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


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

\[ \delta_{\text{IGM}} \sim \delta_{\text{DM}} \quad \text{at scales larger than the Jeans length } \sim 1 \text{ com Mpc} \]

\[ \tau \sim (\delta_{\text{IGM}})^{1.6} T^{-0.7} \]
Quantitative Cosmology with the Lyman-Alpha Forest

The WMAP era......

before WMAP
Croft et al. 2002

Tilt in the spectrum n<1 ?

Running spectral index dn/dlnk < 0 ?

The primordial dark matter power spectrum

CMB physics z = 1100 dynamics

Lyα physics z < 6 dynamics +

termodynamics

CMB + Lyman α → Long lever arm
Constrain spectral index and shape

Relation: P_{FLUX}(k) - P_{MATTER}(k) ??
Quantitative Cosmology with the Lyman-Alpha Forest

\[ \Omega_m = 0.26 \, \Omega_{\Lambda} = 0.74 \, \Omega_b = 0.0463 \quad \text{H} = 72 \, \text{km/sec/Mpc} \quad \text{- grid of models in n and } \sigma_8 \]

**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, \( <z> = 2.25, \Delta z = 13.75 \)

The LUQAS sample –II

Effective optical depth

\[ <F> = \exp \left( -\tau_{\text{eff}} \right) \]

Power spectrum of \( F/<F> \)

The LUQAS sample –III

Metals

M V, Haehnelt, Carswell, Kim, 2004

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

4d detection of runn.spectr.index \( \rightarrow \) no running change in the slope of a factor 0.06 at \( k=0.009 \) s/km
The flux power spectrum from LUQAS

\[
P_{\text{FLUX}}(k) = b^2(k) P_{\text{MATTER}}(k)
\]

Effective bias method \cite{Croft2002}

From hydro-simulations

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 \cite{GalacticwindsDLAsMetals}
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 $\gamma$

$$T = T_0 \left(1 + \delta \right)^{\gamma - 1}$$
Hydro-simulations: scalings

\[ P_{\text{FLUX}}(k) = b^2(k) P_{\text{MATTER}}(k) \]

\[ T = T_0 \left(1 + \delta \right)^{\gamma - 1} \]

Effective optical depth

Hydro-simulations: what have we learnt?

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

<table>
<thead>
<tr>
<th>ERRORS</th>
<th>CONTRIBUTION TO FLUCT. AMPL.</th>
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</thead>
<tbody>
<tr>
<td>Statistical error</td>
<td>4%</td>
</tr>
<tr>
<td>Systematic errors</td>
<td>~ 15%</td>
</tr>
<tr>
<td>( \tau_{\text{eff}} (z=2.125) = 0.17 \pm 0.02 )</td>
<td>8%</td>
</tr>
<tr>
<td>( \tau_{\text{eff}} (z=2.72) = 0.305 \pm 0.030 )</td>
<td>7%</td>
</tr>
<tr>
<td>( \gamma = 1.3 \pm 0.3 )</td>
<td>4%</td>
</tr>
<tr>
<td>( T_0 = 15000 \pm 10000 , \text{K} )</td>
<td>3%</td>
</tr>
<tr>
<td>Method</td>
<td>5%</td>
</tr>
<tr>
<td>Numerical simulations</td>
<td>8%</td>
</tr>
<tr>
<td>Further uncertainties</td>
<td>5%</td>
</tr>
</tbody>
</table>
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?
LUQAS vs SDSS

HPM simulations of the forest

\[ \frac{d\rho}{dt} + H \rho = -\nabla \phi - \frac{1}{\rho} \nabla P, \]

equation of motion for gas element

if \( T = T_0 \left( 1 + \delta \right)^{\gamma - 1} \)

where

\[ \psi = \phi + H, \]

and \( H \), called the specific enthalpy, is

\[ H(\rho) = \frac{P(\rho)}{\rho} + \int_1^\rho \frac{P(\rho')}{\rho'} \, d\rho'. \]

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

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

\[ \sigma_8 = 0.93 \pm 0.07 \quad n = 0.99 \pm 0.03 \]

Cosmological implications: constraints on slow-roll inflation - IV

\[ V = \text{inflaton potential} \]
\[ T/S = r \approx 1.8 \delta_3, \]
\[ n_{\text{run}} \approx -2\delta_3, \]
\[ n_p - 1 \approx -2\delta_3 - \delta_2 - 2\delta_3^2 - \delta_2\delta_3 \]

\[ r = 0.50 \pm 0.30 \]

No evidence for gravity waves

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

SUMMARY

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

2. Hydro-dynamical simulations of the Lyman-\( \alpha \) forest. Systematic Errors? Differences between hydro codes?

3. Cosmological parameters: no fancy things going on
   \( \sigma_8 = 0.93 \quad n = 1 \) 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

- Gunn & Peterson (1965): a uniform IGM at redshift 2 is very highly ionized, to avoid very large H I opacity.
- Bahcall & Rees (1985): if it is not uniformly distributed then absorption lines (gas in clusters of galaxies).
- Lynds (1971): a forest of lines, the Lyman 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. 1993) or dark matter mini halos (Rees 1986).
- Other idea: unified, but not uniform intergalactic medium. Originally from Black (1991) and Cowie (1992), who suggested that Lyman forest was a result of primordial fluctuations with \( \lambda \sim 1\) Mpc.
- McKee (1991): B (1996) considered an evolution of the IGM in cold dark matter models and found that a medium-fluctuated medium, instead of discrete clouds, reproduces most of the observations.
- N-body + Hydro simulations (Cen et al. 1994), semi-analytical models (R1 et al., 1993).

The flux bispectrum

Fourier transform of the 3-points correlation function

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

**Dark energy effects on the Lyman-α forest**

\[ p = w \rho \]

\[ w = -1 \]

ACDM

Transfer function

Hubble parameter

Growth factors

Flux


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**Feedback effects: Galactic winds**

No Feedback

Feedback

Density

Temperature
Feedback effects: Galactic winds-II


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

Line widths distribution

Column density distribution function

Metal enrichment CIV systems at z=3

Strong Feedback $\varepsilon=1$ ---- Role of the UV background

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

Soft background ---- Role of different feedback

$\varepsilon=0$

$\varepsilon=1$

$\varepsilon=0.1$
**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)