Lyman-α quasar spectra as cosmological probes

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The (cosmological) QSO data sets

The Croft et al. (02) sample: 53 QSO spectra (30 at high res from Keck and 23 low.res)

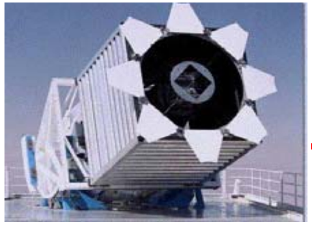
Tytler et al. (04): 77 low resolution low S/N spectra (KAST spectrograph) at <z>=1.9

The LUQAS sample: Large Uves Quasar Absorption Spectra part of the ESO Large programme by J. Bergeron – 27 high.res and high S/N spectra at <z>=2.125 anz <z>=2.72 -- Kim et al. (2004)

The SDSS QSOs (release 1&2): 3300 low. resolution and low S/N QSO spectra z=2.2-4.2. McDonald et al. (2005)

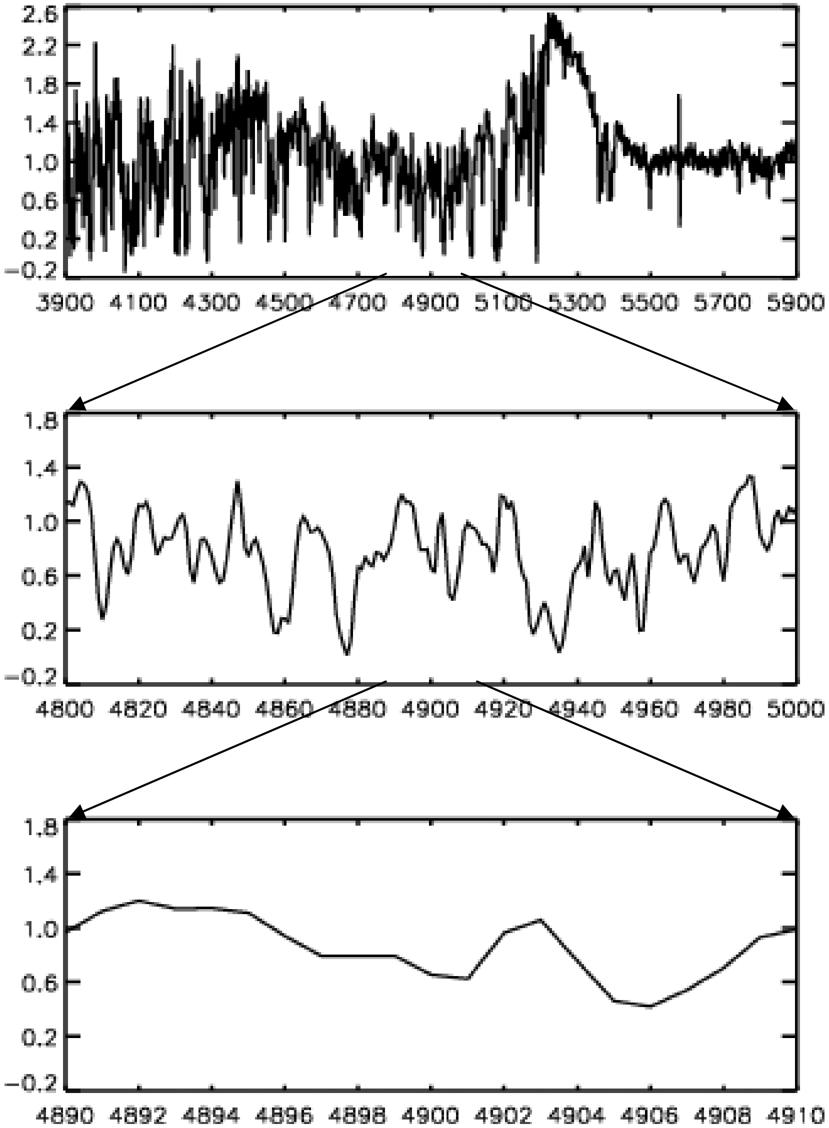
Becker et al. (07) sample: 55 high.res. Spectra spanning z=2-6.4

The data sets-II

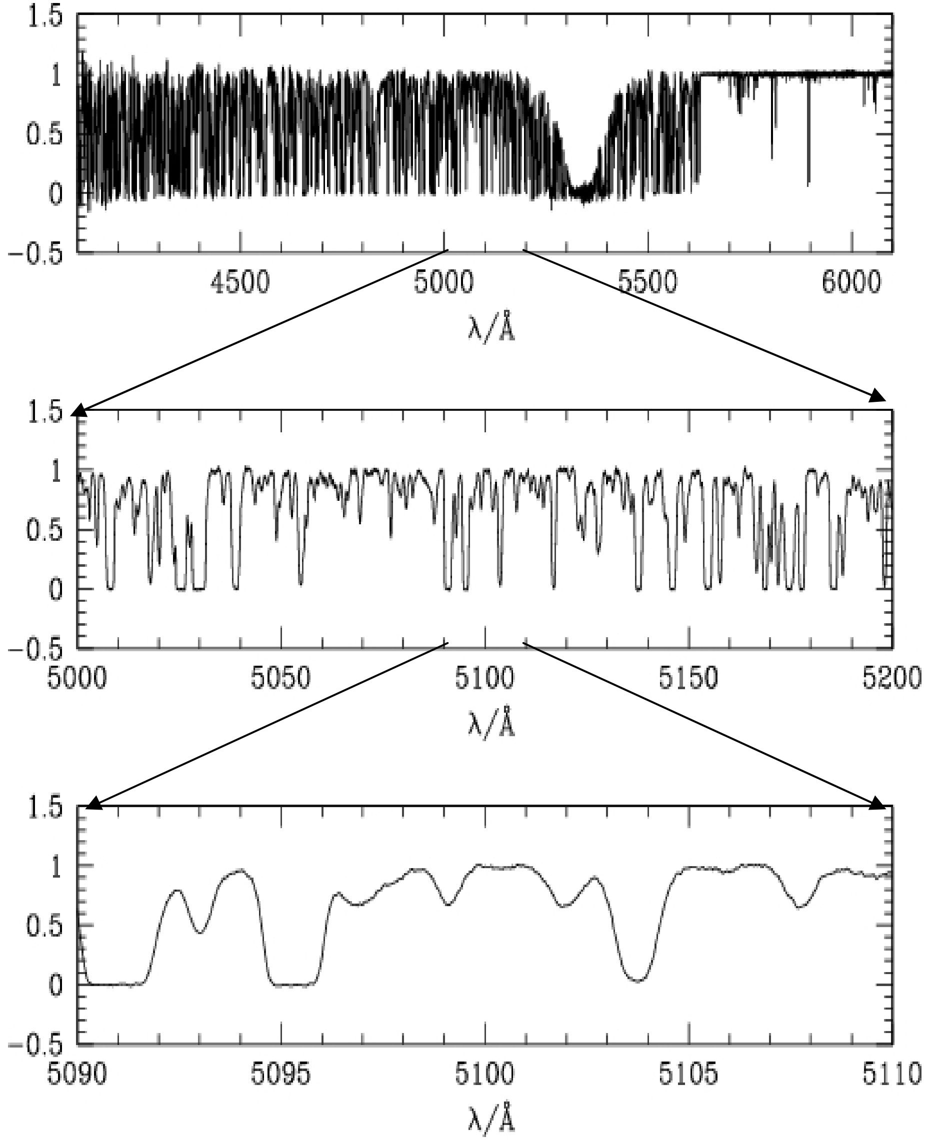


SDSS vs LUQAS

McDonald et al. 2005



Kim, MV et al. 2004



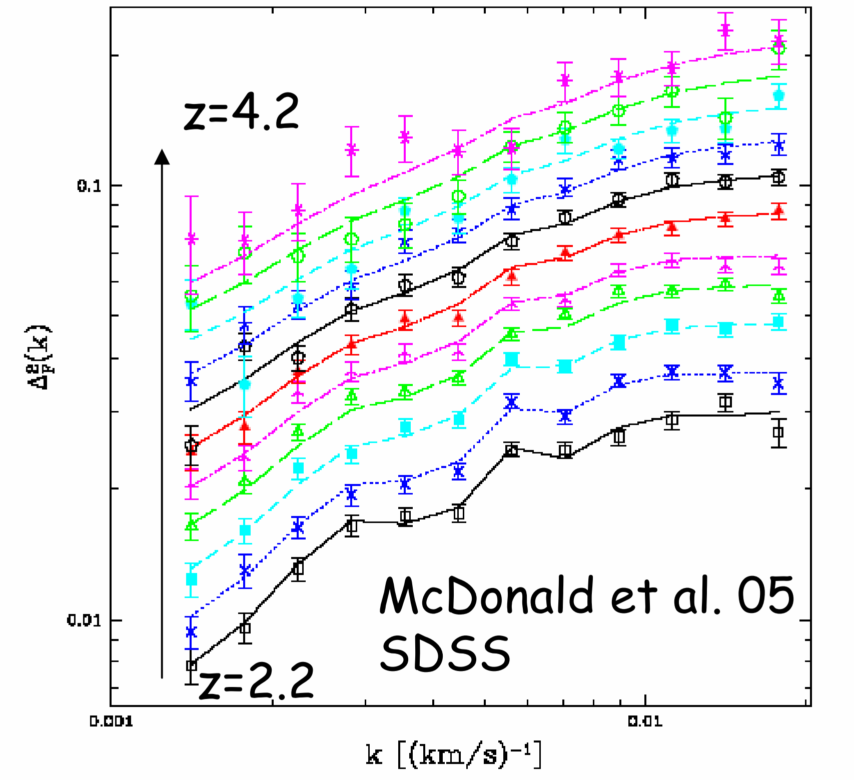
SDSS

3035 LOW RESOLUTION LOW S/N vs

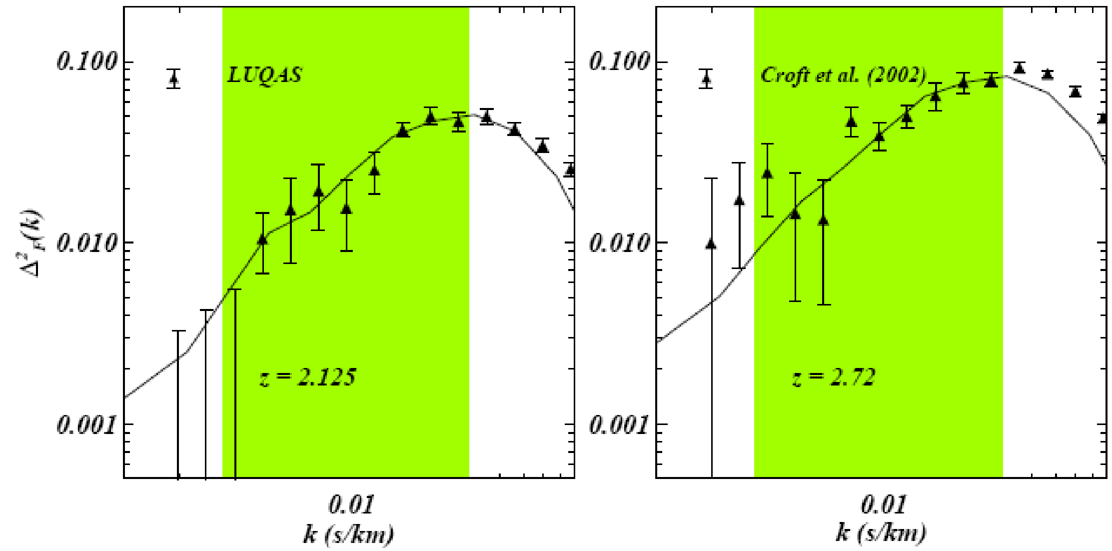
LUQAS

30 HIGH RESOLUTION HIGH S/N

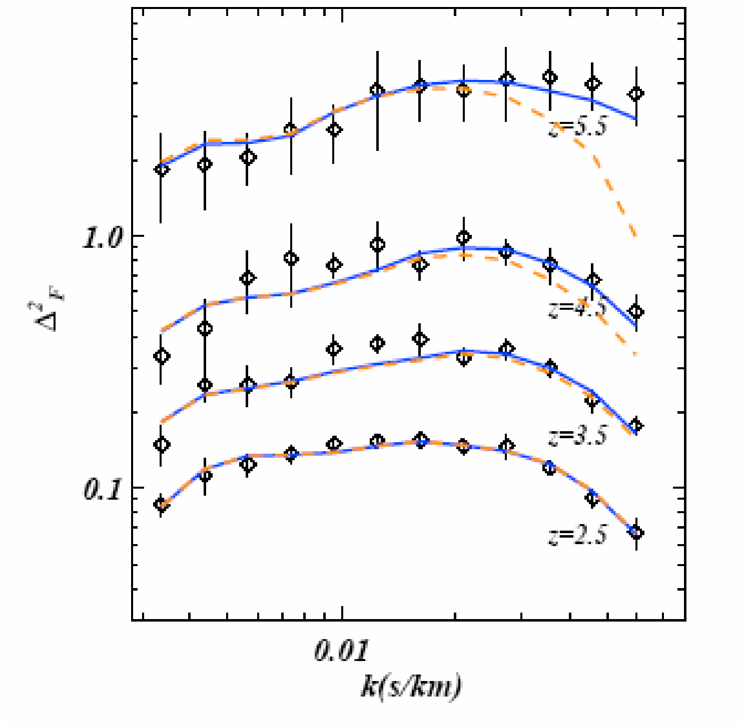
The data sets: the flux power -III



Viel, Haehnelt & Springel 04



Viel et al. 08



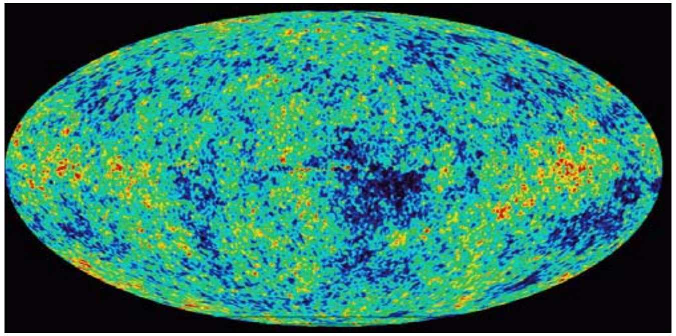
Main systematics:

continuum fitting + metal contamination + mean flux level determination

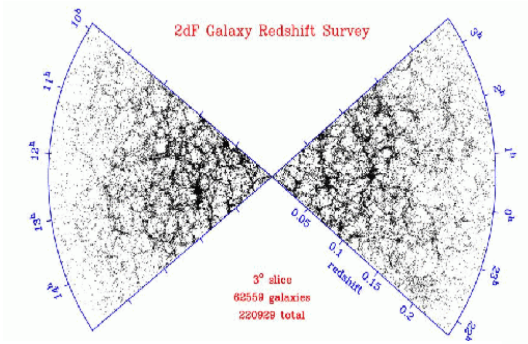
The interpretation: full grid of sims - I

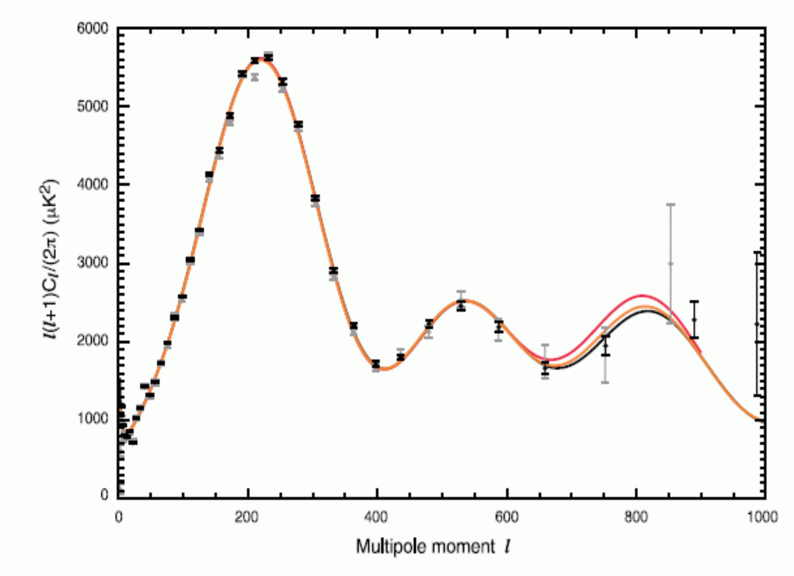
SDSS power analysed by forward modelling motivated by the huge amount of data with small statistical errors

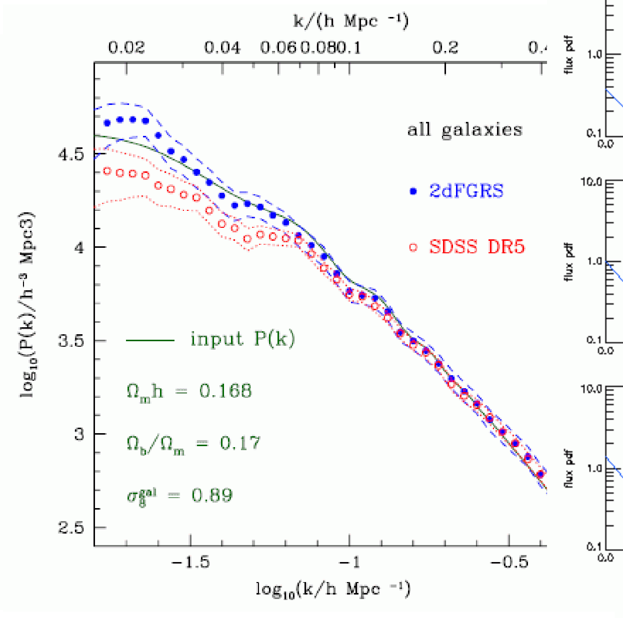
CMB: Spergel et al. (05) Galaxy P(k): Sanchez & Cole (07)

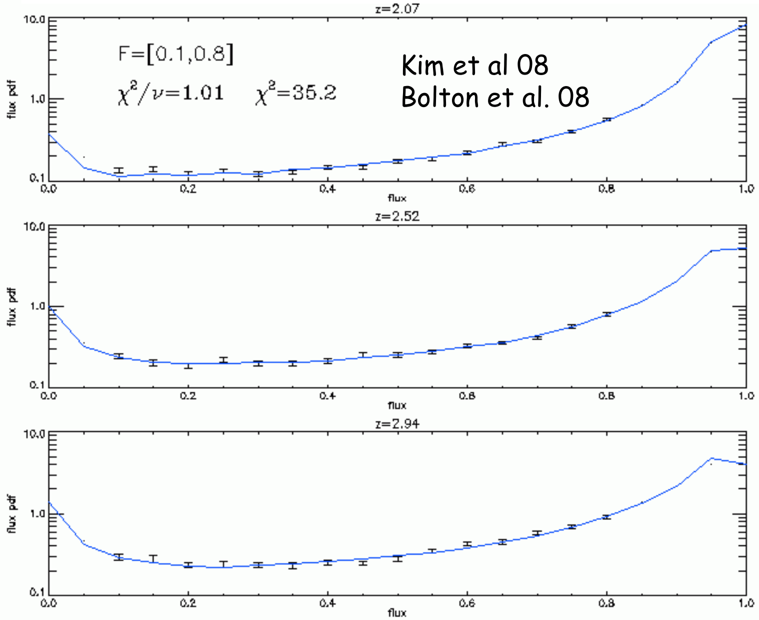


+









Cosmological parameters + e.g. bias

The interpretation: flux derivatives - II

Independent analysis of SDSS power

The flux power spectrum is a smooth function of k and z

Viel & Haehnelt 06: interpolate sparse grid of full hydrodynamical (slow) simulations

Flux power

$$P_F(k, z; \mathbf{p}) = P_F(k, z; \mathbf{p}^0) + \sum_{i=1,N} \left.\frac{\partial P_F(k, z; p_i)}{\partial p_i}\right|_{\mathbf{p} = \mathbf{p}^0} (p_i - p_i^0)$$

Best fit

p: astrophysical and cosmological parameters

but even resolution and/or box size effects if you want to save CPU time

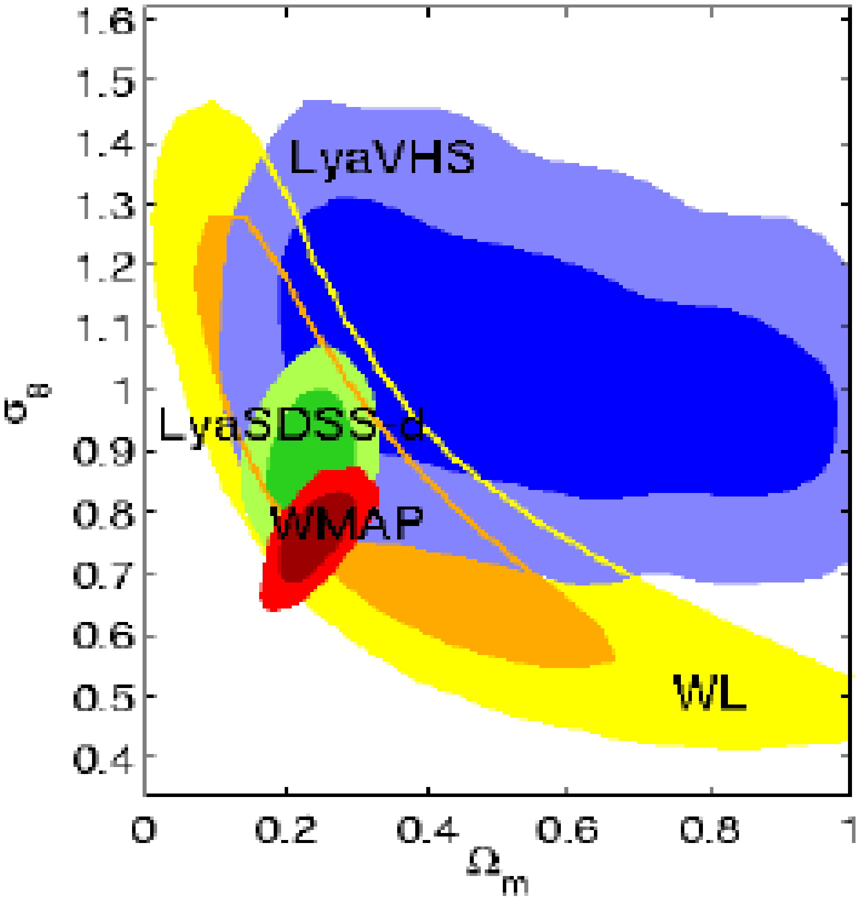
RESULTS

POWER SPECTRUM AND NEUTRINOS

Lyman-α forest + Weak Lensing + WMAP 3yrs

VHS-LUQAS: high res Ly-a from (Viel, Haehnelt, Springel 2004)
SDSS-d: re-analysis of low res data SDSS (Viel & Haehnelt 2006)
WL: COSMOS-3D survey Weak Lensing (Massey et al. 2007) 1.64 sq degree
public available weak lensing COSMOMC module
http://www.astro.caltech.edu/~rjm/cosmos/cosmomc/

AMPLITUDE



MATTER DENSITY **SPECTRAL INDEX**

Lesgourgues, MV, Haehnelt, Massey, 2007, JCAP, 8, 11

Lyman-α forest + Weak Lensing + WMAP 3yrs

Lesgourgues, MV, Haehnelt, Massey, 2007, JCAP, 8, 11

	WL+WMAP3+Lyα VHS	WL+WMAP3+Lyα SDSS-d
σ_8	0.822 ± 0.032	0.800 ± 0.023
n_s	0.960 ± 0.016	0.971 ± 0.011
Ω_{0m}	0.282 ± 0.026	0.247 ± 0.016
h	0.700 ± 0.022	0.730 ± 0.016
τ	0.094 ± 0.028	0.109 ± 0.026

$|dn/d\ln k| < 0.021$

WMAP 5yrs

WMAP5only Dunkley et al. 08
$\sigma_8 = 0.796 \pm 0.036$
$n_s = 0.963 \pm 0.015$
$\Omega_m = 0.258 \pm 0.030$
$h = 71.9 \pm 2.7$
$\tau = 0.087 \pm 0.017$
$dn/d\ln k = -0.037 \pm 0.028$

WMAP5+BAO+SN Komatsu et al. 08

$\sigma_8 = 0.817 \pm 0.026$
$n_s = 0.960 \pm 0.014$
$h = 70.1 \pm 1.3$
$\tau = 0.084 \pm 0.016$

with Lyman-α factor 2 improvements on the running

Summary (highlights) of results

1. Tightest constraints to date on neutrino masses and running of the spectral index

   Seljak, Slosar, McDonald JCAP (2006) 10 014

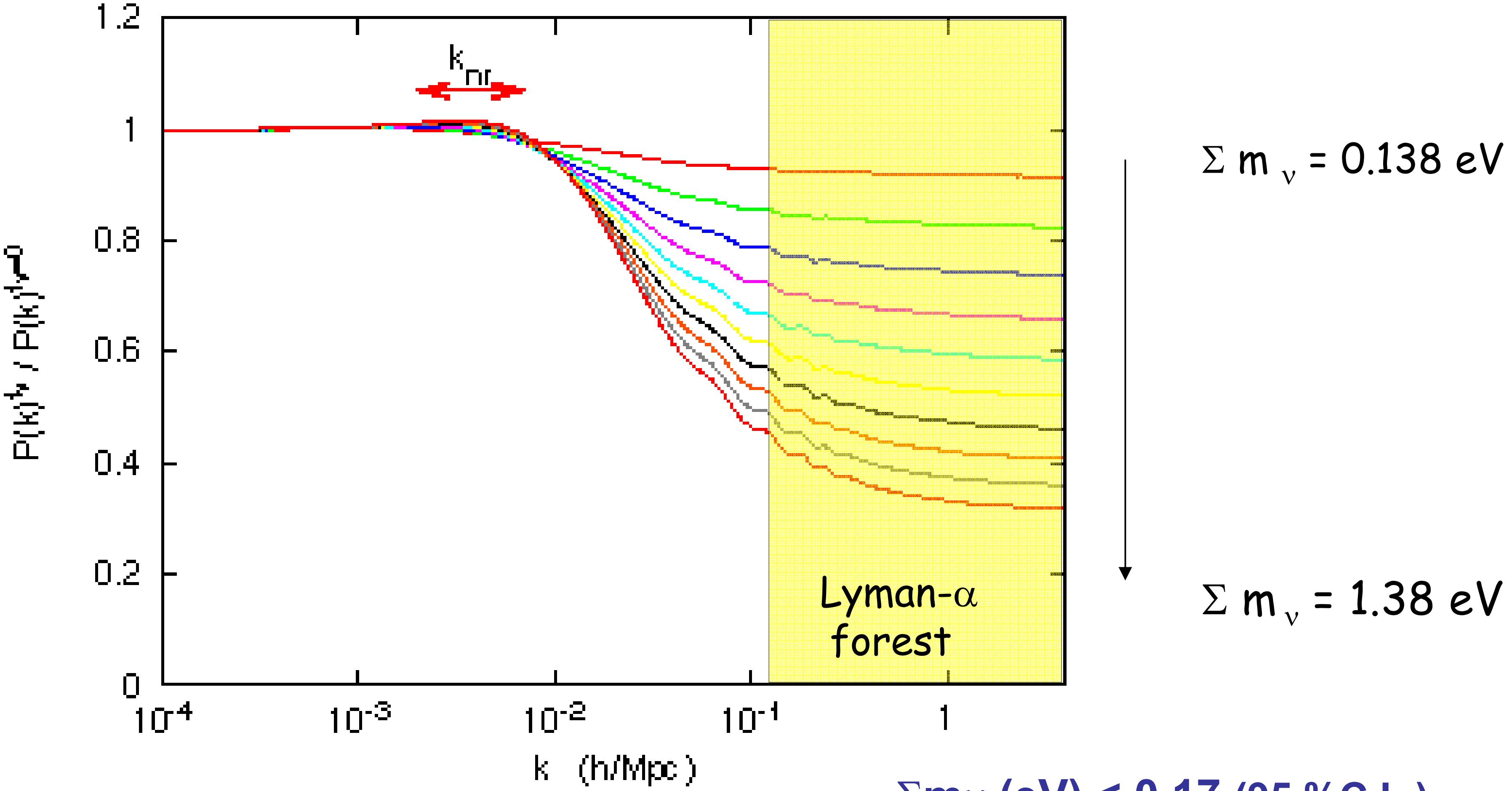
2. Tightest constraints to date on the coldness of cold dark matter

   MV et al., Phys.Rev.Lett. 100 (2008) 041304

Active neutrinos

$$k_{nr} \simeq 0.018\, \Omega_m^{1/2} \left(\frac{m}{1\,\text{eV}}\right)^{1/2} h\,\text{Mpc}^{-1}$$

Lesgourgues & Pastor Phys.Rept. 2006, 429, 307



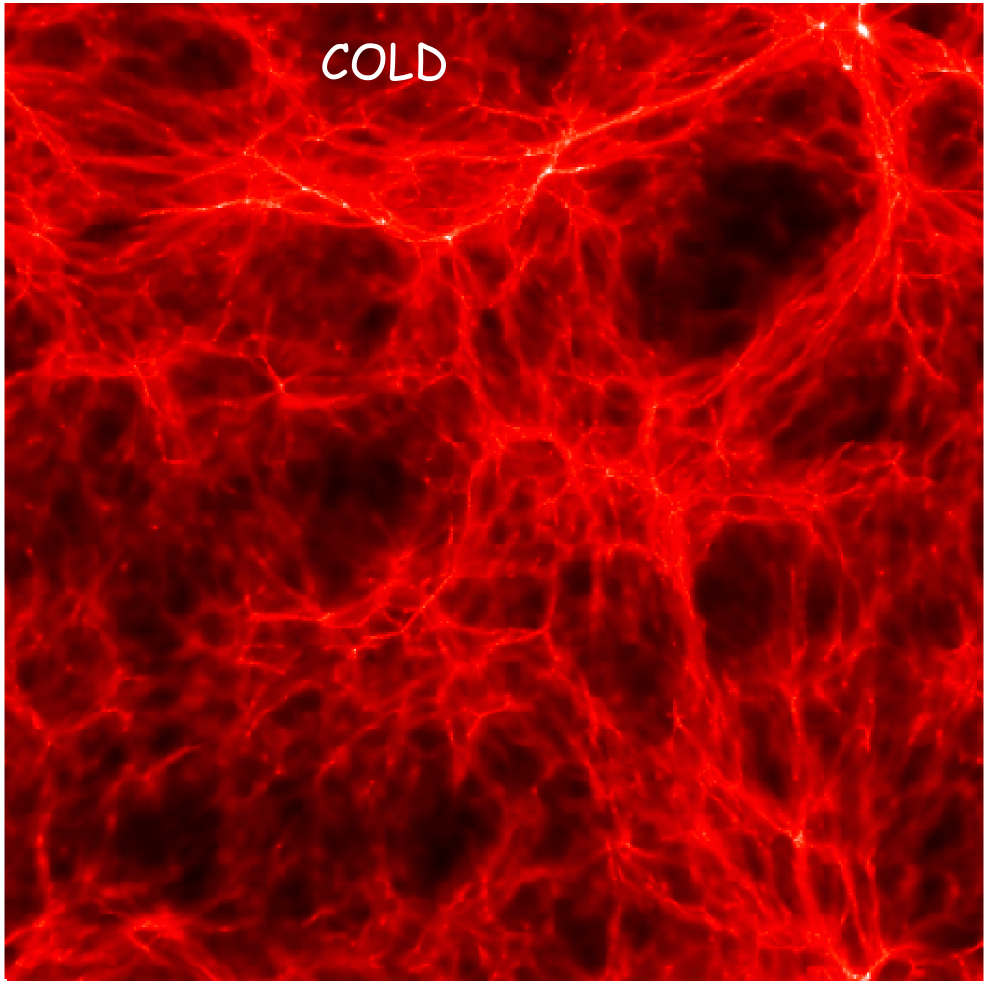
Σmν (eV) < 0.17 (95 %C.L.)
r < 0.22 (95 % C.L.)
running = -0.015 ± 0.012
Neff = 5.2 (3.2 without Ly α)
CMB + SN + SDSS gal+ SDSS Ly-α

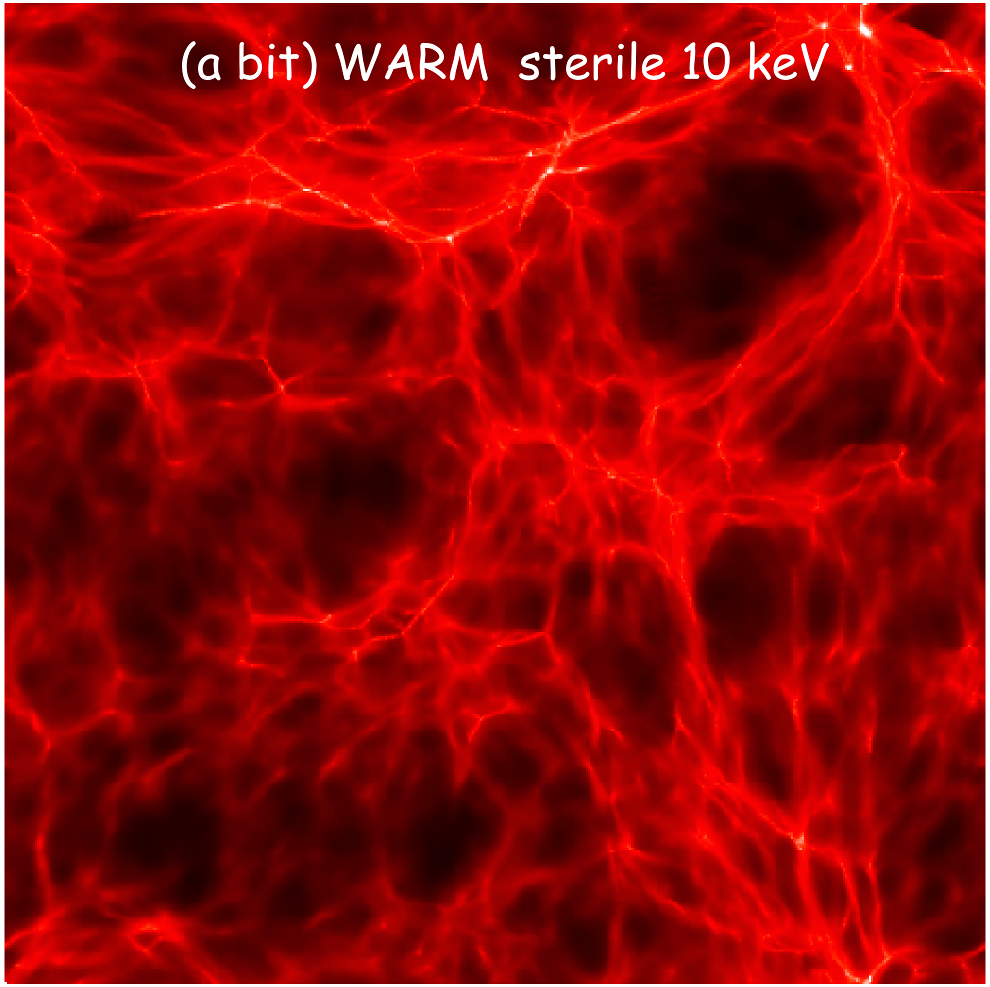
Seljak et al. 2006

$$v_{th} \equiv \frac{\langle p \rangle}{m} \simeq \frac{3T_\nu}{m} = \frac{3T_\nu^0}{m}\left(\frac{a_0}{a}\right) \simeq 150(1+z)\left(\frac{1\,\text{eV}}{m}\right) \text{km}\,\text{s}^{-1}$$

$$k_{FS}(t) = \left(\frac{4\pi G\bar{\rho}(t)a^2(t)}{v_{th}^2(t)}\right)^{1/2}, \qquad \lambda_{FS}(t) = 2\pi\frac{a(t)}{k_{FS}(t)} = 2\pi\sqrt{\frac{2}{3}}\frac{v_{th}(t)}{H(t)}$$

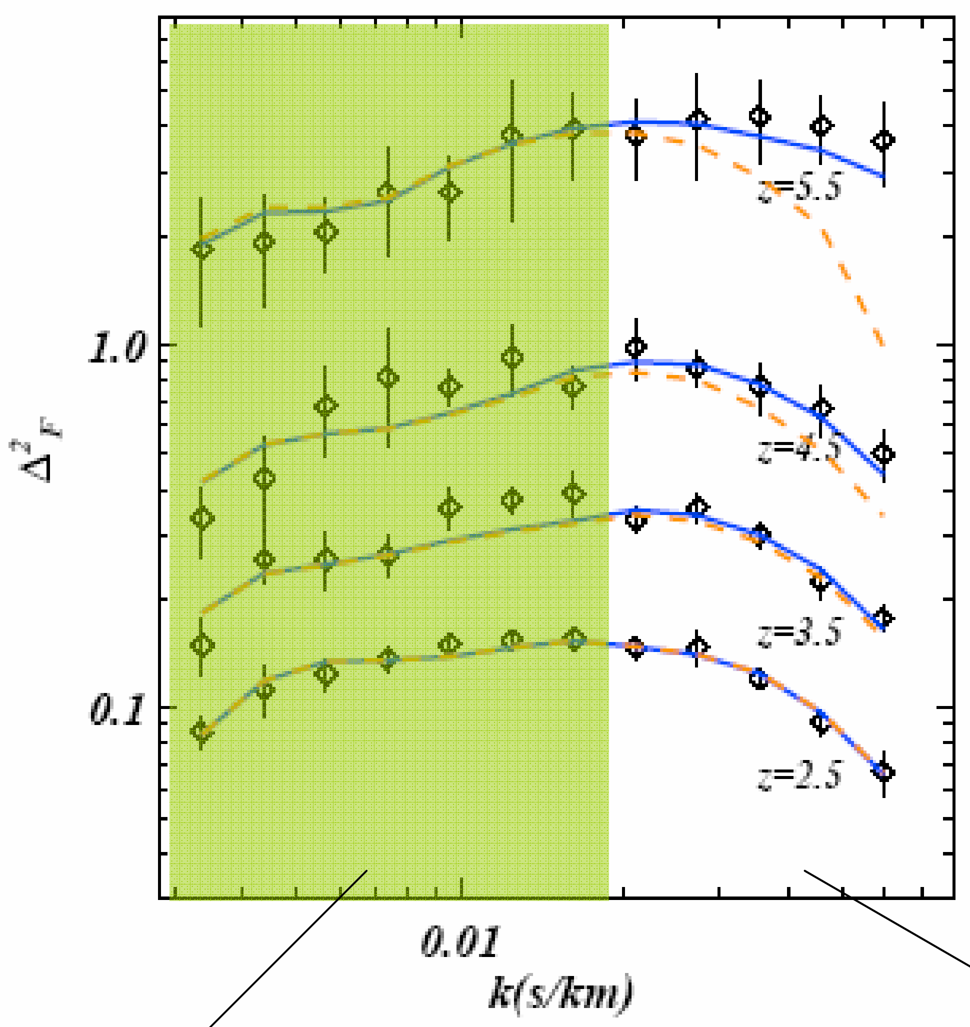
Little room for standard warm dark matter scenarios……
… the cosmic web is likely to be quite “cold”





Lyman-α and Warm Dark Matter

MV, Becker, Bolton, Haehnelt, Rauch, Sargent, Phys.Rev.Lett. 100 (2008) 041304



SDSS + HIRES data

(SDSS still very constraining!)

Tightest constraints on mass of WDM particles to date:

m_{WDM} > 4 keV (early decoupled thermal relics)

$m_{sterile}$ > 28 keV (standard Dodelson-Widrow mechanism)

SDSS range

Completely new small scale regime

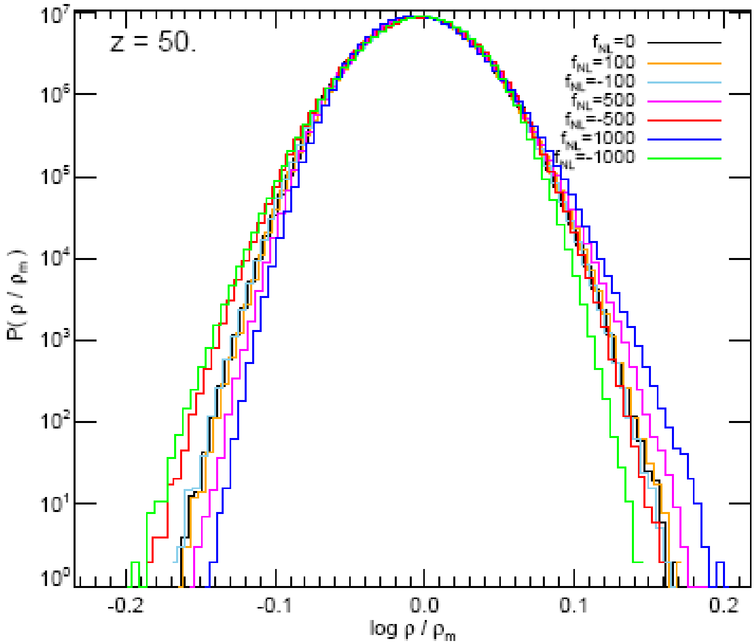
SEARCHING

FOR

NON-GAUSSIANITIES

Non-Gaussianities in the IGM - I

DARK MATTER



Grossi et al. 2008

$$\Phi = \Phi_{\rm L} + f_{\rm NL}\left(\Phi_{\rm L}^2 - \langle\Phi_{\rm L}^2\rangle\right)$$

CMB constraints (Komatsu et al.):

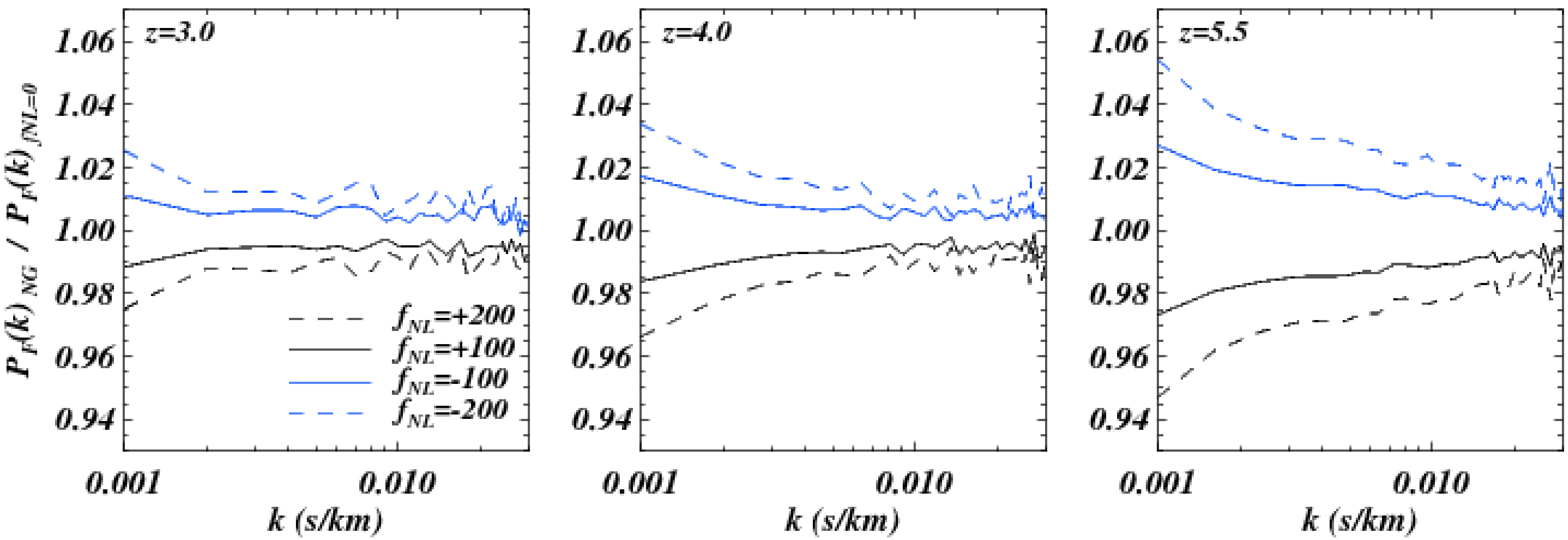
local model $-9 < f_{NL} < 111$

Equilateral model $-151 < f_{NL} < 253$

Non-Gaussianities in the IGM - II

Statistical obs. error 0.6%

FLUX POWER SPECTRUM



Non-Gaussianities in the IGM - III

Lots of astrophysical
information in the high-redshift flux bispectrum

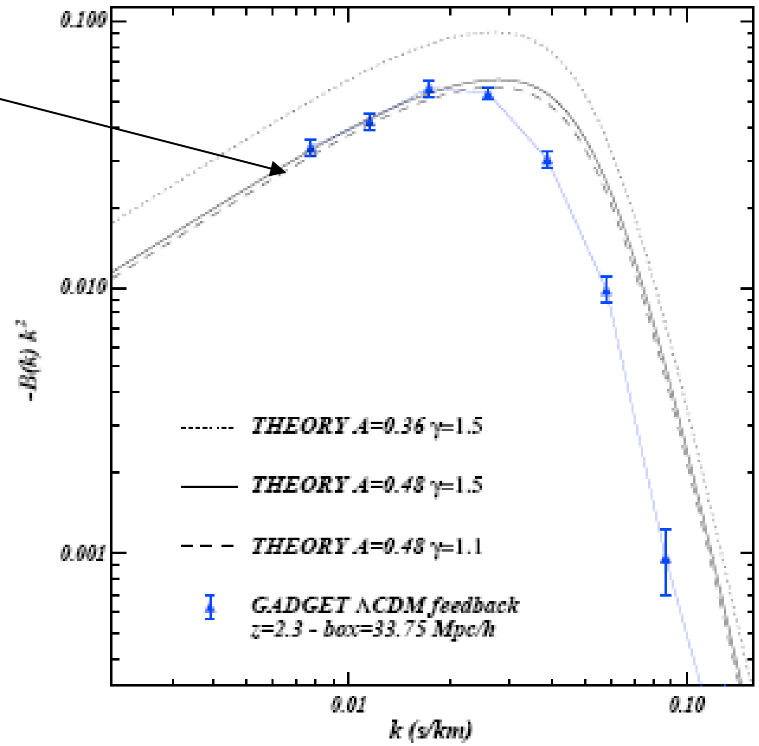
$$F = \exp\left[-A\,(1+\delta_{IGM})^{\beta}\right]$$

$$\delta_F \approx b_1[\delta^{(1)}(\mathrm{x}) + \delta^{(2)}(\mathrm{x})] + \frac{b_2}{2}\delta^{(1)\,2}(\mathrm{x}) \qquad \text{with } b_1 = -A\,\beta \text{ and } b_2 = -A\,\beta\,(\beta-1-A\,\beta)$$

$$\begin{aligned} B(k_1,k_2,k_3) &= \left(\frac{12}{7}c_1 + c_2\right) p(k_1)\,p(k_2) \\ &+ c_1\left[(k_1\,k_2 - \frac{2}{7}k_1^2)\,p^{(-1)}(k_1)\,p(k_2)\right. \\ &+ (k_2\,k_1 - \frac{2}{7}k_2^2)\,p^{(-1)}(k_2)\,p(k_1) \\ &+ \left.\frac{6}{7}k_1^2\,k_2^2\,p^{(-1)}(k_1)p^{(-1)}(k_2)\right] + \mathrm{cyc.}(1,2,3) \end{aligned}$$

where $c_1 = 1/b_1$, $c_2 = b_2/b_1^2$.

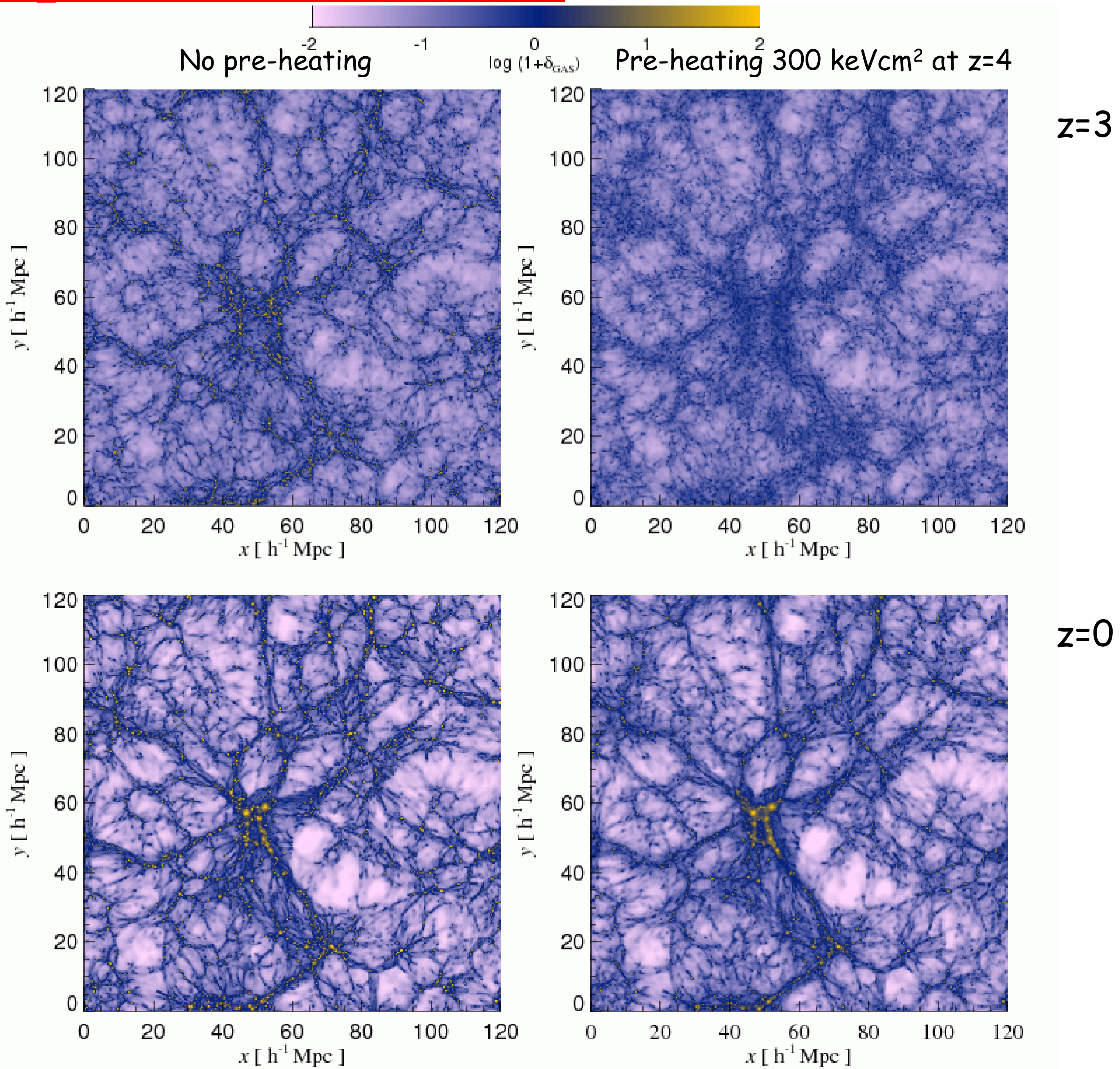
$$p^{(\ell)}(k) = |k|^{2\ell}\,p(k) + 2\,l\int_{|k|}^{\infty} dq\,q^{-2\ell-1}\,p(q)$$



MV et al. 2004, MNRAS, 347, L26

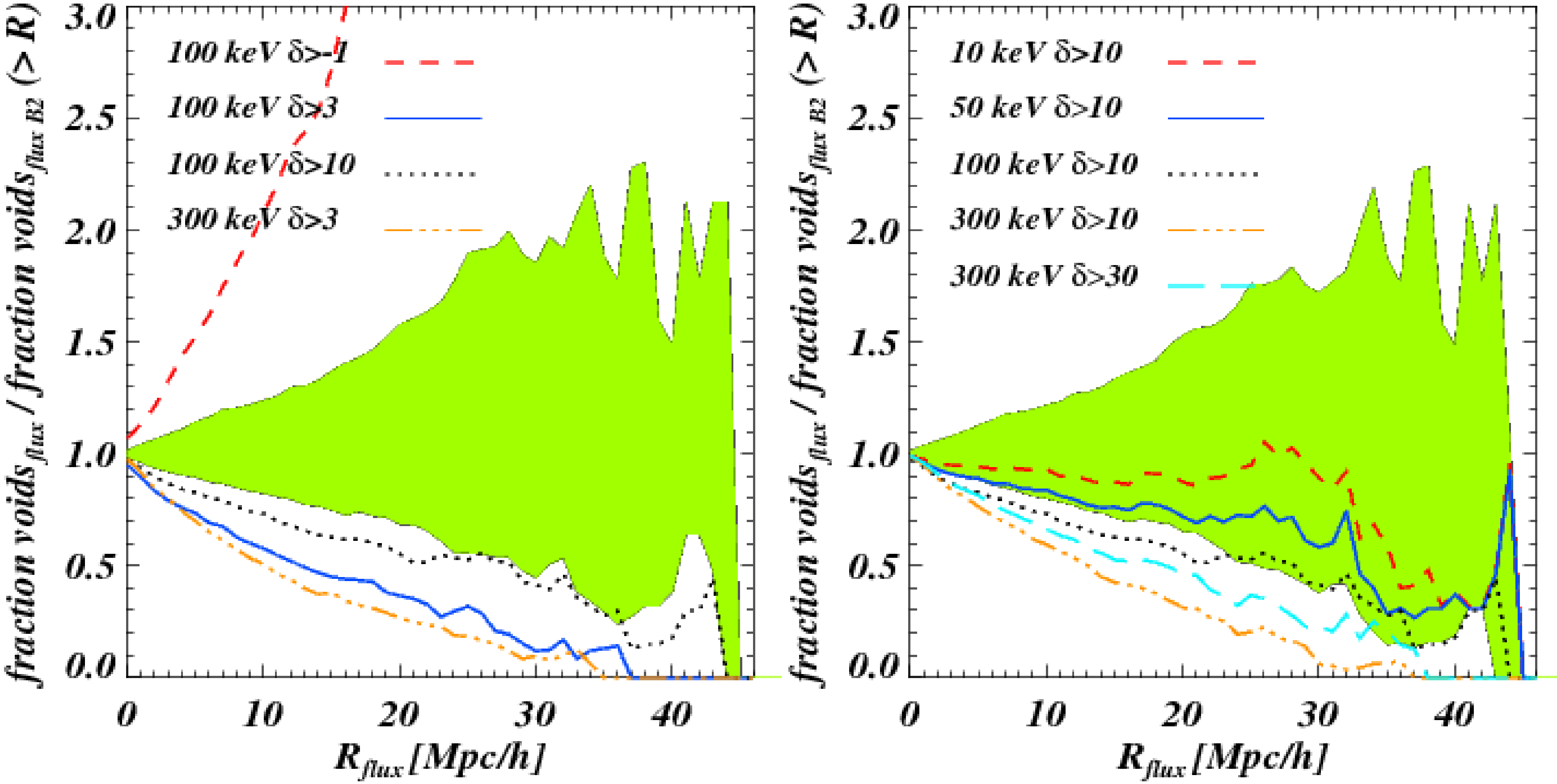
EVOLUTION
OF
A PRE-HEATED
IGM

Preheating the IGM at z=4 - I



Preheating the high-redshift IGM - II

Voids in the flux distribution   Viel, Colberg, Kim 2008 – Borgani & Viel in prep



Preheating the high-redshift IGM - III

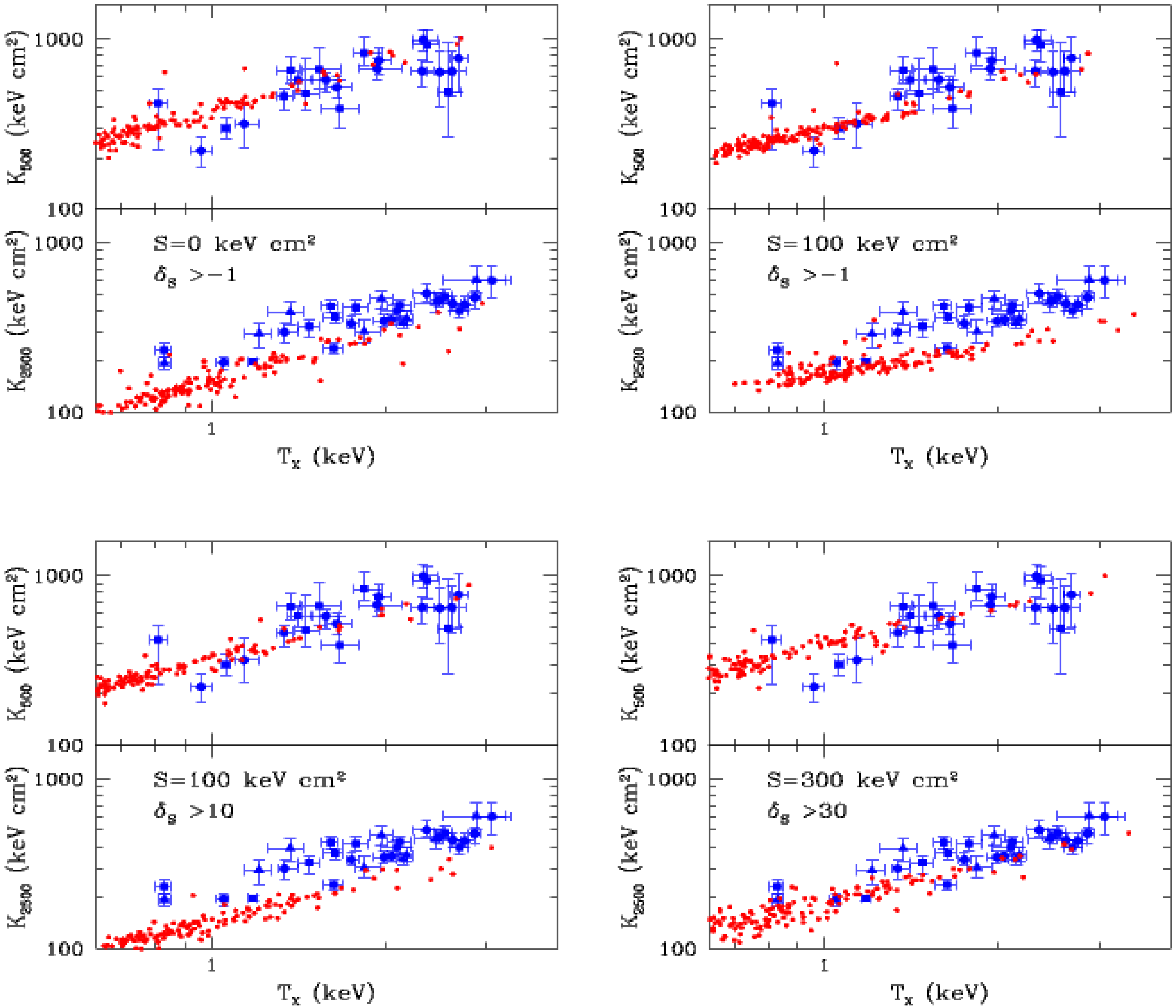
No heating

R_{500}

R_{2500}

R_{500}

R_{2500}



Red: simulations
Blue: Sun et al. 08
CHANDRA data

SUMMARY

- Lyman-α forest is an important cosmological probe at a unique range of scales and redshifts

- Current limitations are theoretical (more reliable simulations are needed for example for neutrino species) and statistical errors are smaller than systematic ones

- Need to fit all the IGM statistics at once (mean flux + flux pdf + flux power + flux bispectrum + …)

- Perspectives for searching non Gaussian signal

- IGM poorly known thermal state could be constrained also from the $z<1$ evolution and by the ICM properties