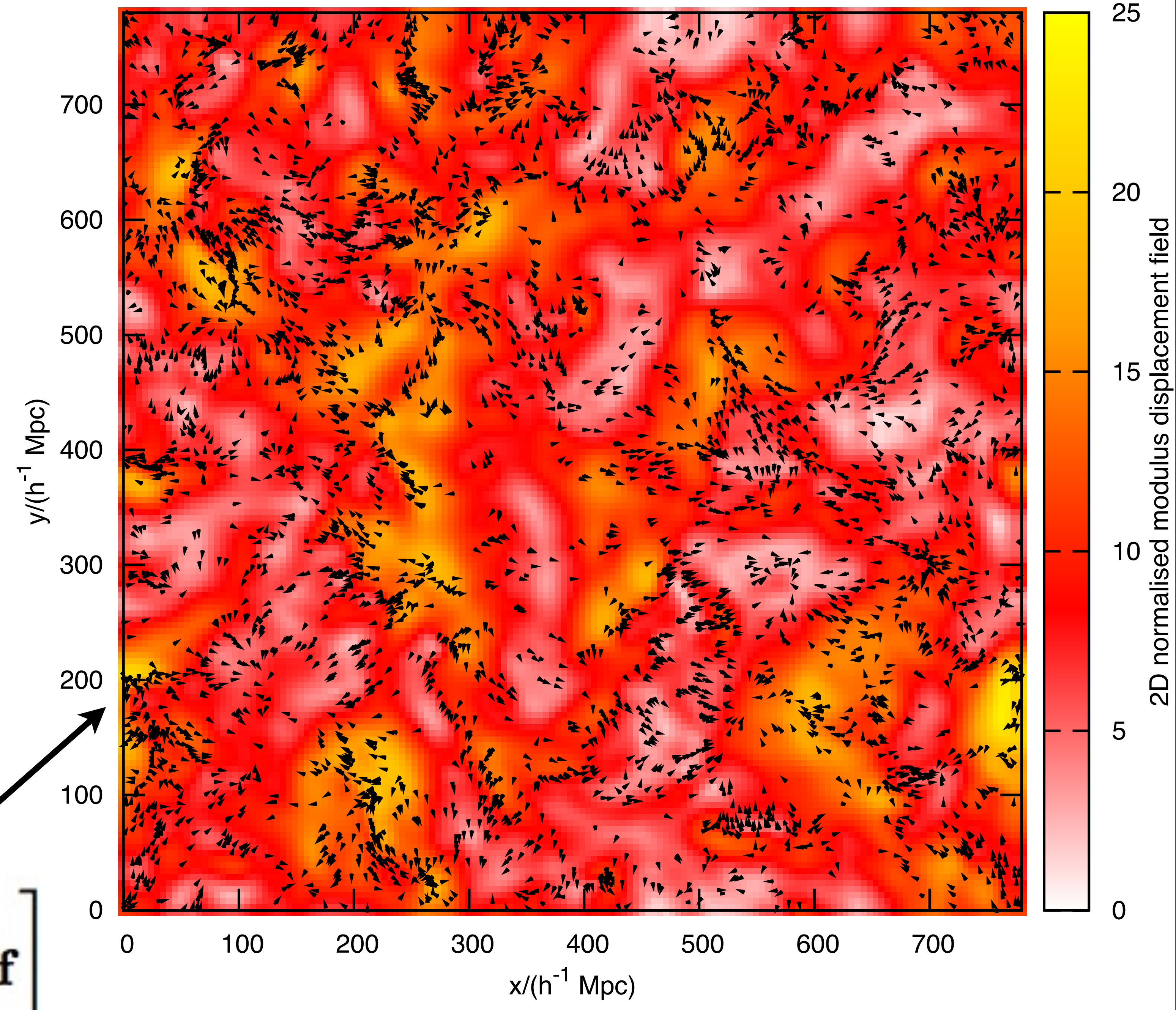
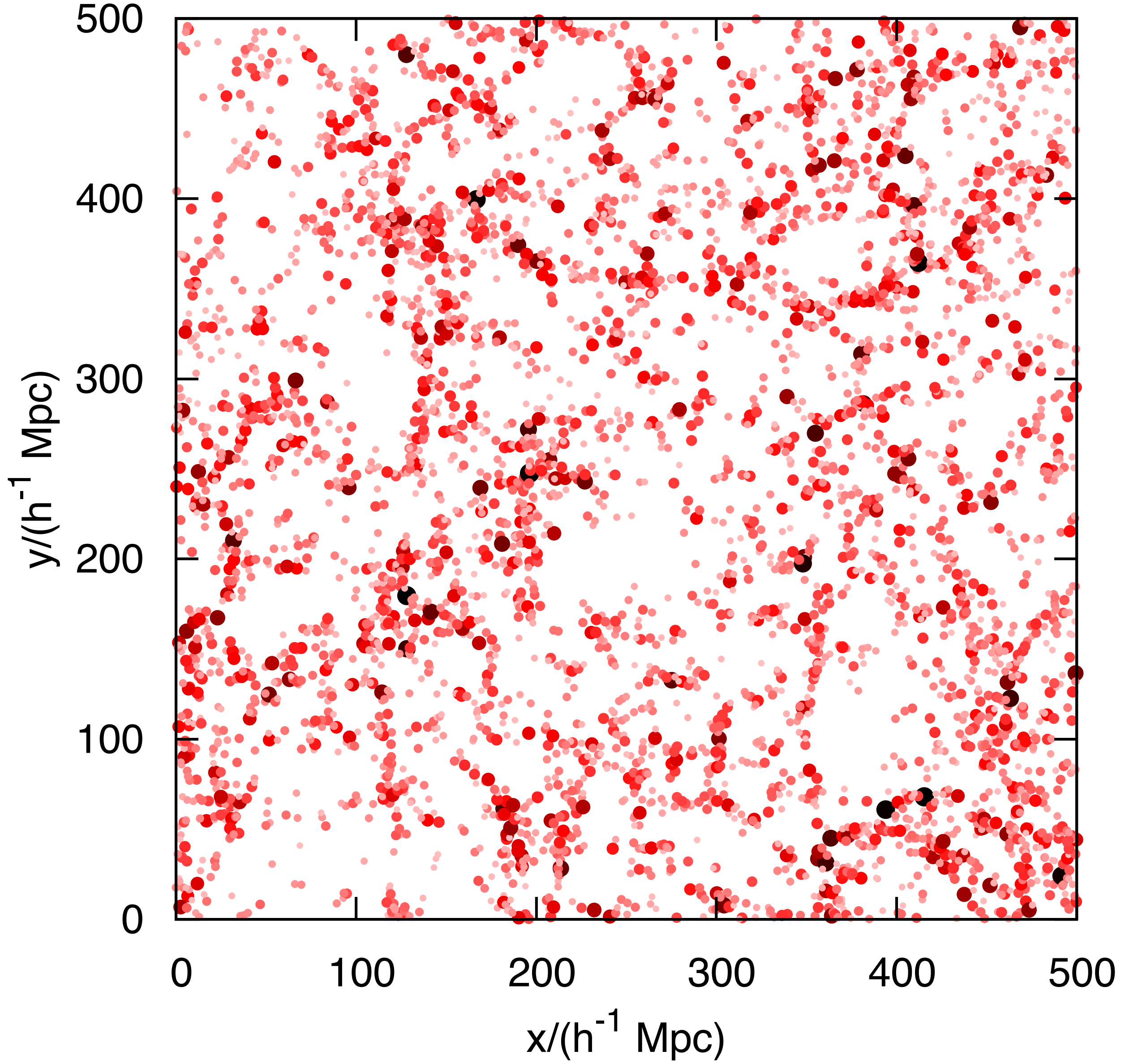
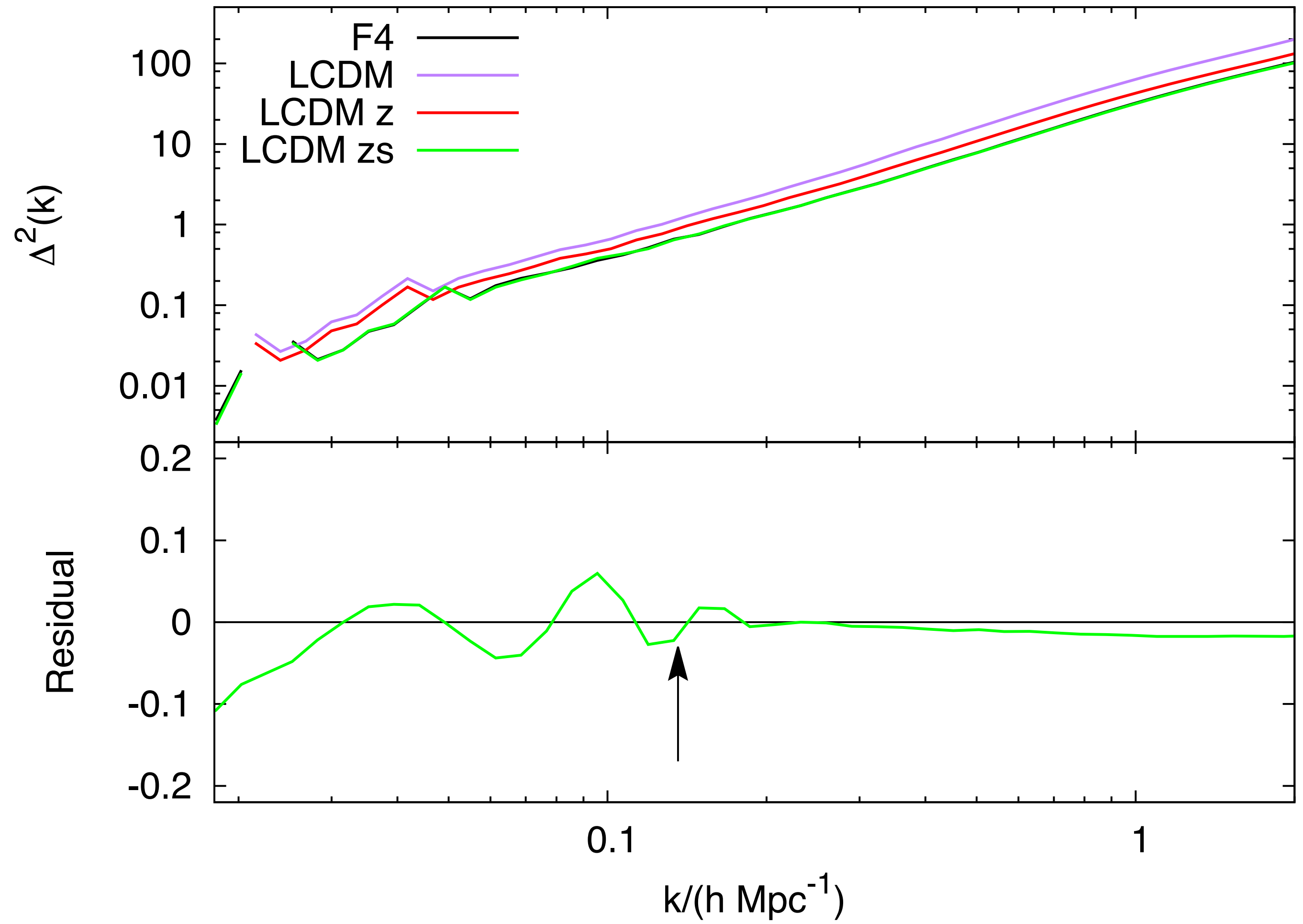


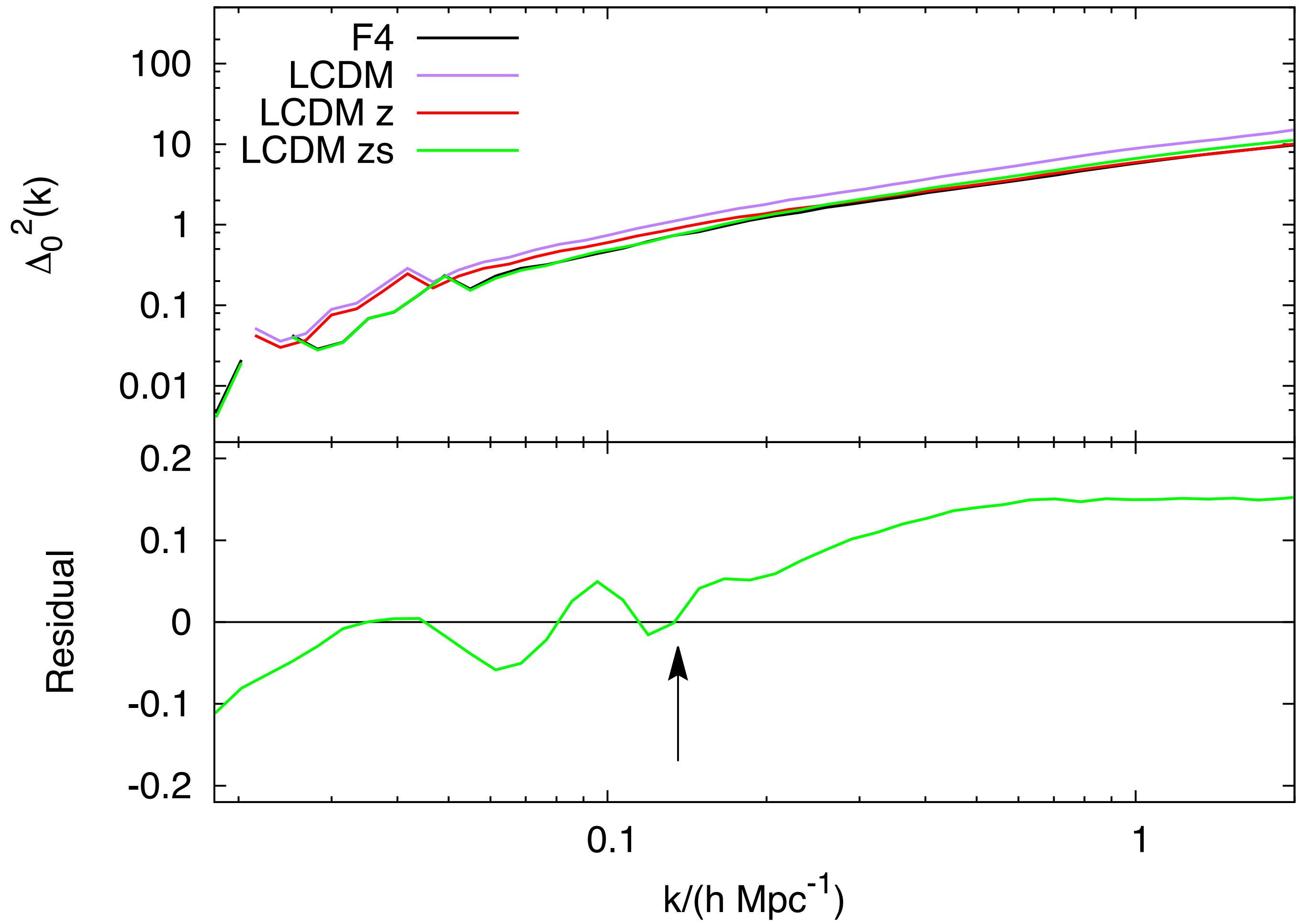
Clustering



500
400
300
200
100
0
0
100
200
300
400
500
y/(h^-1 Mpc)
x/(h^-1 Mpc)

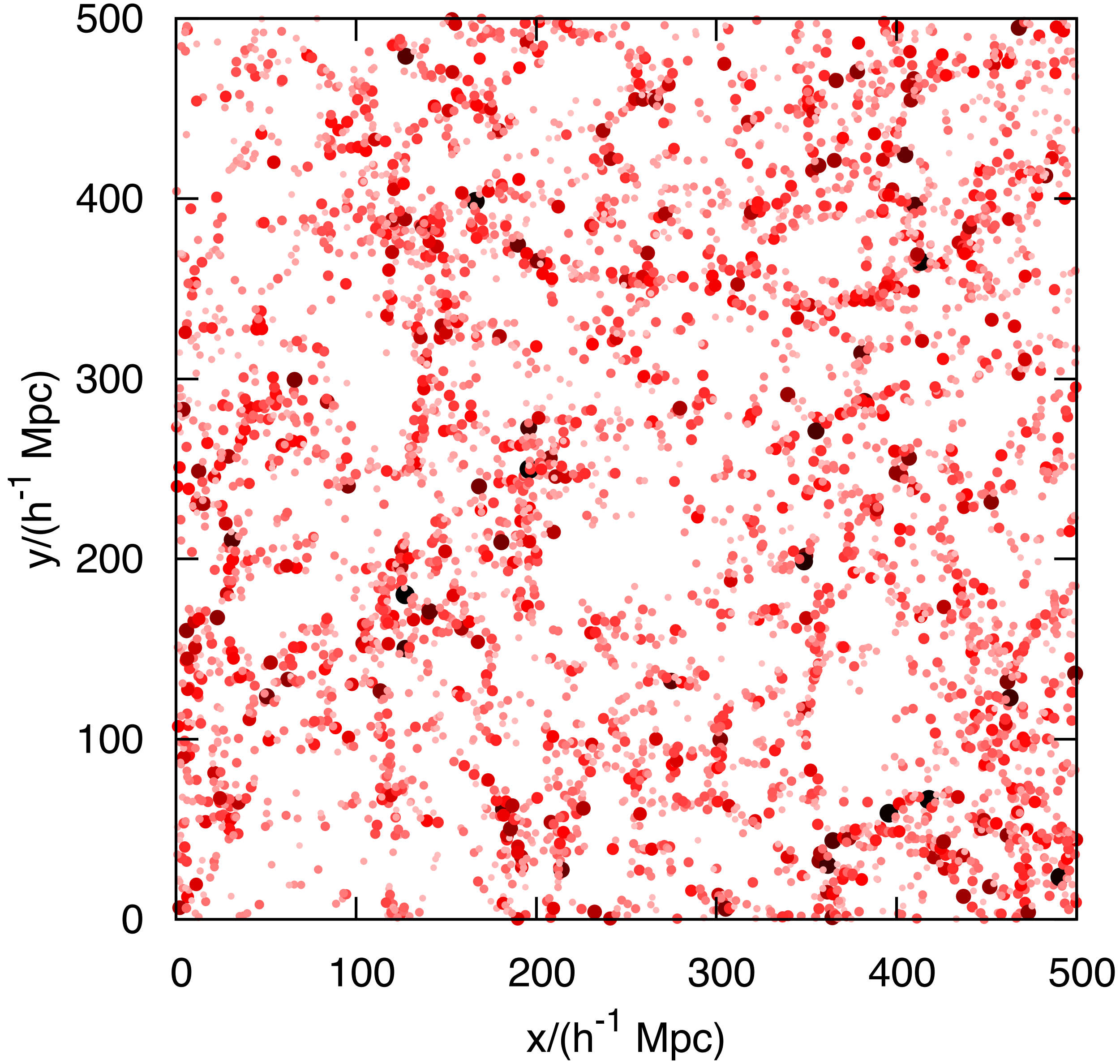


F4
LCDM
LCDM z
LCDM zs
100
10
1
0.1
0.01
Δ^2(k)
0.2
0.1
0
-0.1
-0.2
Residual
0.1
1
k/(h Mpc^-1)

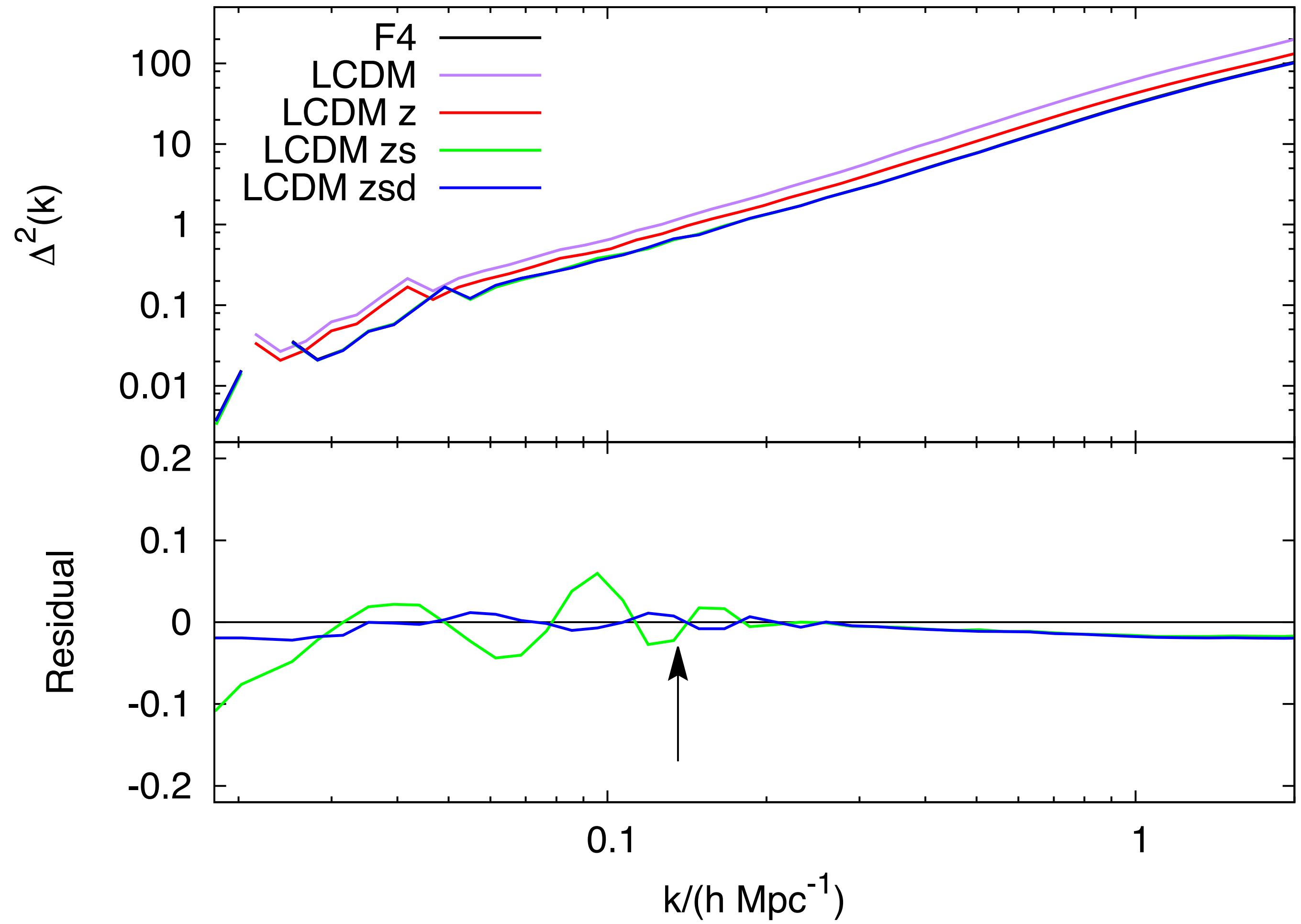


F4
LCDM
LCDM z
LCDM zs
100
10
1
0.1
0.01
Δ_0^2(k)
0.2
0.1
0
-0.1
-0.2
Residual
0.1
1
k/(h Mpc^-1)

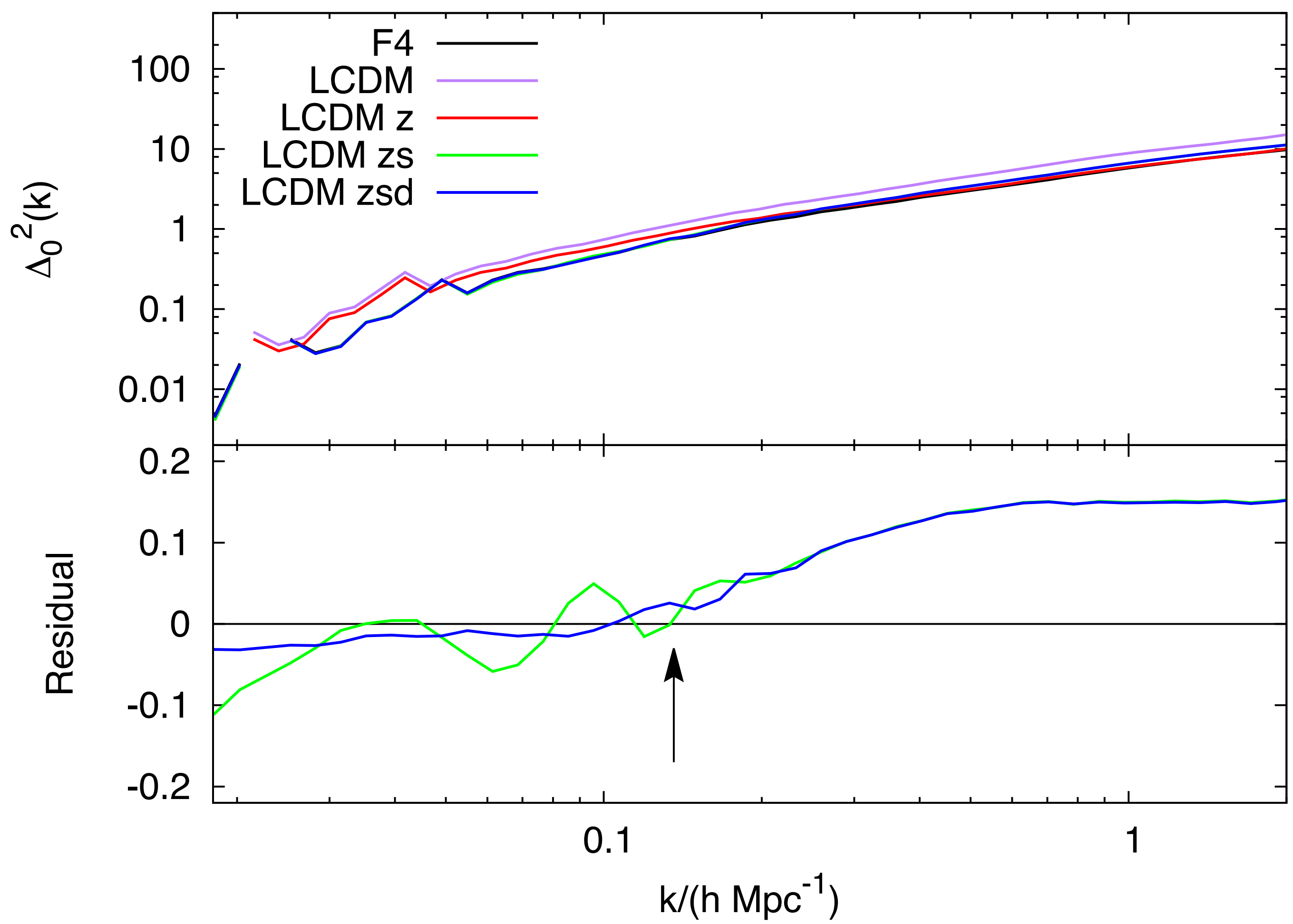
Clustering



y/(h^{-1} Mpc)
x/(h^{-1} Mpc)
0
100
200
300
400
500



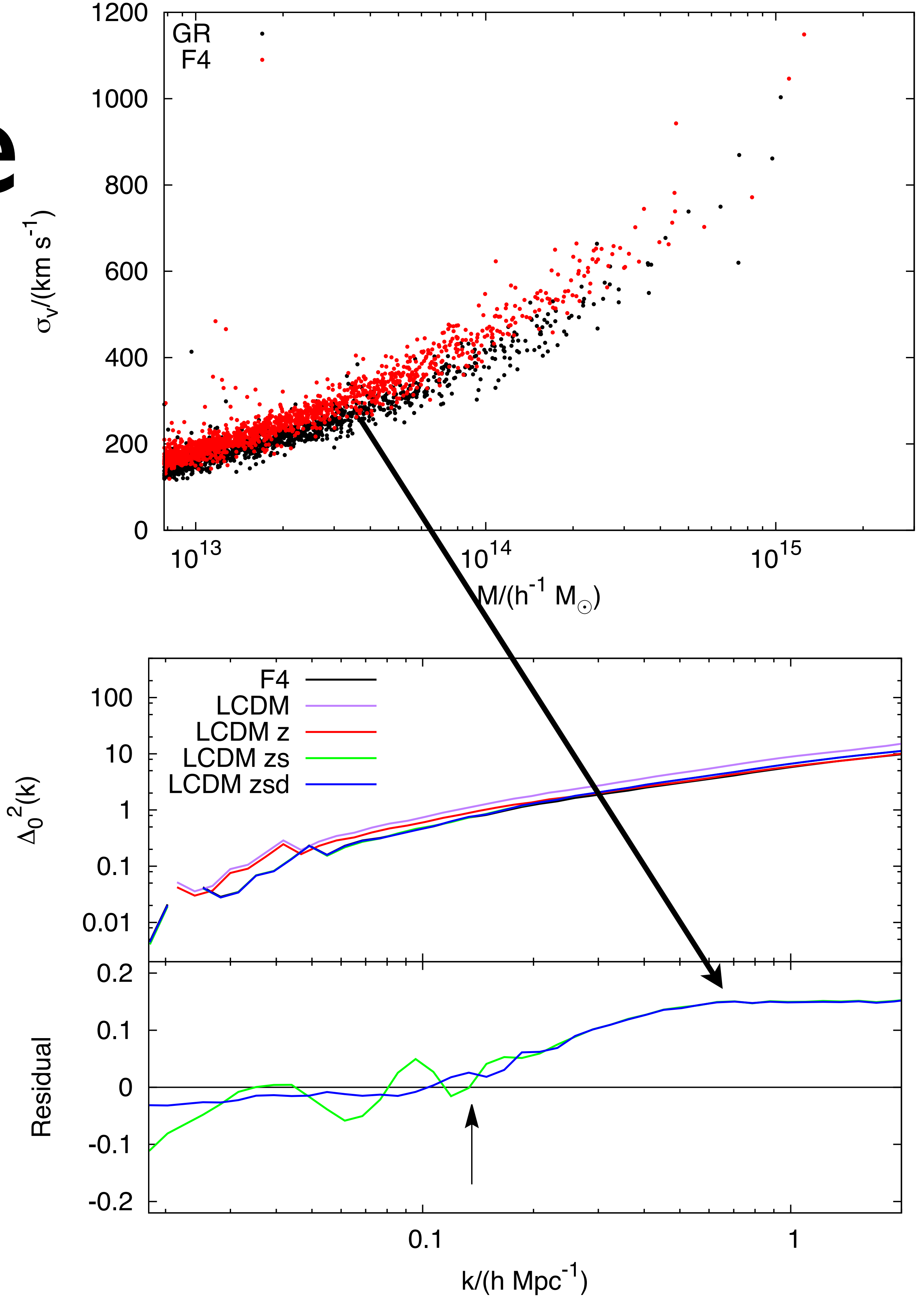
F4
LCDM
LCDM z
LCDM zs
LCDM zsd
$\Delta^2(k)$
Residual
k/(h Mpc^{-1})



F4
LCDM
LCDM z
LCDM zs
LCDM zsd
$\Delta_0^2(k)$
Residual
k/(h Mpc^{-1})

Redshift space

- Enhanced gravity not implemented yet
- Some f(R) haloes unscreened while all scaled haloes will be 'screened'
- Finger-of-God damping is thus not large enough in the scaled simulation
- Rectify by restructuring the halo



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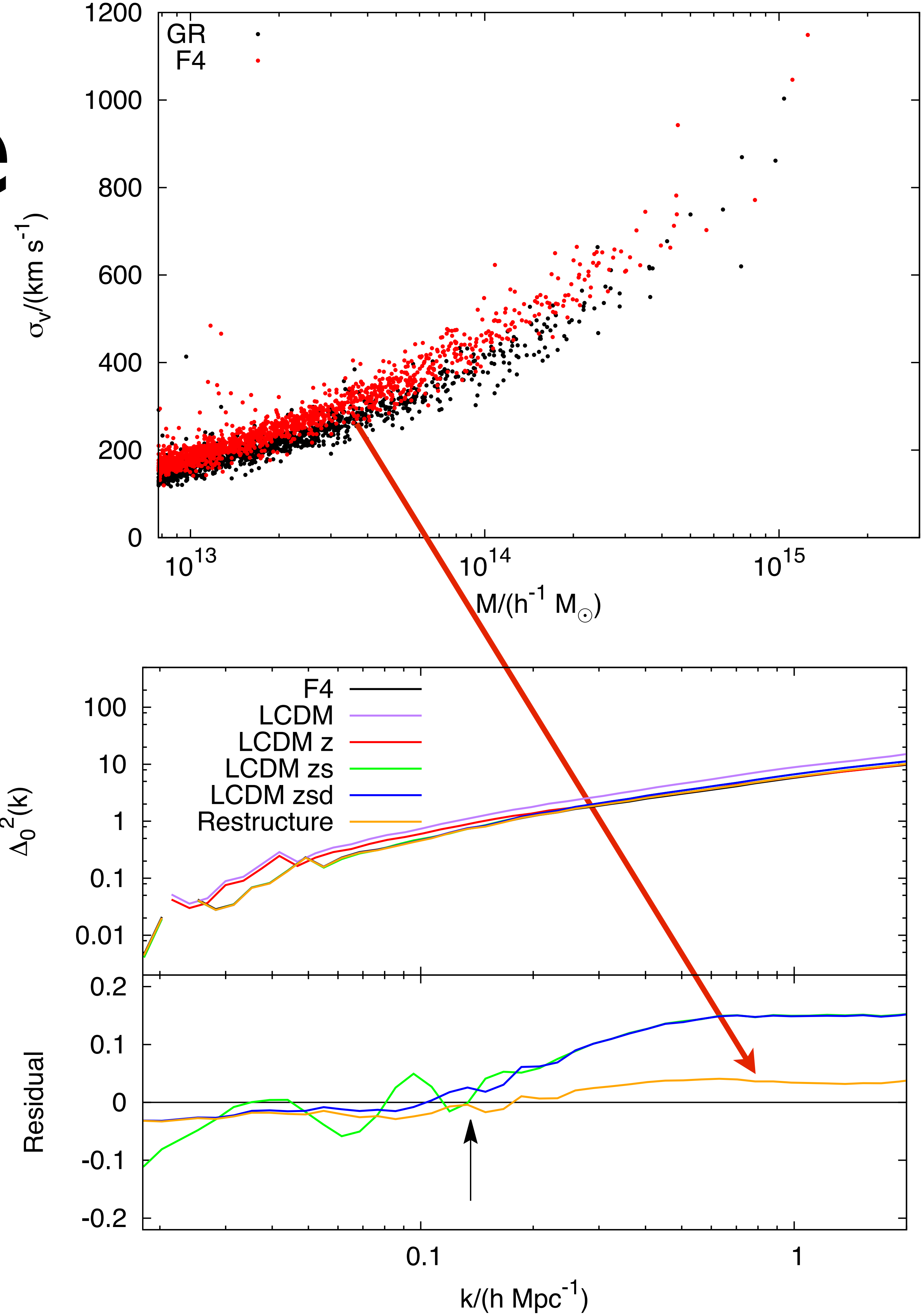

Summary

- Original simulation is scaled in:
  - Box size (L ⟶ sL)
  - Redshift
- Corrects mass function
- Clustering corrected for using Zel'dovich approximation
- No tuned parameters
- Takes ~ minutes
- Only requires particles or catalogue