(quantitative) COSMOLOGY with the LYMAN-α FOREST

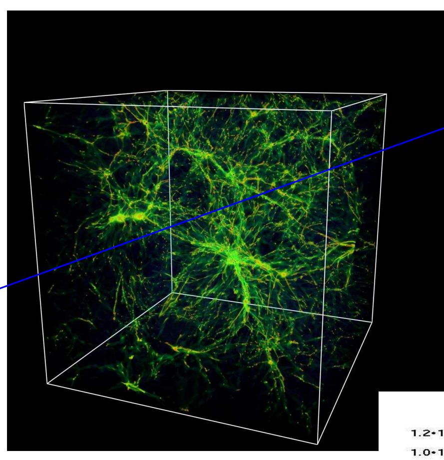
MATTEO VIEL

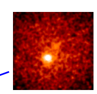
1. Cosmological significance of the Lyman-α forest
2. LUQAS: The observational sample
3. Hydro-dynamical simulations of the Lyman-α forest
4. Cosmological parameters – Implications for: Inflation, (Neutrinos and WDM masses) & Ionizing Background

Viel, Haehnelt, Springel, 2004, MNRAS, 354, 684
Viel, Weller, Haehnelt, astro-ph/0407294, MNRAS, in press

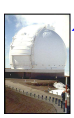
www.ast.cam.ac.uk/~rtnigm/luqas.htm

Santa Barbara, 23rd November 2004

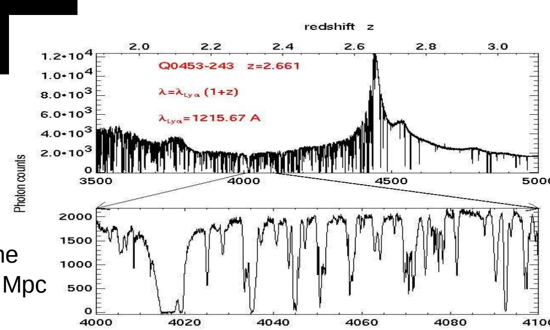




80 % of the baryons at z=3 are in the Lyman-α forest



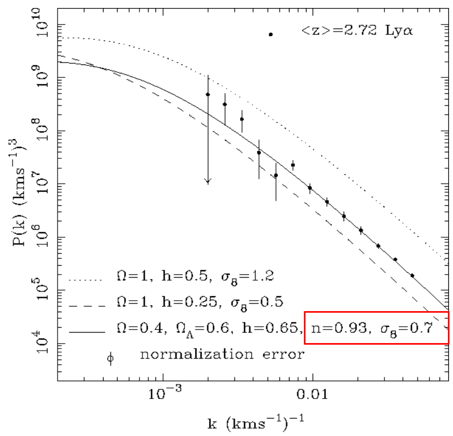
baryons as tracer of the dark matter density field



$\delta_{IGM} \sim \delta_{DM}$ at scales larger than the Jeans length ~ 1 com Mpc

$\tau \sim (\delta_{IGM})^{1.6}\, T^{-0.7}$

the WMAP era.......



before WMAP

Croft et al. 2002

Tilt in the spectrum   n<1 ?

Running spectral index dn/dlnk < 0 ?

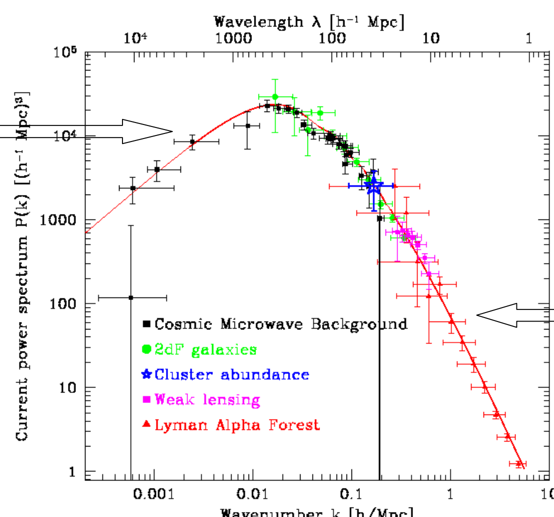
WMAP

Verde et al. 2003

LCDM model				
Parameter	WMAP	+HST	+SN	
Ω_{tot}	$1.038^{+0.027}_{-0.04}$	1.001 ± 0.018	1.008 ± 0.017	
Parameter ($\Omega_{tot} \equiv 1$)	WMAP	+CBI+ACBAR	+2dFGRS	+Lyα
n_s	0.99 ± 0.04	0.97 ± 0.03	0.97 ± 0.03	0.96 ± 0.02
Running index model	($r \equiv 0$	$\Omega_{tot} \equiv 1$)		
Parameter	WMAP	+CBI+ACBAR	+2dFGRS	+Lyα
n_s ($k_0 = 0.05 Mpc^{-1}$)	0.93 ± 0.07	0.91 ± 0.06	$0.93^{0.04}_{0.08}$	0.93 ± 0.03
$dn_s/d\ln k$	-0.047 ± 0.04	-0.055 ± 0.038	$-0.031^{0.028}_{0.025}$	$-0.031^{0.016}_{0.017}$
Running index Tensors		($\Omega_{tot} \equiv 1$)		
Parameter	WMAP		+2dFGRS	+2dFGRS+Lyα
n_s ($k_0 = 0.002 Mpc^{-1}$)	$1.20^{+0.12}_{-0.11}$		$1.18^{+0.12}_{-0.11}$	1.13 ± 0.08
$dn_s/d\ln k$	$-0.077^{+0.050}_{-0.052}$		$-0.075^{+0.044}_{-0.045}$	$-0.055^{+0.028}_{-0.029}$
r ($k_0 = 0.002 Mpc^{-1}$)(95% constraint)	< 1.28		< 1.14	< 0.9

The primordial dark matter power spectrum

CMB physics
z = 1100
dynamics



Lyα physics
z < 6
dynamics
+
termodynamics

Tegmark & Zaldarriaga 2002

CMB + Lyman α ⟹ Long lever arm

Relation: P_{FLUX} (k) - P_{MATTER} (k) ??

Constrain spectral index and shape

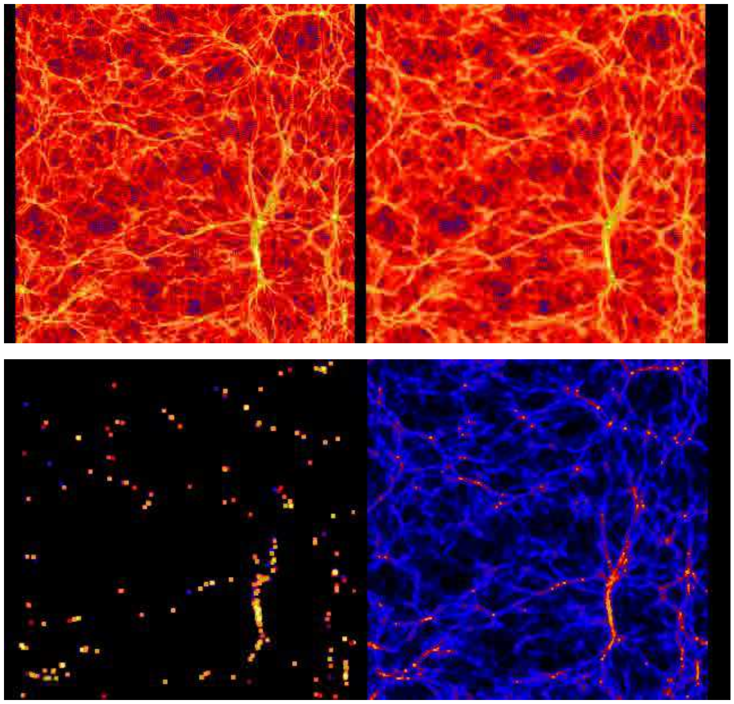
$\Omega_m = 0.26$ $\Omega_\Lambda = 0.74$ $\Omega_b = 0.0463$ H = 72 km/sec/Mpc - grid of models in n and σ_8

DM

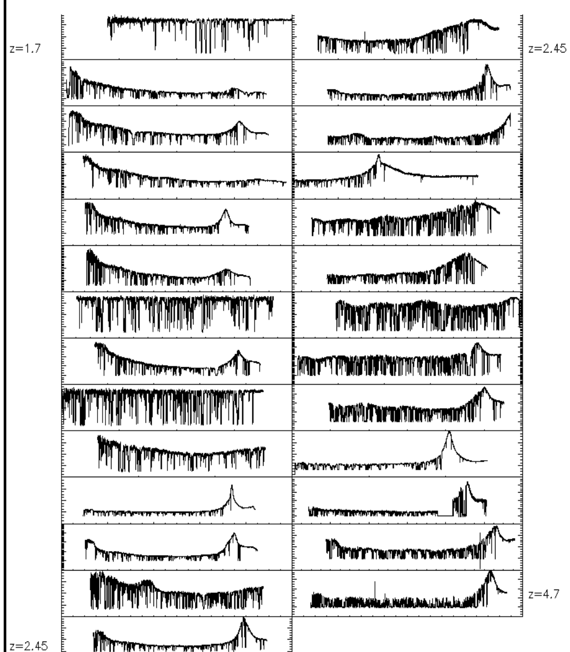
GAS

STARS

NEUTRAL HYDROGEN

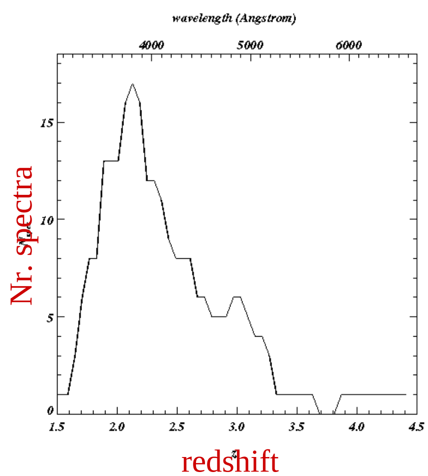


The LUQAS sample -I



Large sample Uves Qso Absorption Spectra
(LP-UVES program P.I. J. Bergeron)

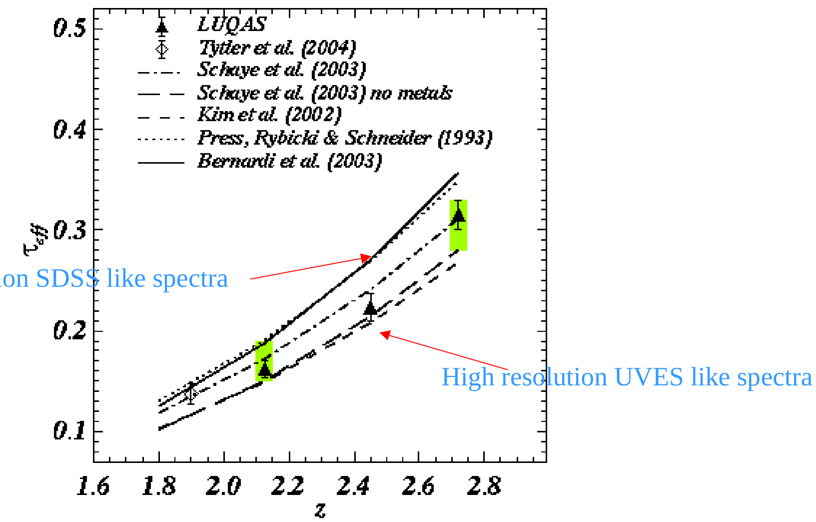
high resolution 0.05 Angstrom, high S/N > 50
low redshift, <z>=2.25, Δz = 13.75



Kim, MV, Haehnelt, Carswell, Cristiani, 2004, MNRAS, 347, 355

The LUQAS sample –II systematic errors

Effective optical depth



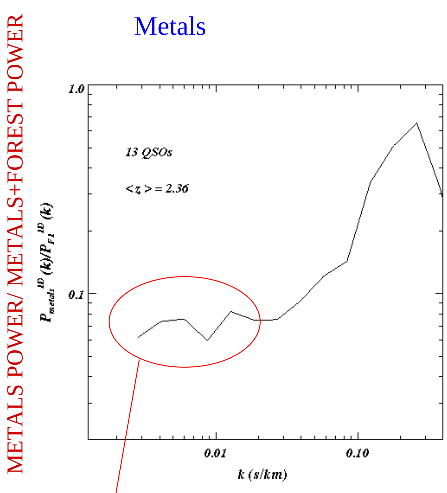
$\langle F \rangle = \exp(-\tau_{eff})$ Power spectrum of $F/\langle F \rangle$

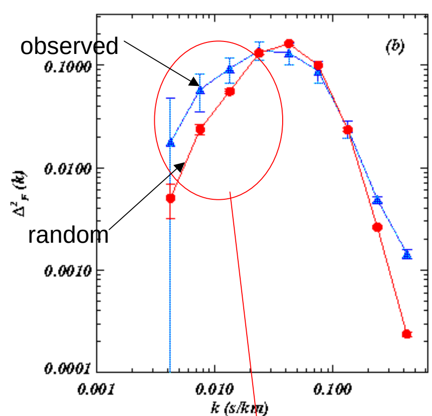
The LUQAS sample –III systematic errors

MV, Haehnelt, Carswell, Kim, 2004

Metals

Strong absorption systems

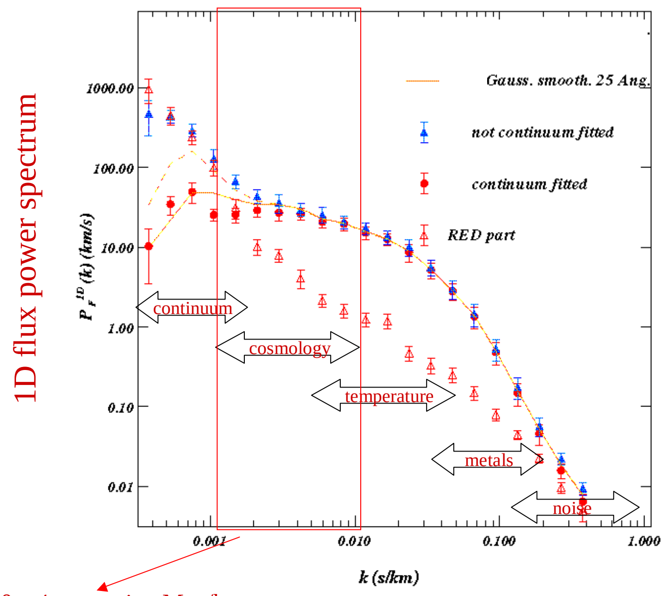




Few % even at very large scales

Clustering can contribute up to 20-30 %
- inclusion of this effect by the SDSS dramatically changes their results
4σ detection of runn.spectr.index → no running
change in the slope of a factor 0.06 at k=0.009 s/km

The flux power spectrum from LUQAS



~ 40 – 4 comoving Mpc/h

wavenumber

Effective bias method (Croft et al.2002)

From hydro-simulations

$$P_{FLUX}(k) = b^2(k)\ P_{MATTER}(k)$$

Depends on cosmological parameters, mean flux level, temperature

for critical discussion see Gnedin & Hamilton 2002 and Zaldarriaga Scoccimarro Hui 2003

Main drawbacks: it misses dependence on cosmological parameters
mode coupling is expected
are the forest structure really linear ?

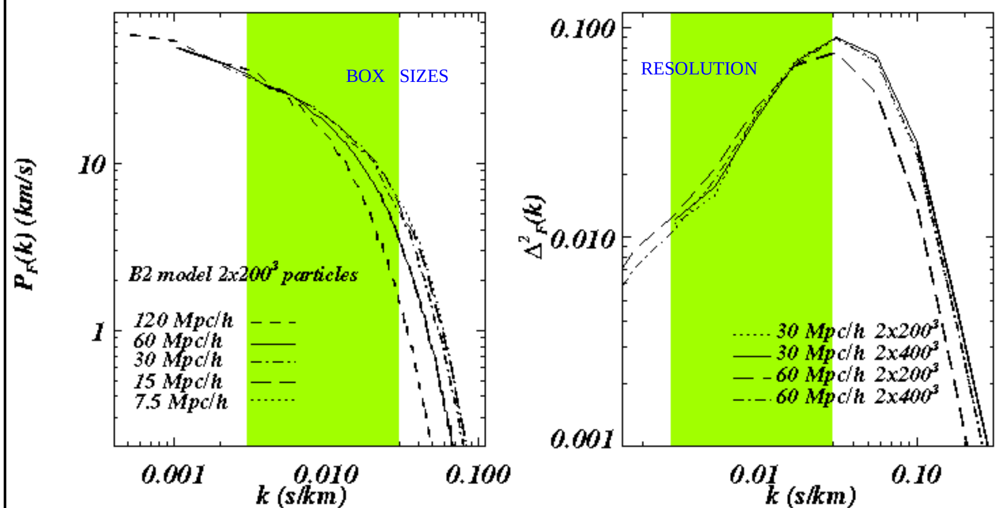
The flux power spectrum seems to be a robust statistics (Galactic winds, DLAs, metals…)
e.g. McDonald et al. (2004)

Hydro-simulations: resolution & box size

COSMOS computer at DAMTP - Cambridge

1D power spectrum of the flux

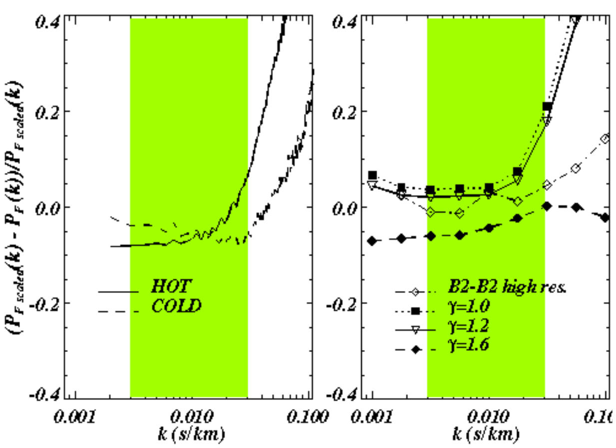
3D power spectrum of the flux



Hydro-simulations: systematics effects

Different equation of state

Different γ



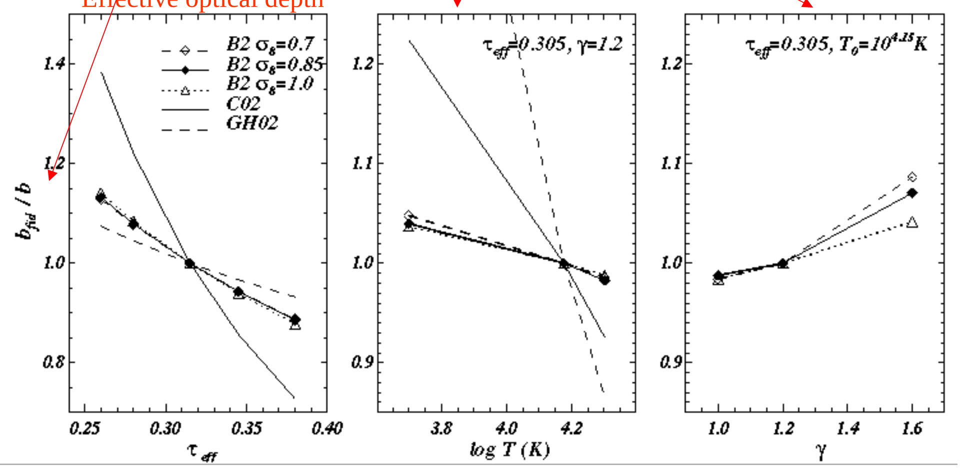
$T = T_0\,(1 + \delta)^{\gamma-1}$

Hydro-simulations: scalings

$P_{FLUX}(k) = b^2(k)\, P_{MATTER}(k)$

$T = T_0 (1 + \delta)^{\gamma-1}$

Effective optical depth

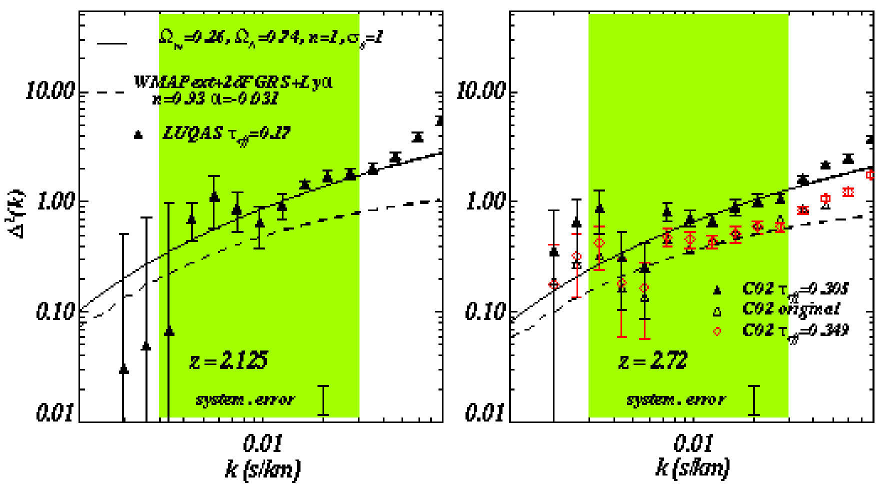


Hydro-simulations: what have we learnt?

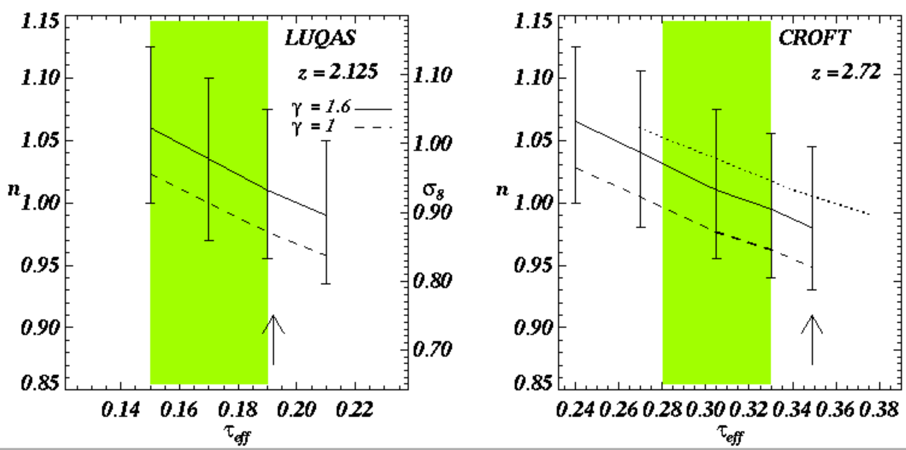
Many uncertainties which contribute more or less equally
(statistical error is not an issue!)

ERRORS	CONTRIBUTION TO FLUCT. AMPL.
Statistical error	4%
Systematic errors	~ 15 %
τ_{eff} (z=2.125)=0.17 ± 0.02	8 %
τ_{eff} (z=2.72) = 0.305 ± 0.030	7 %
γ = 1.3 ± 0.3	4 %
T_0 = 15000 ± 10000 K	3 %
Method	5 %
Numerical simulations	8 %
Furhter uncertainties	5 %

The linear dark matter power spectrum at z=2.72 and z =2.125



Cosmological implications: combining the forest data with CMB - I

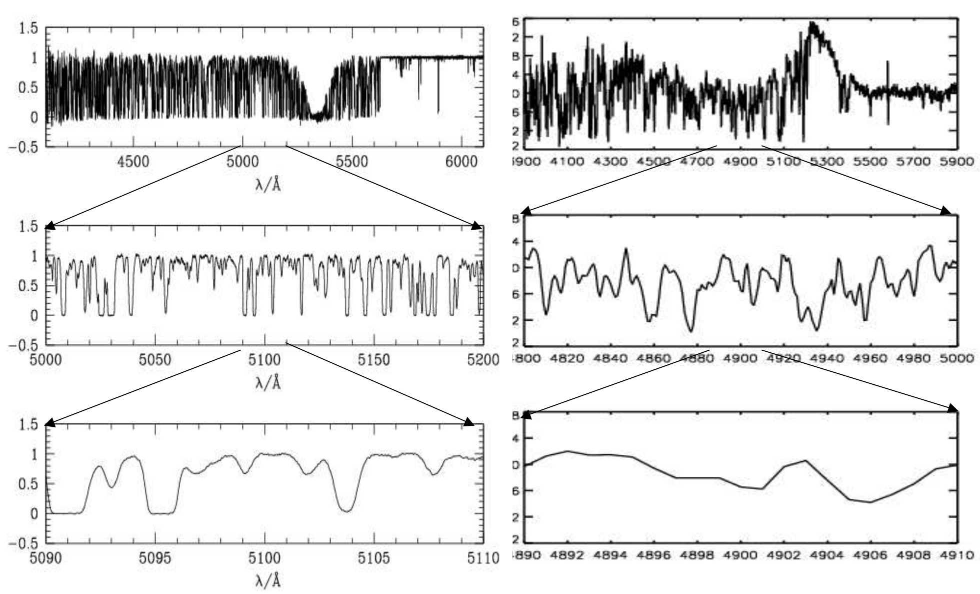


TWO QUESTIONS:

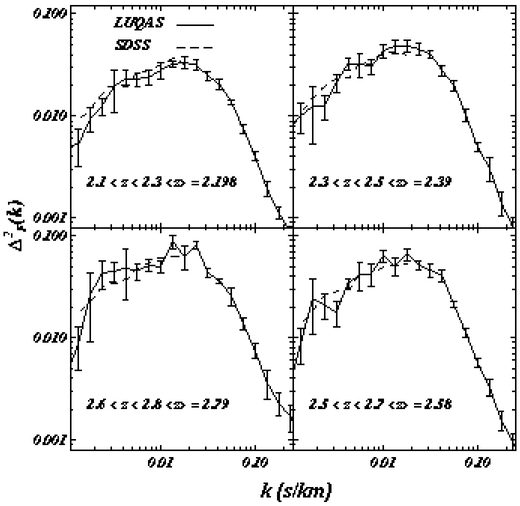
1) WHICH OBSERVATIONS ?
high or low resolution?

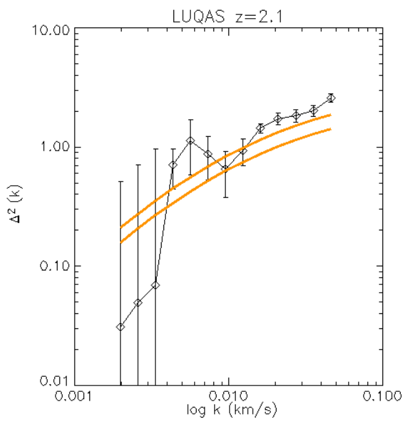
2) WHICH SIMULATIONS ?
full hydro or hydro-pm codes?

HIGH RESOLUTION HIGH S/N vs LOW RESOLUTION LOW S/N



LUQAS vs SDSS





HPM simulations of the forest

$$\frac{d\boldsymbol{v}}{dt} + H\boldsymbol{v} = -\nabla\phi - \frac{1}{\rho}\nabla P,$$

equation of motion for gas element

if $T = T_0\,(1+\delta)^{\gamma-1}$

$$\frac{d\boldsymbol{v}}{dt} + H\boldsymbol{v} = -\nabla\psi$$

where

$$\psi = \phi + \mathcal{H},$$

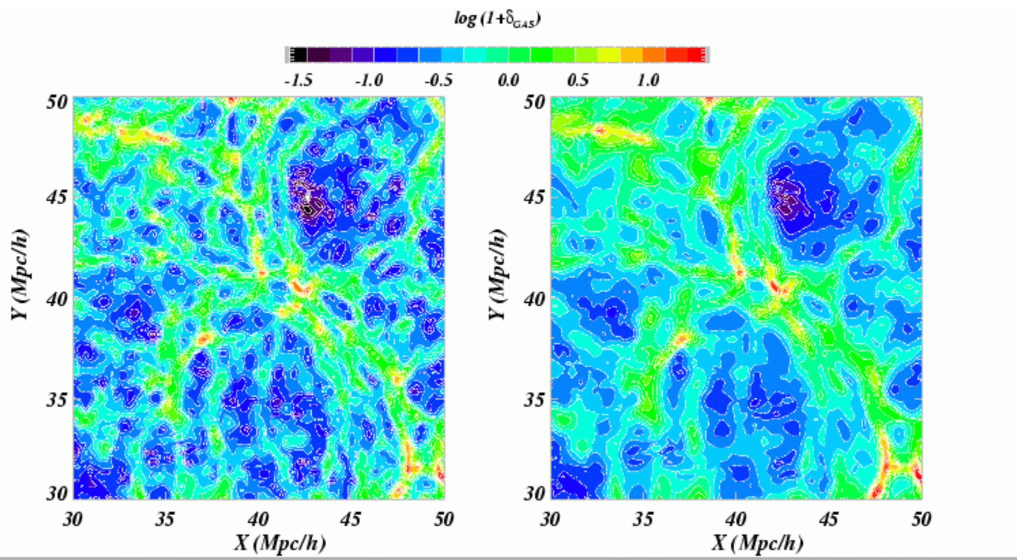
and $\mathcal{H}$, called *the specific enthalpy*, is

$$\mathcal{H}(\rho) = \frac{P(\rho)}{\rho} + \int_1^{\rho} \frac{P(\rho')}{\rho'}\frac{d\rho'}{\rho'}.$$

We thus conclude that the HPM approximation can be successfully used to model the Lyman-alpha forest when a 10-15% accuracy is sufficient.

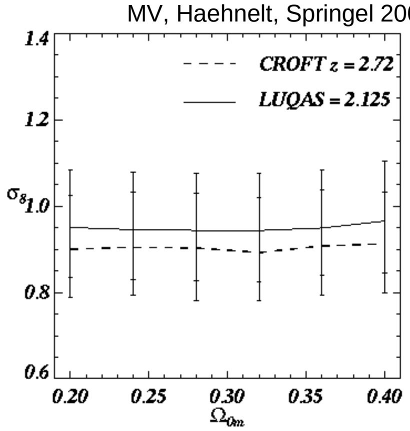
Gnedin & Hui 1998

HYDRO vs HPM : flux statistics

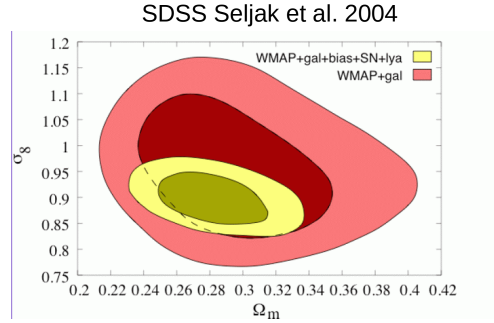


Cosmological implications: combining the forest data with CMB - II

MV, Haehnelt, Springel 2004



SDSS Seljak et al. 2004



$n = 1.01 \pm 0.02 \pm 0.06$

$\sigma_8 = 0.93 \pm 0.03 \pm 0.09$

Systematic error

MV, Haehnelt, Springel (2004)

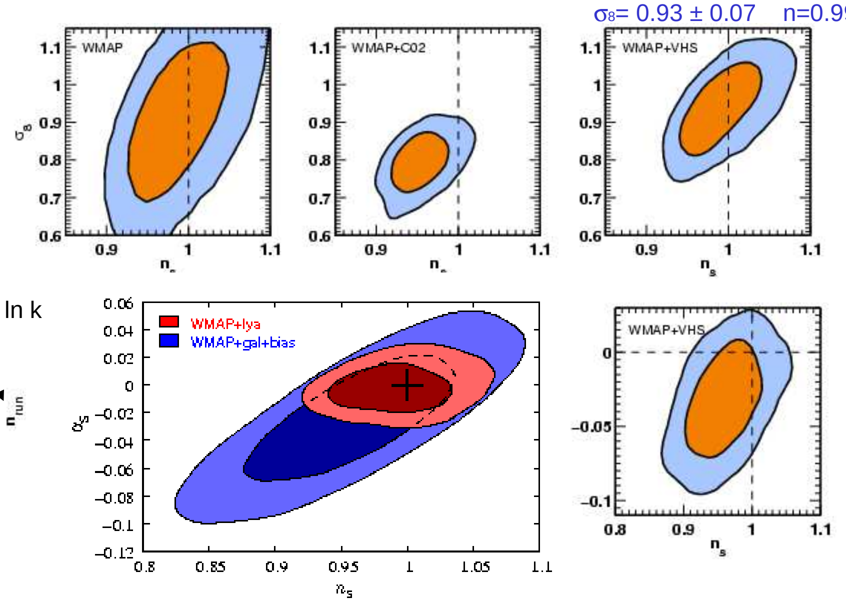
Statistical error

Note that the flux bispectrum analysis agrees with these values
MV, Matarrese, Heavens, Haehnelt, Kim, Springel, Hernquist, 2004

Cosmological implications: combining the forest data with CMB - III

σ_8= 0.93 ± 0.07 n=0.99 ± 0.03

d n_S/ d ln k → n_{run}



σ_8= 0.90 ± 0.03 n=0.98 ± 0.02 n_{run} = -0.003 ± 0.010 nrun=-0.033± 0.025

Cosmological implications: constraints on slow-roll inflation - IV

V = inflaton potential

$$\epsilon_1 \simeq \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 ,$$

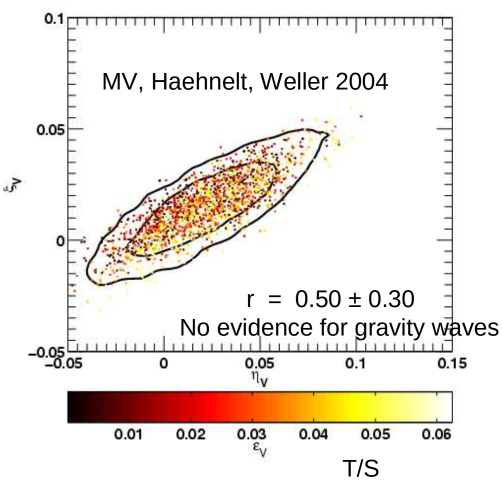
$$\epsilon_2 \simeq 2M_{Pl}^2\left[\left(\frac{V'}{V}\right)^2 - \frac{V''}{V}\right] ,$$

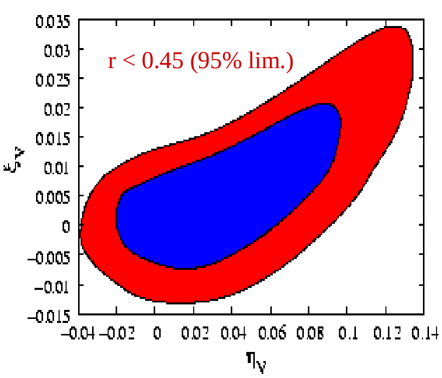
$$\epsilon_2\epsilon_3 \simeq 2M_{Pl}^4\left[\frac{V'''V'}{V^2} - 3\frac{V''}{V}\left(\frac{V'}{V}\right)^2 + 2\left(\frac{V'}{V}\right)^4\right]$$

$$\text{T/S} = r \approx 16\epsilon_1 ,$$

$$n_{run} \approx -\epsilon_2\epsilon_3 ,$$

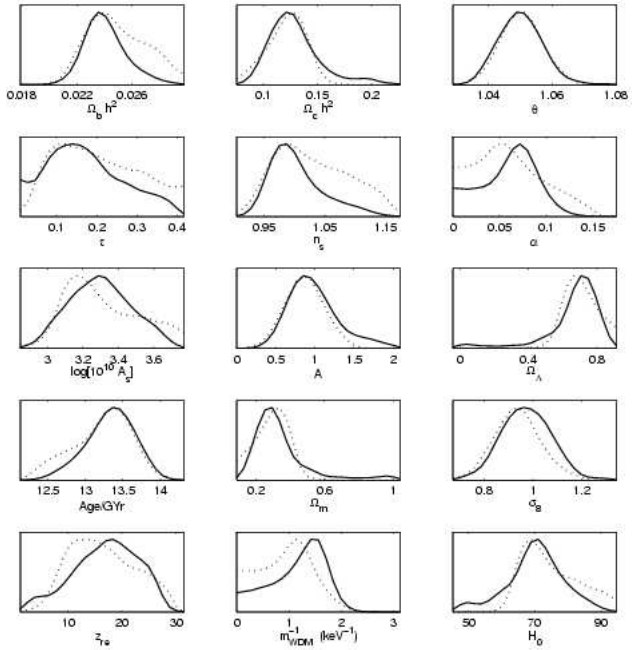
$$n_s - 1 \approx -2\epsilon_1 - \epsilon_2 - 2\epsilon_1^2 - C\epsilon_2\epsilon_3$$





SDSS Seljak et al. 2004

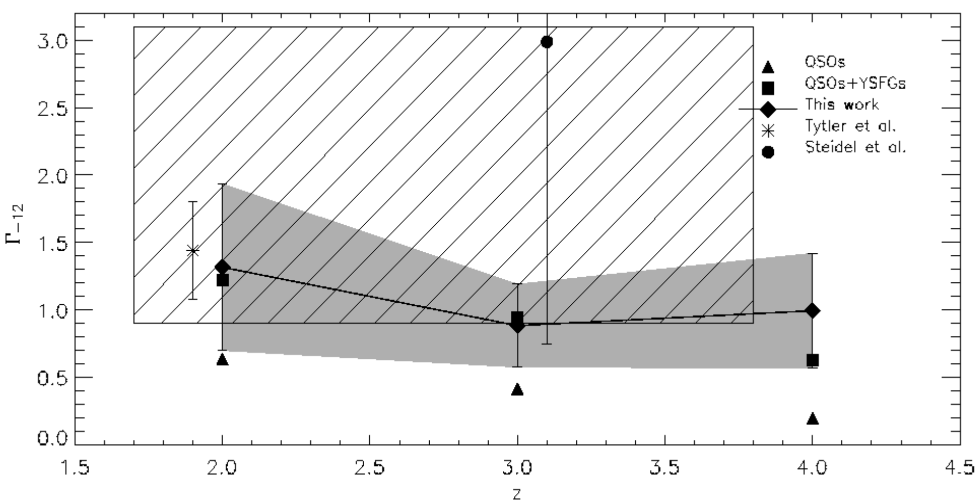
Cosmological implications: constraints on neutrinos and WDM -V



Viel, Lesgourgues, Matarrese, Riotto, Haehnelt in prep.

Ionizing background

With the fluctuating Gunn – Peterson approximation



Bolton, Haehnelt, MV, Springel, 2004, astro-ph/0411072

SUMMARY

1. LUQAS: a unique high resolution view on the Universe at z=2.1

2. Hydro-dynamical simulations of the Lyman-α forest. Systematic Errors? Differences between hydro codes?

3. Cosmological parameters: no fancy things going on
   $\sigma_8 = 0.93$ n = 1 no running
   substantial agreement between SDSS and LUQAS but SDSS has smaller error bars not because of the larger sample but because of the different theoretical modelling
   Some (weak) constraints on inflationary models.

Brief historical overview

'ISOLATED' CLOUDS

- Gunn & Peterson (1965): a uniform IGM at redshift 2 is very highly ionized, to avoid very large HI opacity;
- Bahcall & Salpeter (1965): if it is not uniformly distributed then absorption lines [gas in clusters of galaxies ?];
- Lynds (1971): a forest of lines, the Lyα forest, not related to clusters, but intergalactic clouds along the line of sight;

⇒ The idea was of a "two-phase" medium: clouds confined by the intercloud medium [IGM], with pressure confinement (Sargent et al. 1980) or dark-matter mini halos (Rees 1986);

⇒ Other idea: unified, but not uniform intergalactic medium. Originally from Black (1981) and Oort (1981), who suggested that Lyα forest was a relic of primordial fluctuations with $\lambda \sim 1$ Mpc;

- McGill (1991), Bi (1992) considered an evolution of the IGM in cold dark matter models and found that a "median-fluctuated" medium, instead of discrete clouds, reproduced most of the observations;
- N-body + Hydro simulations (Cen et al. 1994), semi analytical models (Bi et al., 1993).

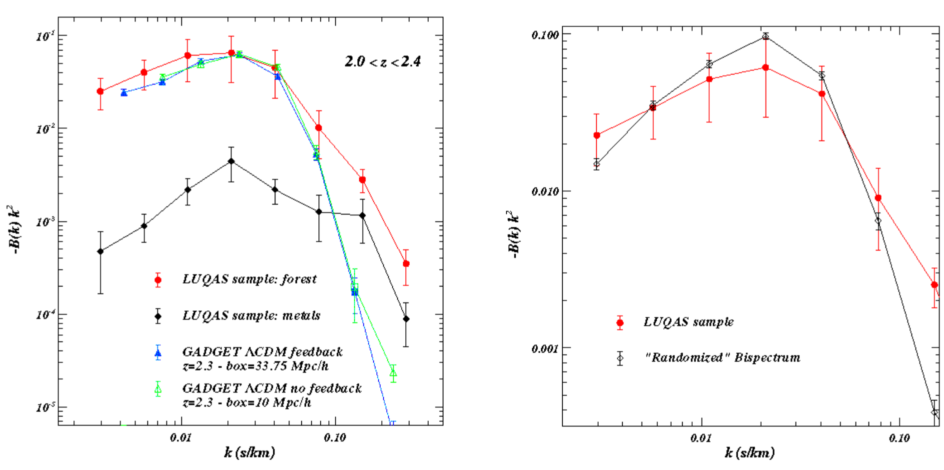
NETWORK OF FILAMENTS

PROBES OF THE JEANS SCALE

COSMOLOGICAL PROBES

The flux bispectrum

Fourier transform of the 3-points correlation function



Feedback in the form of galactic winds does not affect the forest

MV, Matarrese, Heavens, Haehnelt, Kim, Springel, Hernquist, 2004, MNRAS, 347, 26L

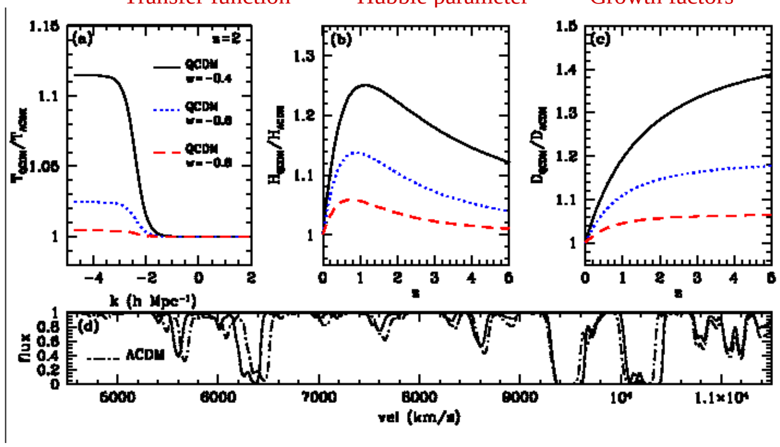
Dark energy effects on the Lyman-α forest

$p = w\,\rho$

$w = -1$ ΛCDM

Transfer function　Hubble parameter　Growth factors

Flux



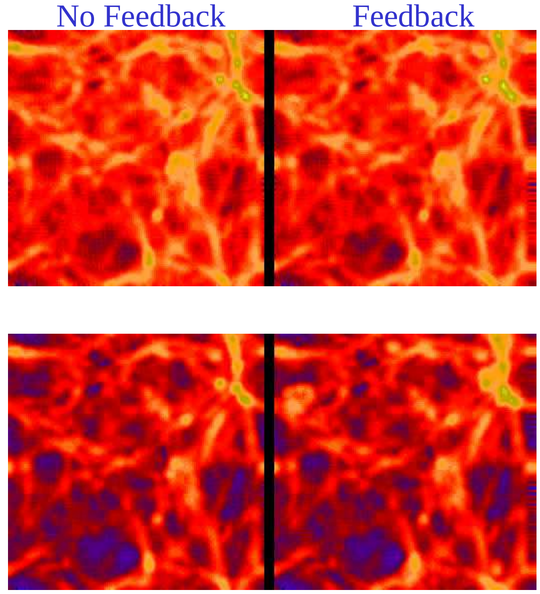
MV, Matarrese, Theuns, Munshi, Wang, 2003, MNRAS, 340, L47

Feedback effects: Galactic winds

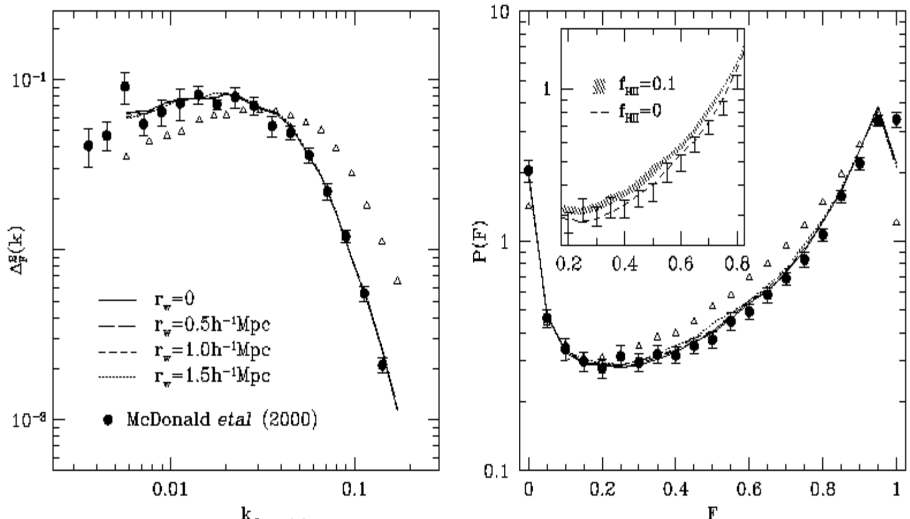
No Feedback　Feedback

Density

Temperature



Feedback effects: Galactic winds-II

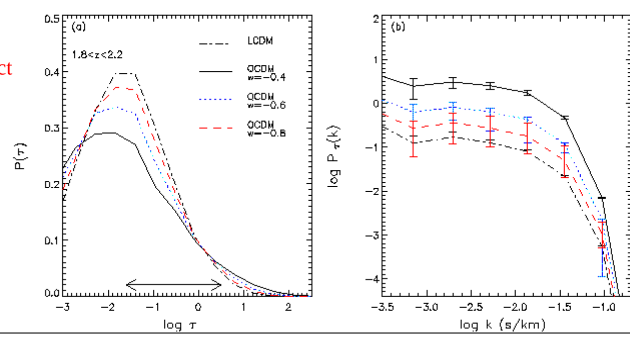


Desjacques et al. 2004

Theuns T., MV, Kay S., Schaye J., Carswell R., Tzanavaris P., 2002, ApJL, 578, 5

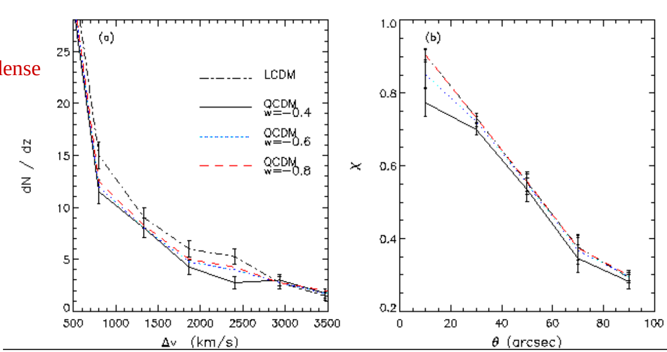
Dark energy effects on the Lyman-α forest-II

Optical depth prob. distrib. funct



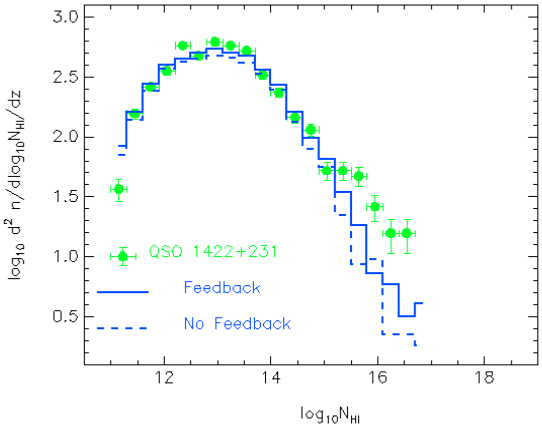
Optical depth power spectrum

Number of underdense regions



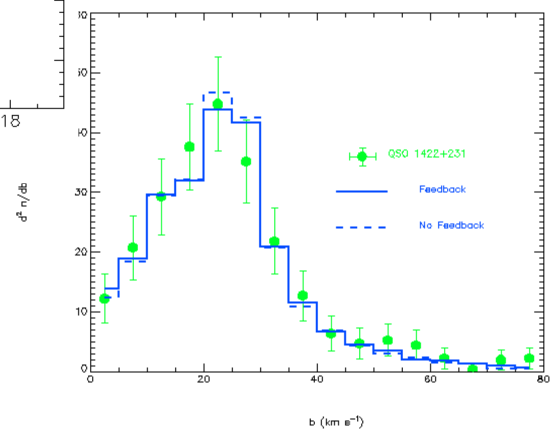
Cross correlation coefficient between QSO pairs

Feedback effects: Galactic winds-III



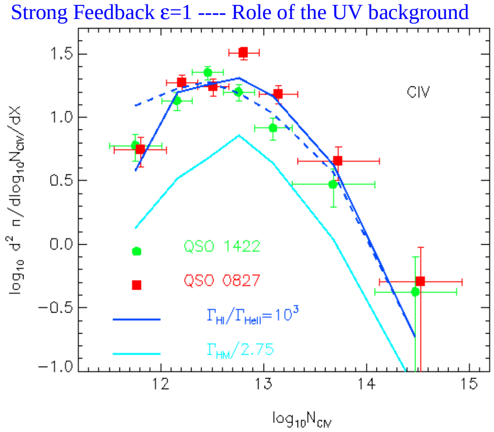
Column density distribution function

Line widths distribution



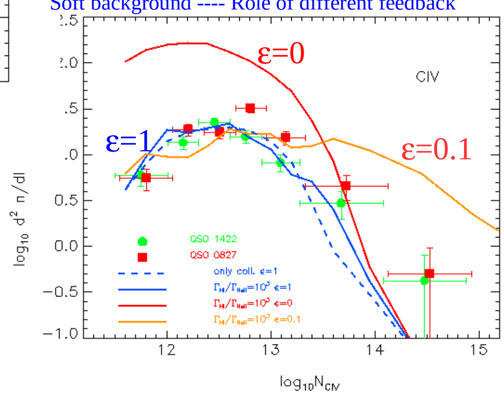
Metal enrichment CIV systems at z=3

Strong Feedback ε=1 ---- Role of the UV background



Mori, Ferrara, Madau 2000; Rauch, Haehnelt, Steinmetz 1996; Schaye et al. 2003

Soft background ---- Role of different feedback



Lyman-α: Pros & Cons

'Simple' physics in which baryons trace the underlying dark matter density field

It probes a range of scales and redshifts not probed by other observations such as galaxies or CMB ($0 < z < 6.3$, $0.1 < k < 1$ h/Mpc)

Many QSOs spectra available (SDSS, Keck, UVES)

Continuum fluctuations from distant QSOs or 'real' fluctuations of the matter distribution? (see Hui et al. 2001)

Modelling of the IGM still needs high resolution hydro-dynamical simulations (discrepancy between different simulations)

Understanding of the systematic errors has recently led to controversial results (mean flux level, metal lines, strong absorption systems)

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