Lyman-alpha power spectrum as a probe of modified gravity

Cosmo-Club
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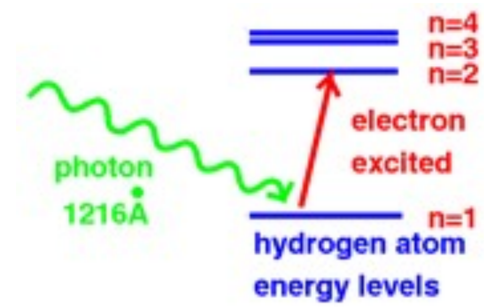
arXiv:1810.06661

0. LYMAN-ALPHA FOREST PHYSICS

J. Cohn webpage

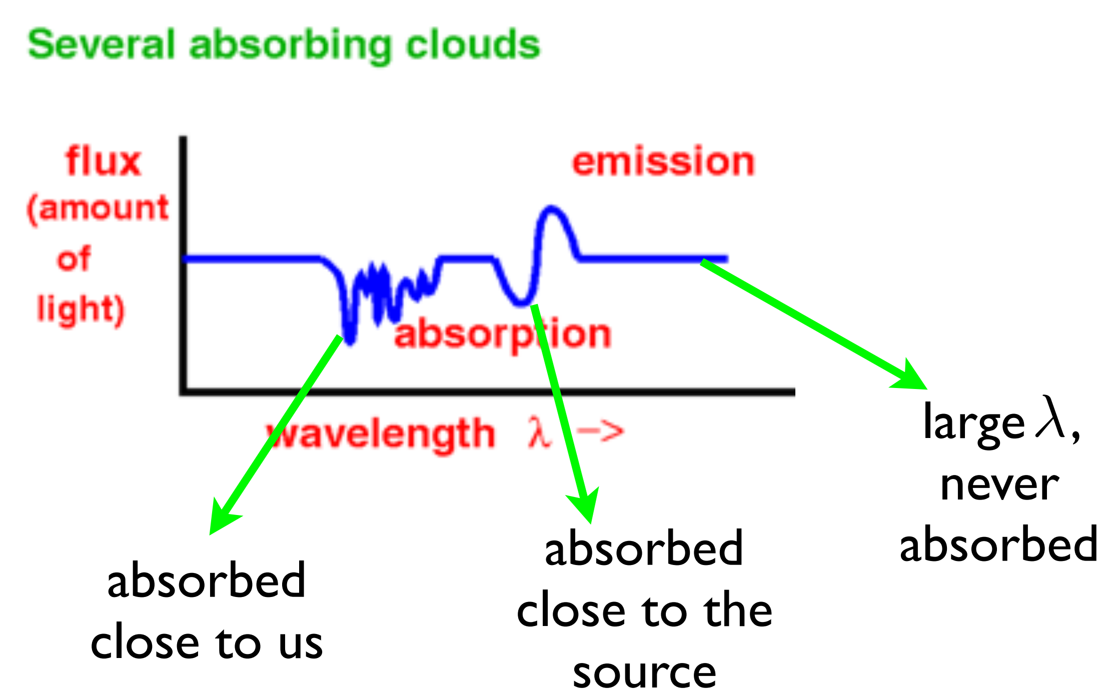
Absorption of light by neutral hydrogen



Absorption along the line of sight
by clouds (or density fluctuations)

Because of the Hubble expansion, the wavelength of the light ray from the source grows with time

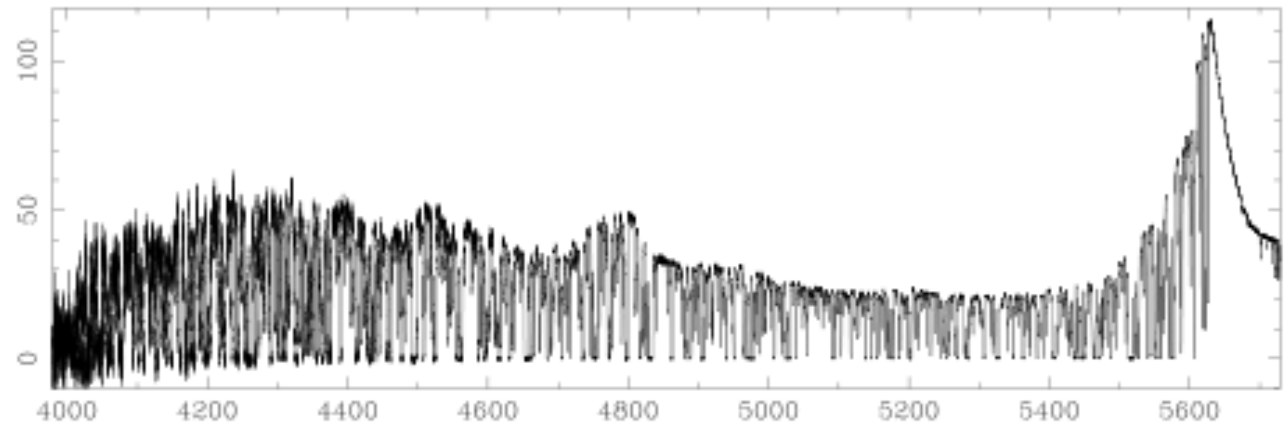
The absorption takes place at the position along the line of sight where the photon was at 1216 A



→ the measured spectrum is a map of the density along the line of sight !

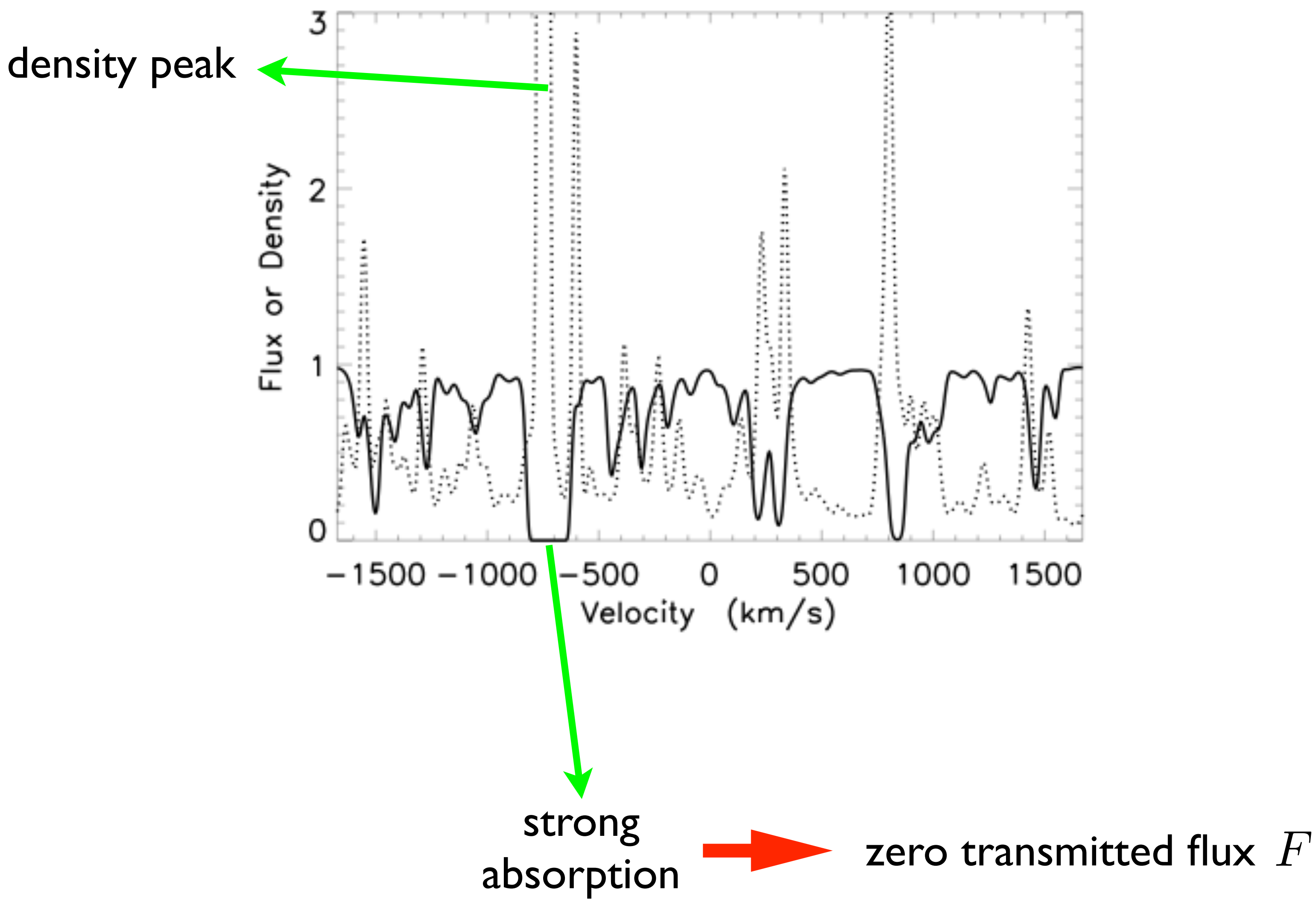
M. White

Spectrum of the light received from a distant quasar



QSO 1422+23

Spectrum '=' density



M. White

Galaxy-IGM connection

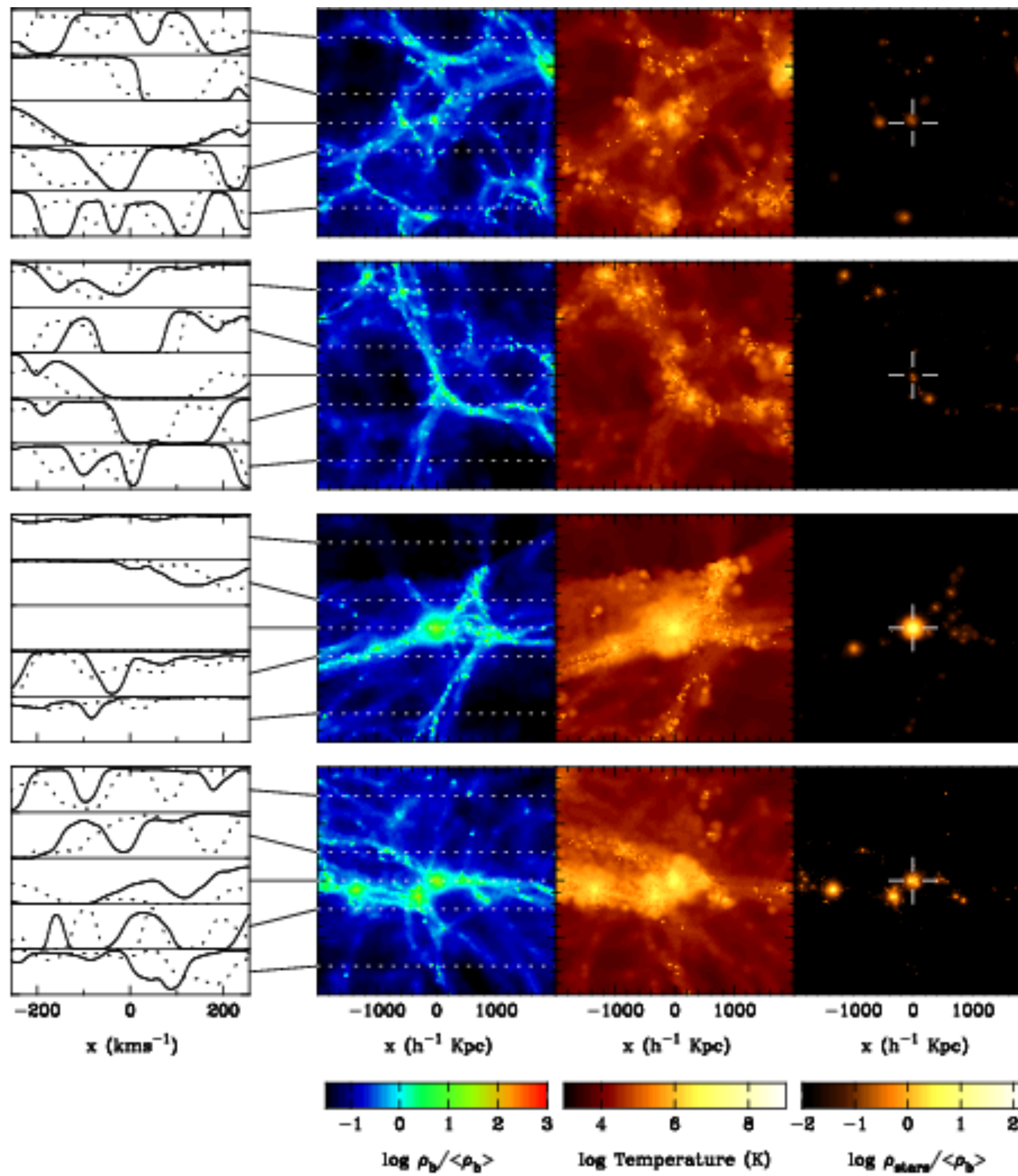
Probe of the IGM

↓

Matter distribution on large scales

↓

Moderate density fluctuations in filaments and pancakes, outside of galaxies (which correspond to Lyman-limit or damped systems)



I. MODIFIED-GRAVITY THEORIES

A- 5th force

Scalar-tensor theories: add a new scalar field φ

5th force → typically amplifies gravity and the growth of perturbations.

On small scales, quasi-static approximation, linear regime:

$$\tilde{\delta}'' + \mathcal{H}\tilde{\delta}' - \frac{3\Omega_{\rm m}}{2}\mathcal{H}^2\mu(k,a)\tilde{\delta} = 0,$$

$$\mu(k,a) = 1 + \epsilon(k,a) \qquad \epsilon(k,a) = \frac{2\beta^2(a)}{1+\frac{m^2(a)a^2}{k^2}}.$$

coupling strength (β)

mass (1/range) of the scalar field (m)

B- f(R) theories

$$S_{f(R)} = \frac{1}{16\pi\mathcal{G}_{\rm N}} \int d^4x \sqrt{-g}\, f(R)$$

$$f(R) = R - 2\Lambda^2 - f_{R_0} \frac{R_0^2}{R},$$

$$f_{R_0} = -10^{-4},\ -10^{-5}\ \text{and}\ -10^{-6}.$$

Strong lensing, dynamics in dwarfs, equiv. principle in solar system:

$$|f_{R_0}| \lesssim 10^{-6}$$

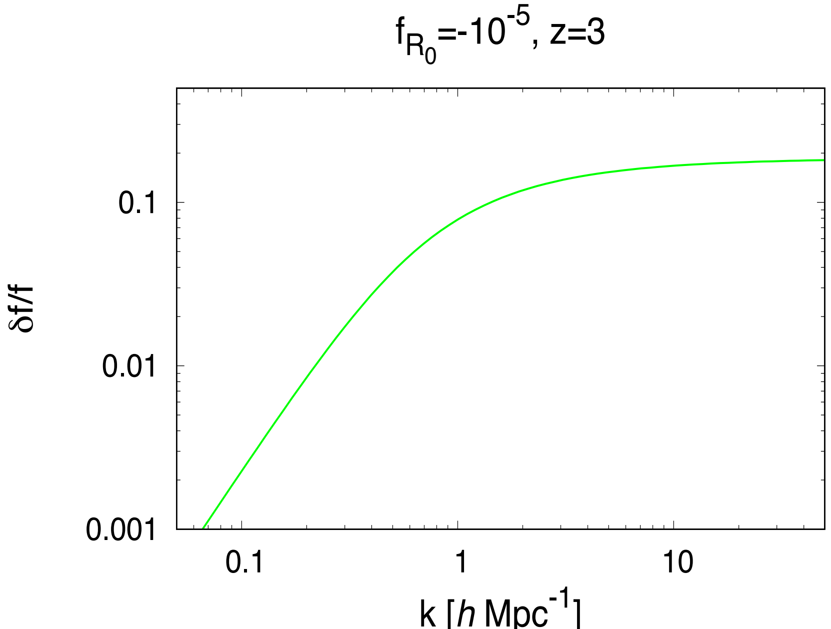
Background=LCDM, perturbations slightly amplified.

$$\beta = 1/\sqrt{6}$$

$$m_0 = \frac{H_0}{c} \sqrt{\frac{\Omega_{m0} + 4\Omega_{\Lambda 0}}{(n+1)|f_{R_0}|}} \sim 1 \mathrm{Mpc}^{-1}$$

Relative deviation of the linear growth-rate from LCDM:

$$f(k,a) = \frac{\partial \ln D_+}{\partial \ln a}(k,a).$$



C- K-mouflage model

$$S = \int d^4x \sqrt{-\tilde{g}} \left[\frac{\tilde{M}_{\rm Pl}^2}{2} \tilde{R} + \tilde{\mathcal{L}}_\varphi(\varphi) \right] + \int d^4x \sqrt{-g} \mathcal{L}_{\rm m}(\psi_{\rm m}^{(i)}, g_{\mu\nu})$$

coupling of matter to the scalar field: $g_{\mu\nu} = A^2(\varphi)\tilde{g}_{\mu\nu}.$ $A(\varphi) = 1 + \frac{\beta\varphi}{\tilde{M}_{\rm Pl}} + \dots,$

nonlinear kinetic function (screening): $\tilde{\mathcal{L}}_\varphi(\varphi) = \mathcal{M}^4 K(\tilde{\chi})$ with $\tilde{\chi} = -\frac{1}{2\mathcal{M}^4} \tilde{\nabla}^\mu \varphi \tilde{\nabla}_\mu \varphi.$

linear (unscreened) regime: $\tilde{\chi} \to 0: \; K(\tilde{\chi}) \simeq -1 + \tilde{\chi} + \dots,$

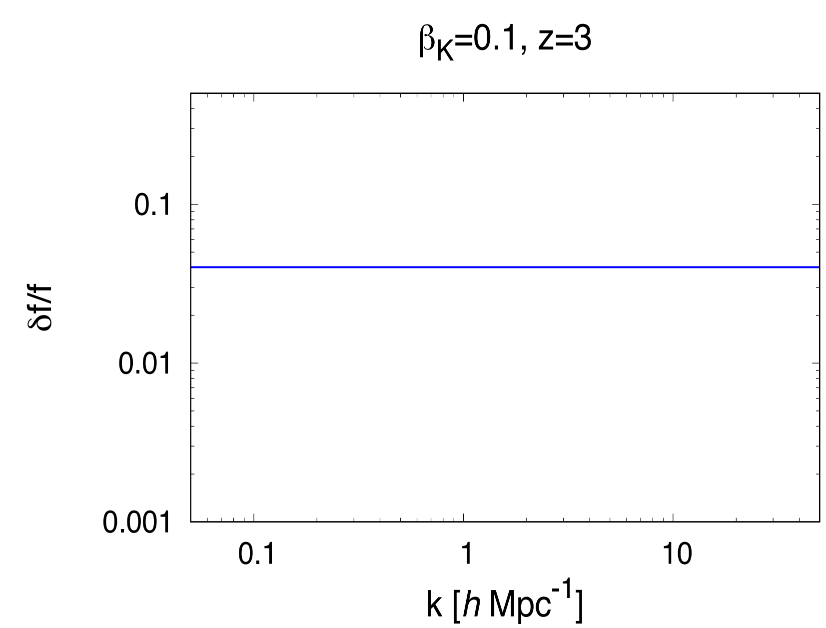
no potential → zero mass → long range, scale-independent

Both the background and the perturbations are slightly perturbed.

CMB, Solar System: $\beta \lesssim 0.1$

Relative deviation of the linear growth-rate from LCDM:

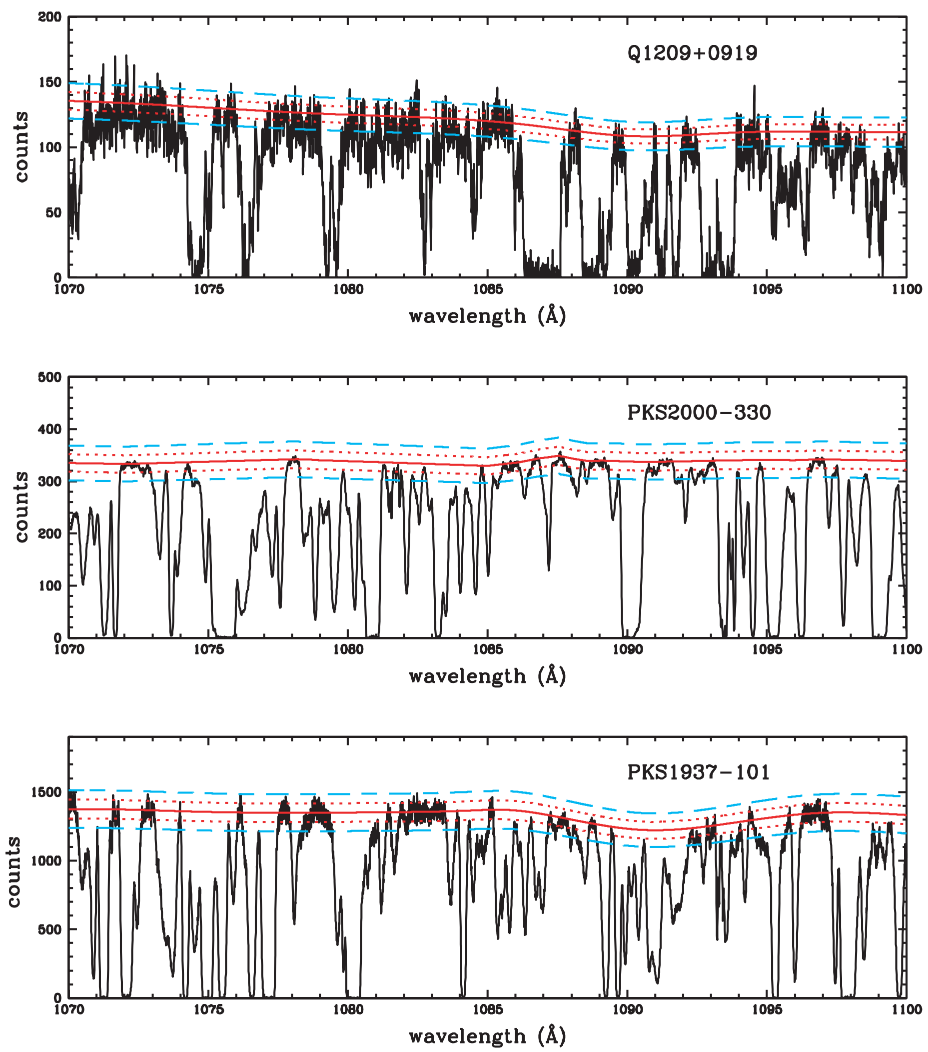
$$f(k,a) = \frac{\partial \ln D_+}{\partial \ln a}(k,a).$$



II. FLUX PROBABILITY DISTRIBUTION

Transmitted flux $F = e^{-\tau}$ $\tau \propto n_{HI}$

Probability distribution function $\mathcal{P}(F)$



data

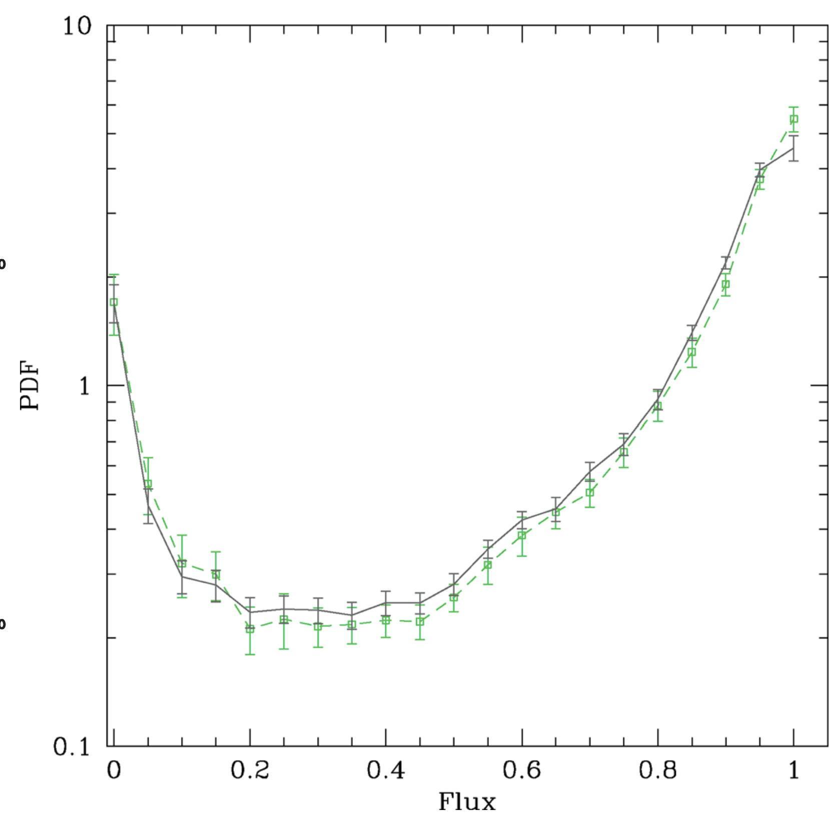
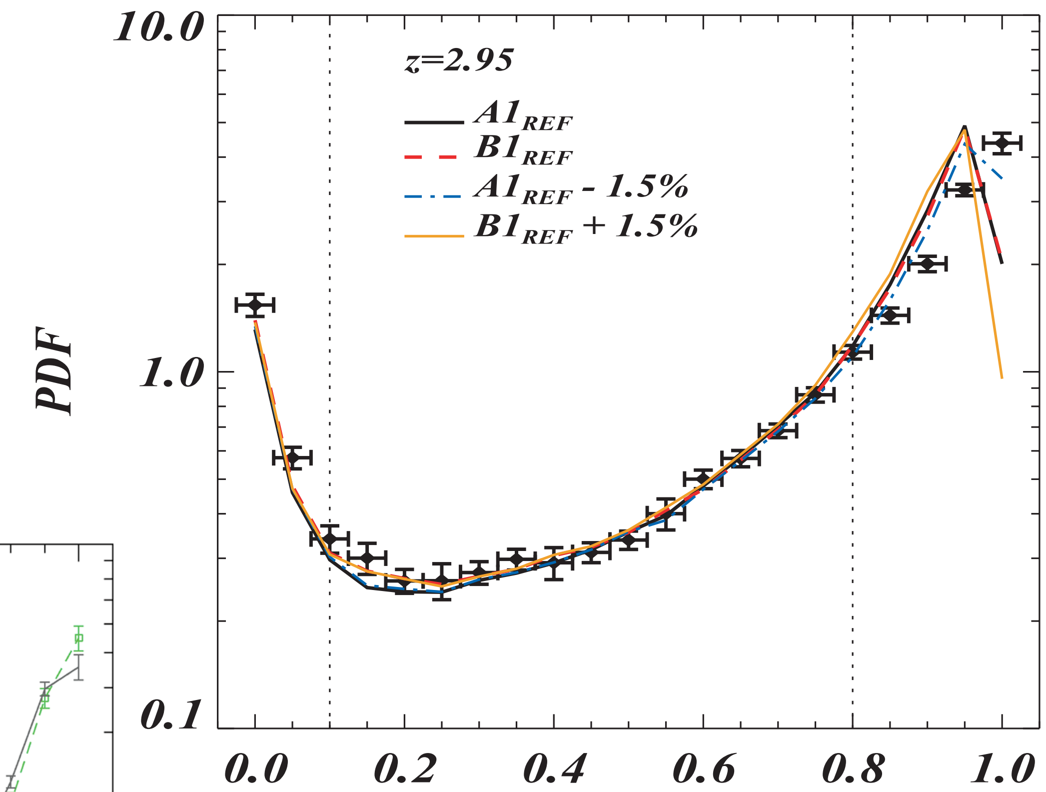


Figure 12. The flux PDF measured by K07 at $\langle z \rangle = 2.94$ (dark-grey curve) plotted with error bars compared to the PDF measured from the two spectra in our sample, Q0055−269 and PKS 2126−158, used in the K07 measurement (open squares and long dashed curve). This comparison uses pixels in the same wavelength range as adopted by K07.



hydro simulations

Calura et al. (2012)

Equilibrium between photo-ionisation and recombination:

éq. de photo-ionisation : $\Gamma_H \, n_{HI} = \alpha_H \, n_{HII} \, n_{e-}$

$\alpha_H(T_0) \simeq 4{,}36 \cdot 10^{-10} \, T_0^{-0{,}75} \, s^{-1} \, cm^3$ à $T_0 \geq 5.000$ K : taux de recombinaison

Γ_H : en s^{-1} : taux d'ionisation

$\Gamma_H = \int_{\nu_0}^{\infty} d\nu \, 4\pi \, \frac{J(\nu)}{h\nu} \, \sigma_{HI}(\nu)$ $\quad$ ν_0 : seuil d'ionisation : 13,6 eV = 912 Å

$\sigma_{HI} = 6{,}3 \cdot 10^{-18} \left(\frac{\nu}{\nu_0}\right)^{-3} cm^2$: section efficace

$$n_{HI} = \frac{\alpha(T_0)}{G_1 J_{21}} (1-Y)\left(1-\frac{Y}{2}\right) \left[\frac{\Omega_b}{\Omega_0} \frac{\rho}{m_p}\right]^2$$

$$\tau \propto n_{HI} \propto (1+\delta)^2 T^{-0.7}$$

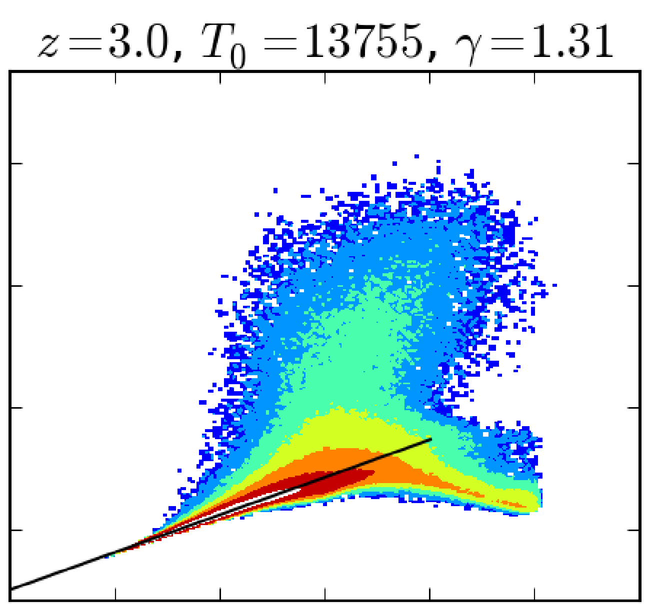
Temperature of the IGM:

$$\frac{1}{T}\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{2}{3}\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t} + \frac{1}{t_{10}}\frac{\rho}{\rho_J}\left(\frac{T}{T_J}\right)^{-\nu}$$

photo-ionization heating

adiabatic cooling

$$T \propto \rho^{\gamma-1}$$



Borde et al. (2014)

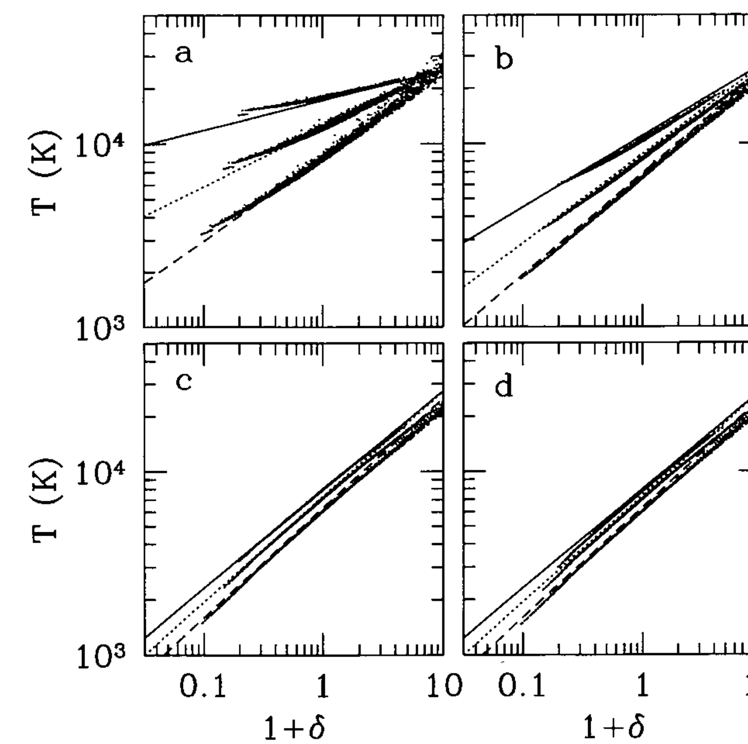


Figure 3. The temperature–density relation for 4 different sudden-reionization models: sudden reionization (see equation 6) at $z=5$ (a), $z=7$ (b), $z=10$ (c) and $z=10$ (d). For each reionization

Hui & Gnedin (1997)

Fluctuating Gunn-Peterson approximation:

$$\tau \propto \rho^2 T^{-0.7} \propto (1+\delta)^\alpha \quad \text{with} \quad \alpha = 2 - 0.7(\gamma - 1), \qquad T \sim 10^4\text{K}, \quad \gamma \sim 1.3$$

$$F = e^{-\tau} = e^{-A(1+\delta)^\alpha}.$$

Factor A related to the photo-ionizing flux. In practice, it is set by the matching with data of the mean flux: $\langle F \rangle$

Smoothing scale: $$k_s = 2.2\, k_\mathrm{J} \quad \text{with} \quad k_\mathrm{J} = \frac{a}{c_s}\sqrt{4\pi \mathcal{G}_\mathrm{N} \bar{\rho}}, \quad c_s = \sqrt{\frac{5 k_\mathrm{B} T}{3 \mu m_p}},$$

Jeans scale was smaller in the past

Gnedin & Hui (1998)

Jeans wave number

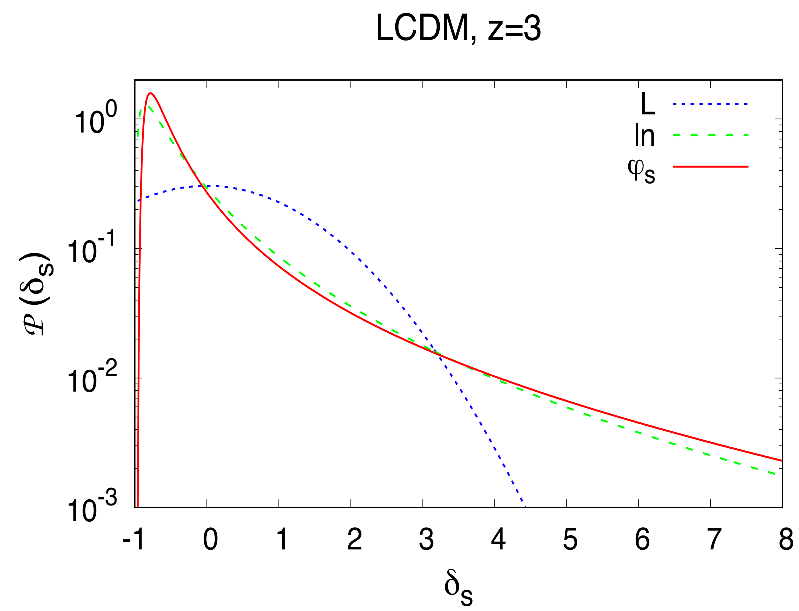
PDF of the flux in terms of the PDF of the matter density: $$\mathcal{P}(F) = \mathcal{P}(\delta_s) \left| \frac{d\delta_s}{dF} \right|.$$

$$\mathcal{P}(\delta_s) = \int_{-\mathrm{i}\infty}^{\mathrm{i}\infty} \frac{dy}{2\pi \mathrm{i} \sigma_s^2} e^{[y\delta_s - \varphi_s(y)]/\sigma_s^2} \quad \text{with} \quad \varphi_s(y) = -\sum_{n=2}^{\infty} \frac{(-y)^2}{n!} \frac{\langle \delta_s^n \rangle_c}{\sigma_s^{2(n-1)}},$$

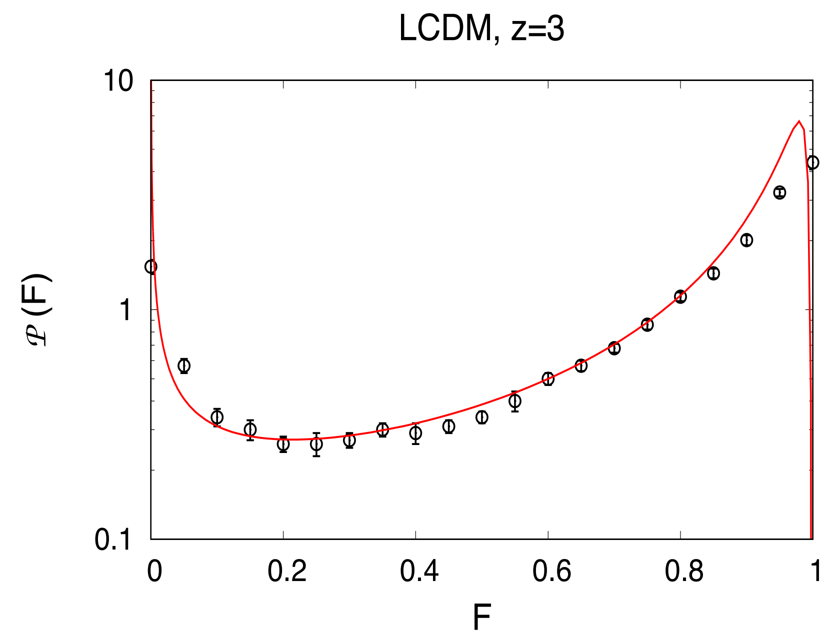
(explained in previous talk by S. Codis)

LCDM:

density contrast

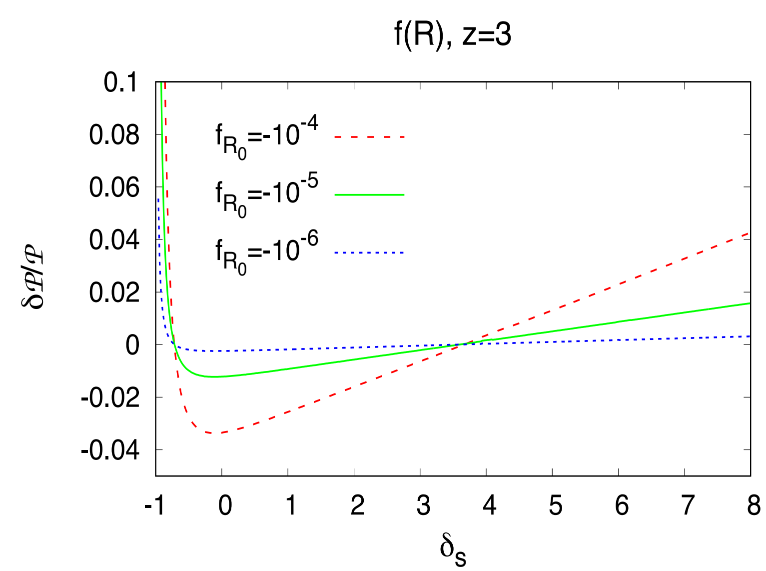


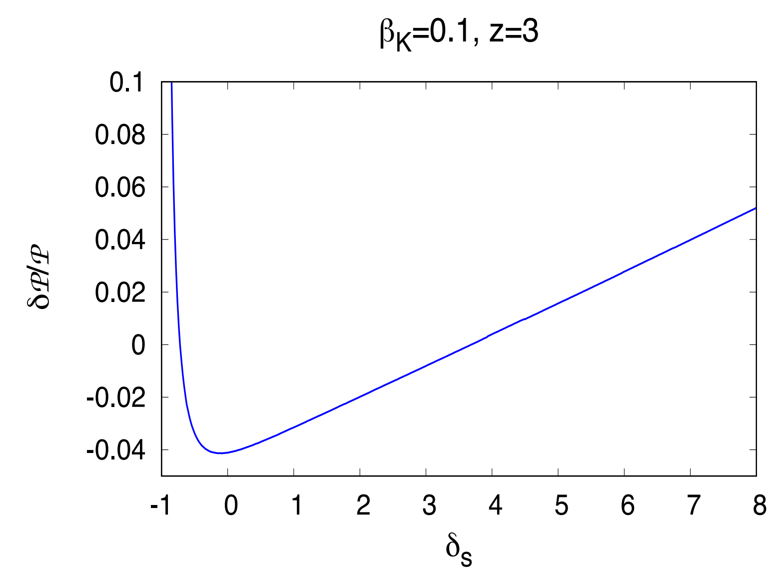
Flux



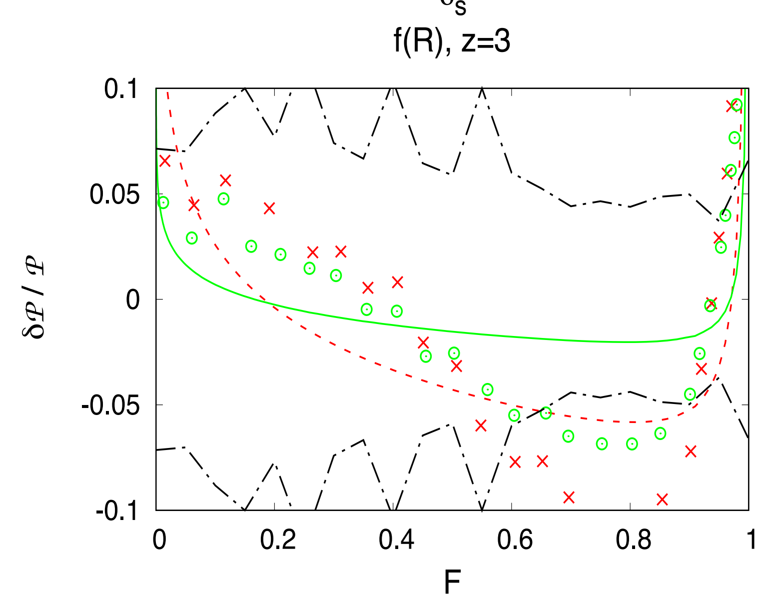
Modified-gravity:

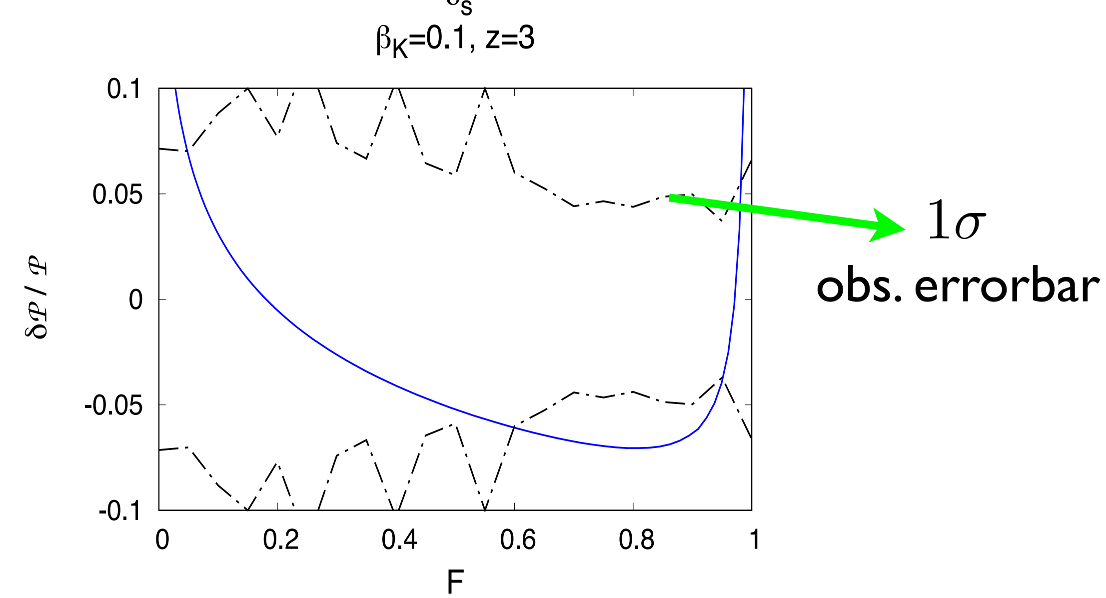
relative deviation for PDF of the density contrast





relative deviation for PDF of the flux

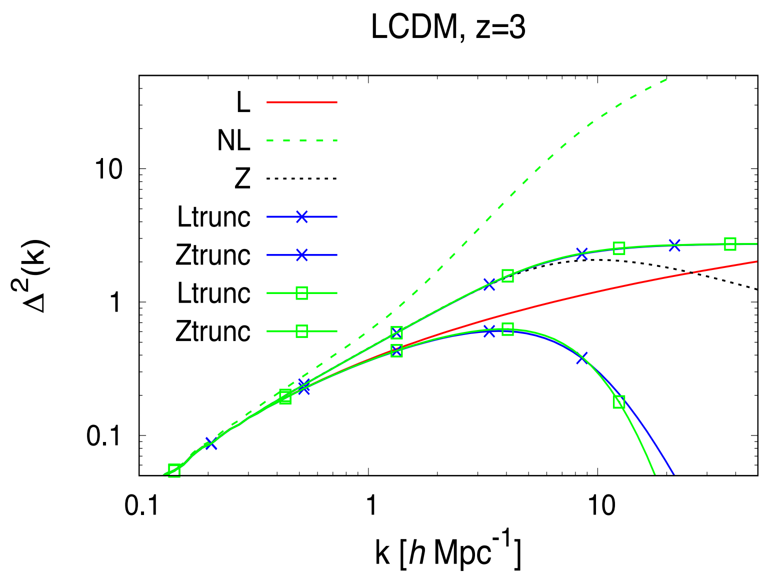


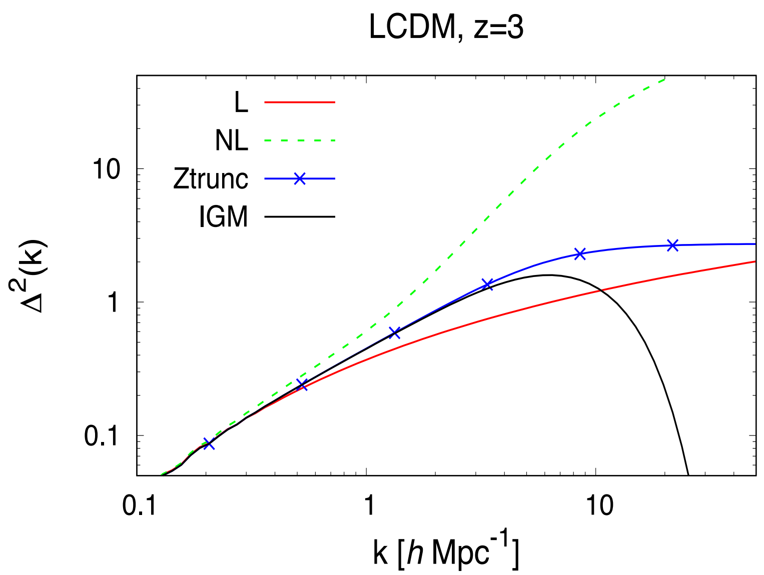


III. IGM power spectrum

Use a truncated Zeldovich approximation: $P_{\rm IGM}(k) = P_{\rm Ztrunc}(k)\ e^{-(k/k_s)^2}$

$$P_{\rm Ztrunc} = \max_{k_{\rm trunc}} P_{\rm Z}[P_{\rm Ltrunc}] \quad \text{with} \quad P_{\rm Ltrunc}(k) = P_{\rm L}(k)/(1+k^2/k_{\rm trunc}^2)^2.$$

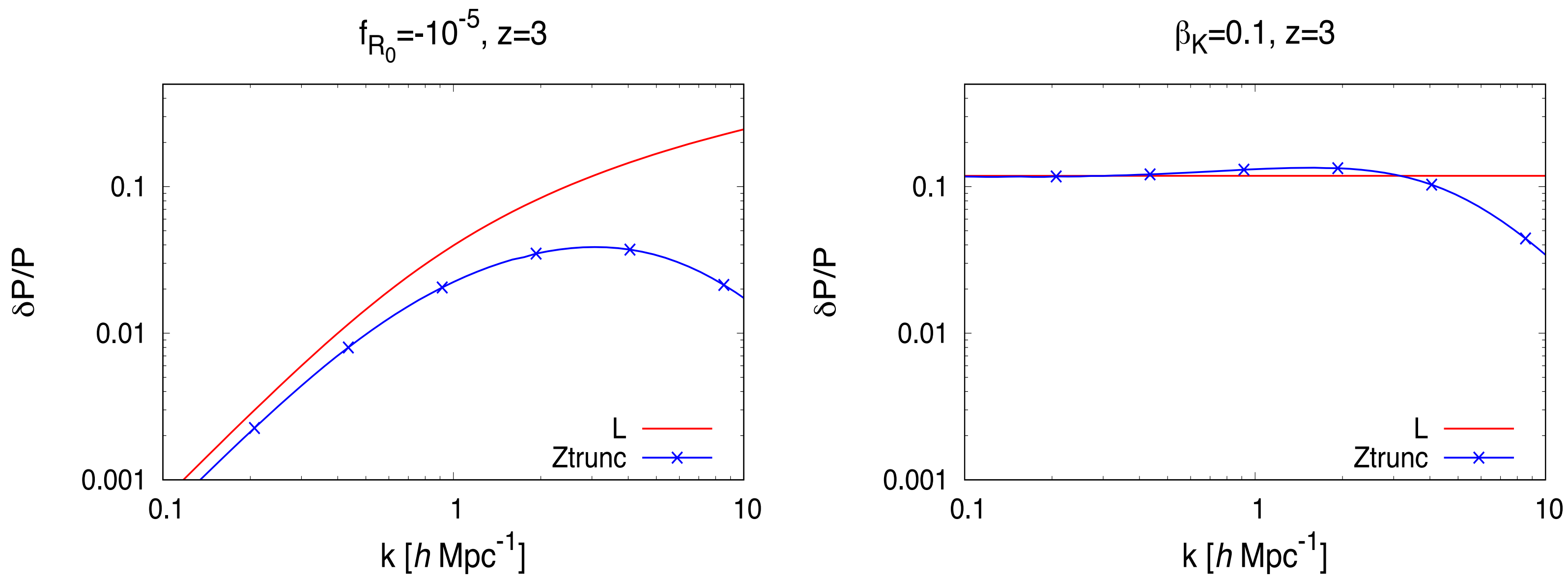




Recovers the large-scale cosmic web, associated with moderate density fluctuations.
Highly nonlinear virialized halos do not contribute to the Lyman-alpha forest.

Modified-gravity:

Relative deviation of the matter power spectrum



IV. Lyman-alpha power spectrum

A- 3D power spectrum

$$P_{\delta_F}(\mathbf{k},z) = b_{\delta_\mathrm{F}}^2 (1+\beta\mu^2)^2 \, P_\mathrm{IGM}(k)/(1+f|k\mu|/k_\mathrm{NL}) \, e^{-(k\mu/k_\mathrm{th})^2},$$

free parameter

Kaiser effect

velocity dispersion in collapsed structures

thermal broadening

$$k_\mathrm{th} = \frac{aH}{b_\mathrm{th}}, \quad b_\mathrm{th} = \sqrt{\frac{k_\mathrm{B}T}{2m_p}},$$

$$\mathbf{s} = \mathbf{x} + \frac{v_\parallel}{aH}\mathbf{e}_z,$$

- We noticed that if we use the nonlinear matter power spectrum instead of P_IGM we get a steep growth for the Lyman-alpha power spectrum at high k.

- We take $\beta = 1.3f$ (simulations)

In principle, we could define (Seljak 2012): $\beta = f\frac{b_{\delta_F,\eta}}{b_{\delta_F,\delta}}$

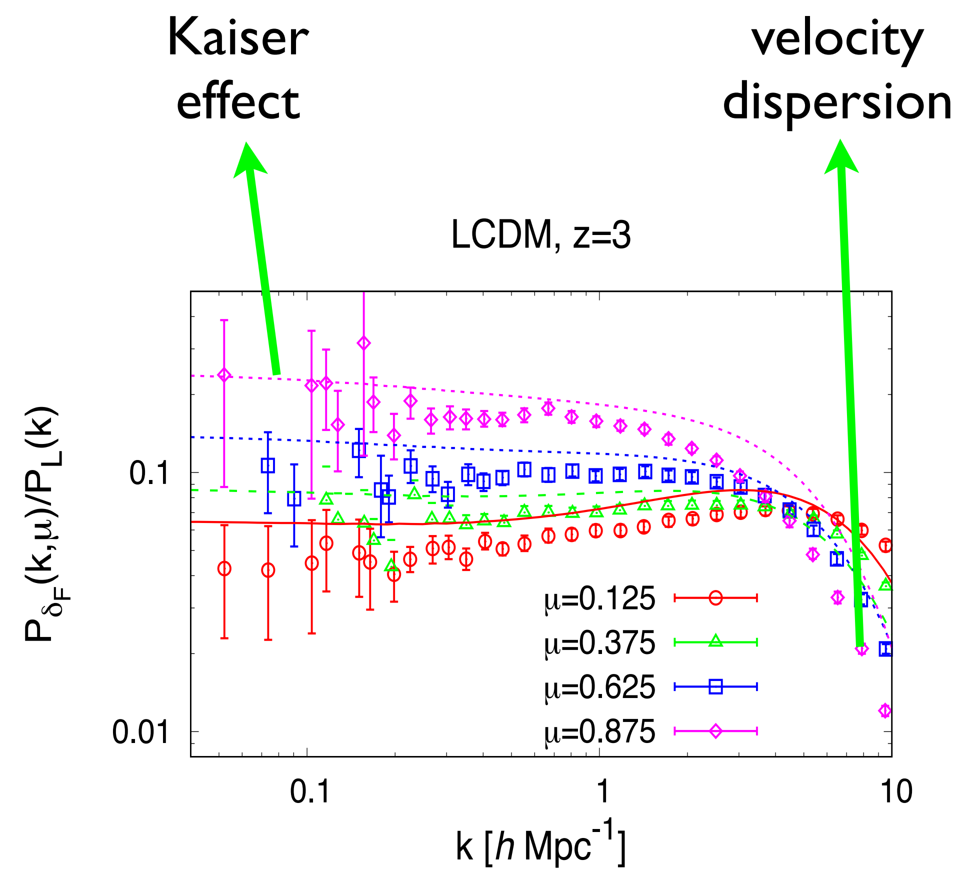
$$\eta = -\frac{\frac{\partial v_\parallel}{\partial x_\parallel}}{aH}$$

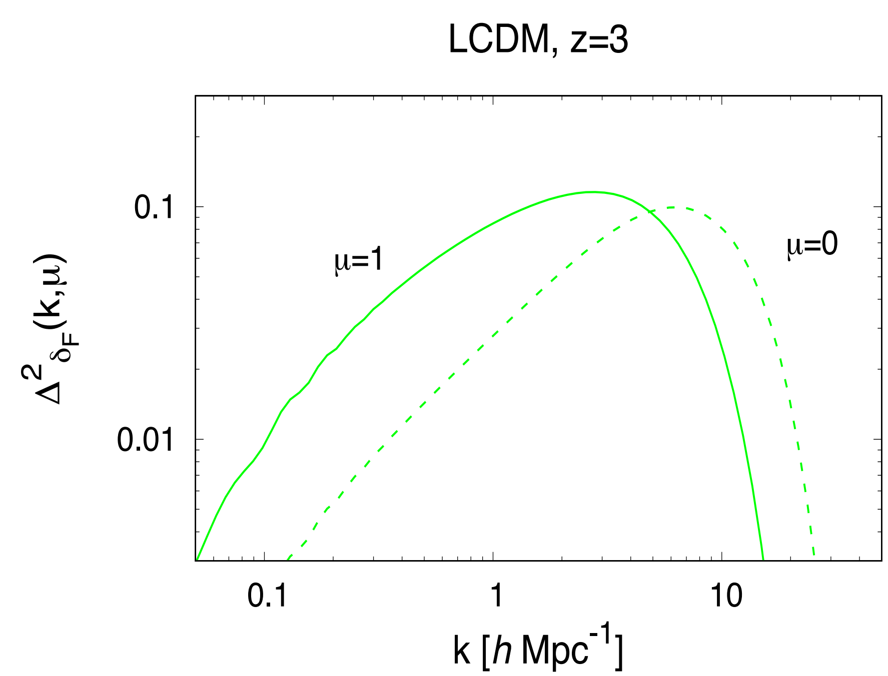
$$b_{\delta_F,\delta} = \frac{\partial \delta_F}{\partial \delta} \qquad b_{\delta_F,\eta} = \frac{\partial \delta_F}{\partial \eta}$$

However, analytical models do not work very well, especially because of the velocity part (Cieplak & Slosar 2016).

ratio $P_F(k,\mu)/P_L$

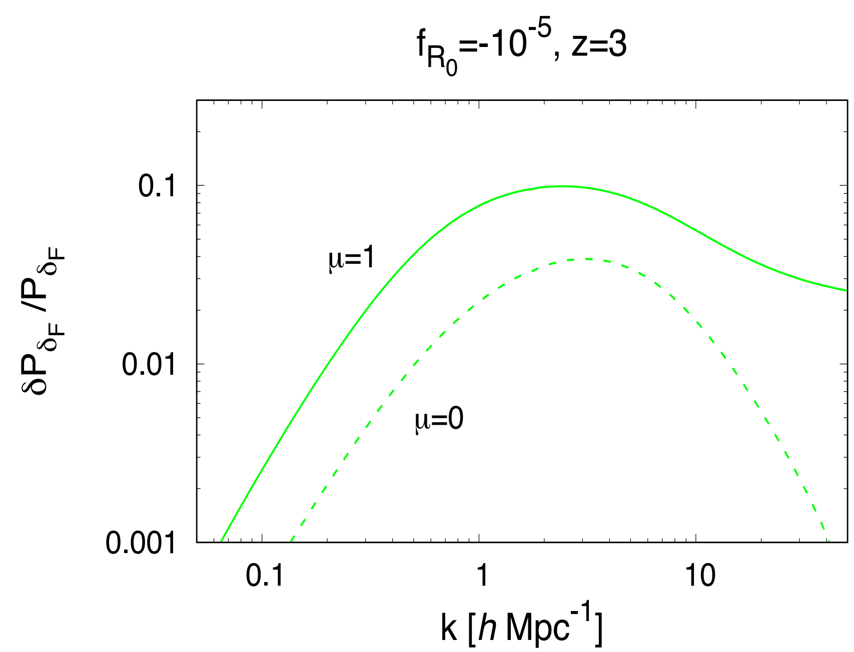
LCDM:

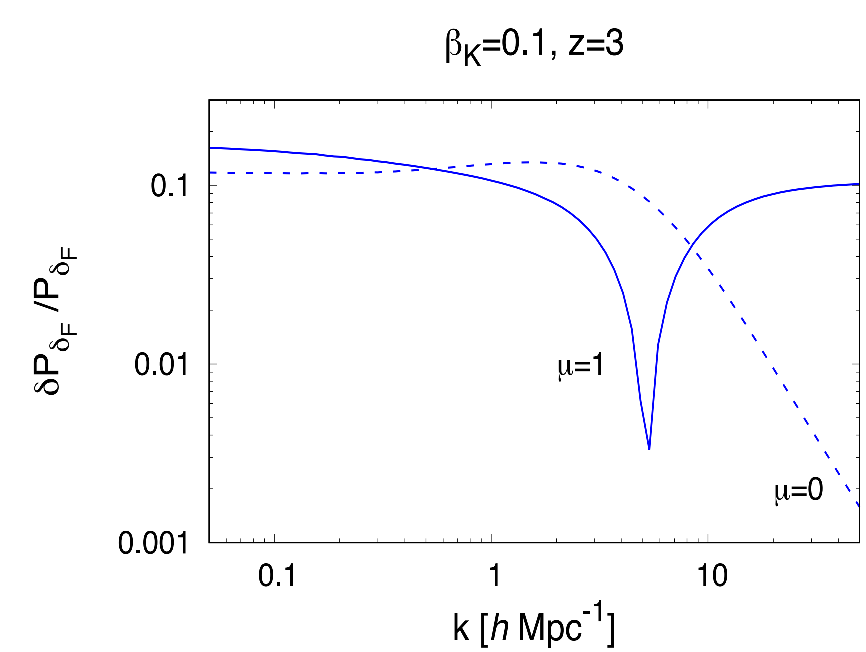




Modified-gravity:

Relative deviation of the 3D Lyman-alpha power spectrum



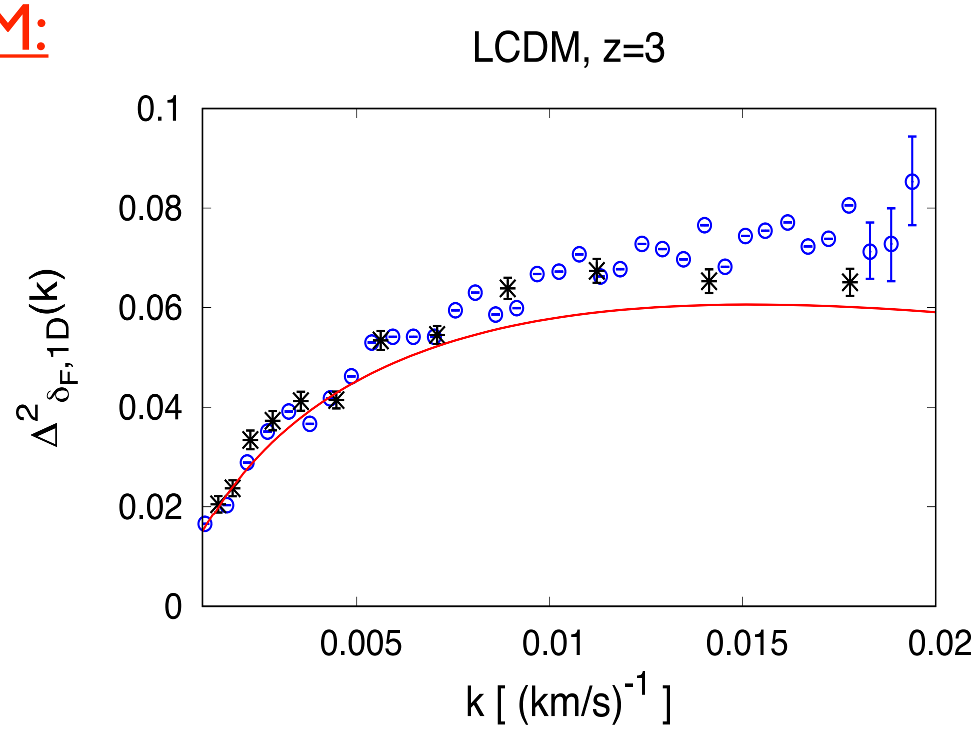


B- 1D power spectrum

1D Lyman-alpha power spectrum along the line of sight

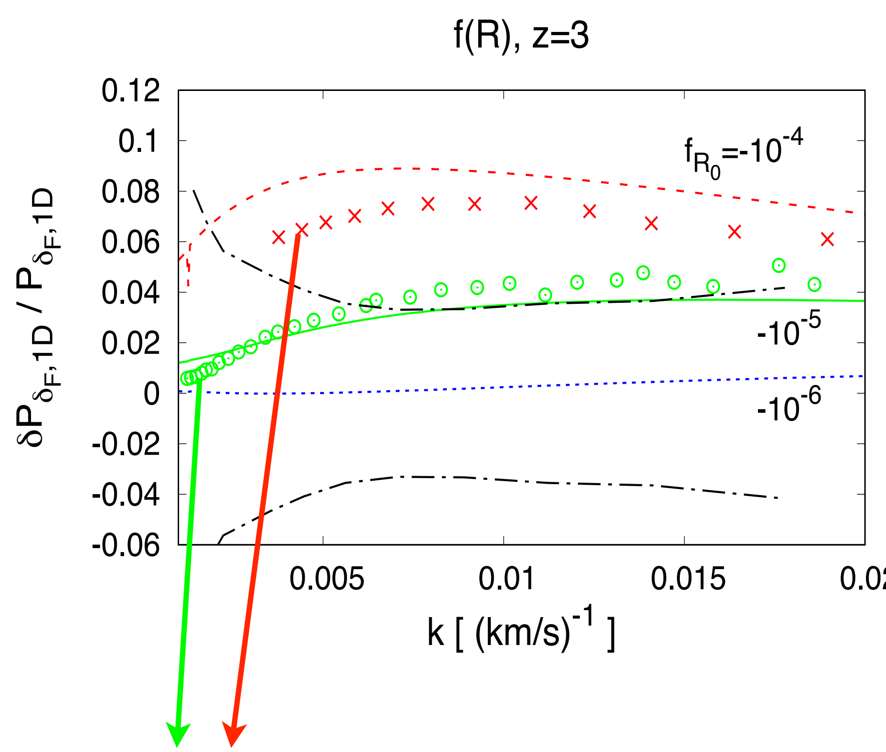
$$P_{\delta_F,1\mathrm{D}}(k_z) = \int_{-\infty}^{\infty} dk_x dk_y P_{\delta_F}(\mathbf{k}) = 2\pi \int_{k_z}^{\infty} dk\, k P_{\delta_F}(k, \mu = k_z/k).$$

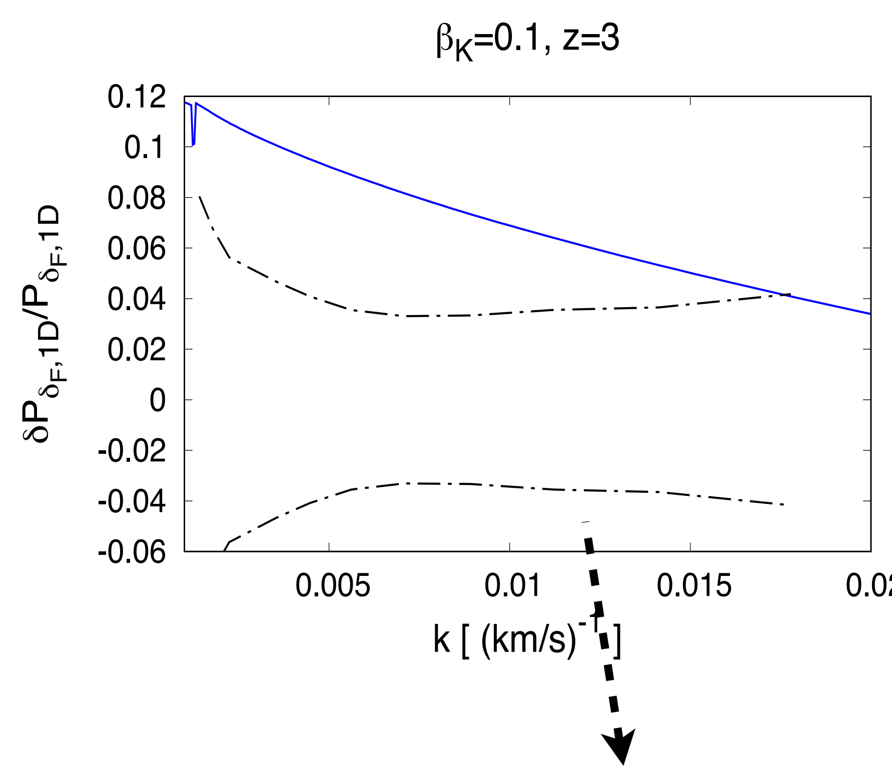
LCDM:



Modified-gravity:

Relative deviation of the 1D Lyman-alpha power spectrum





simulations

Arnold et al. (2015)

1σ

obs. errorbar