The Lyman-α Forest and the Cosmic Web

Avery Meiksin

IAU Symposium 308: The Zeldovich Universe

Genesis and Growth of the Cosmic Web

Tallinn, 23-28 June 2014

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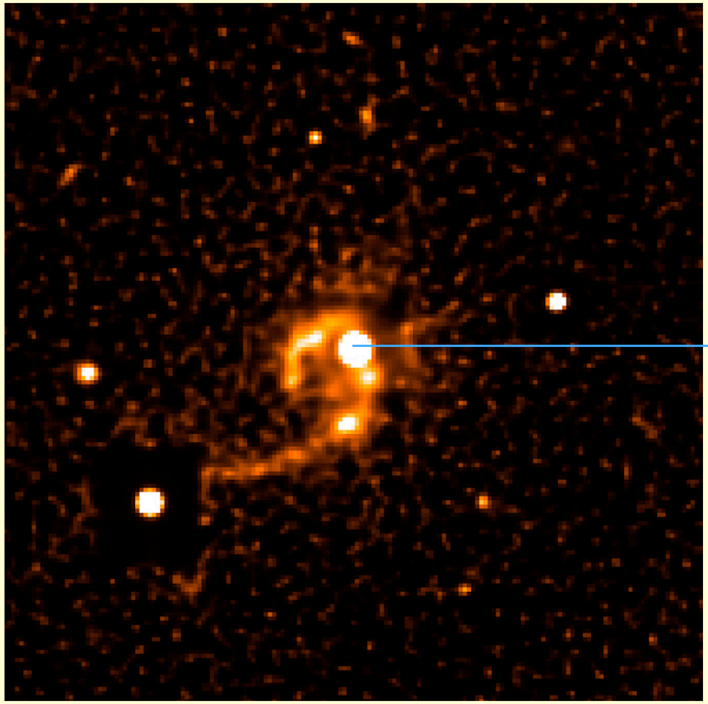
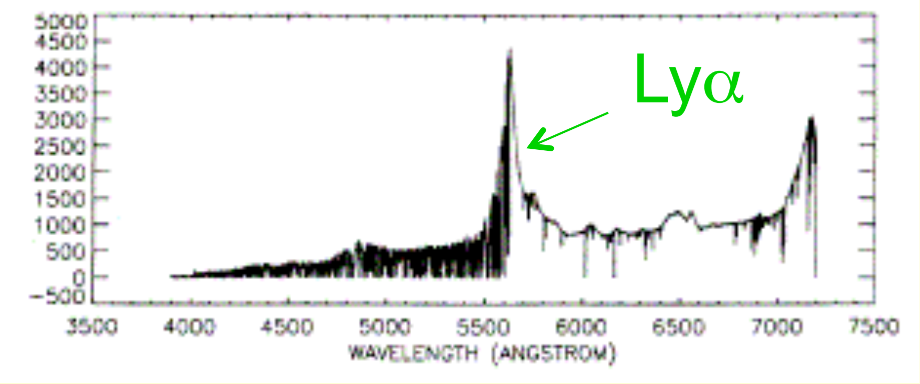
AM (2009) Rev. Mod. Physics 81:1405

The Lyman-α Forest



Q1422+231; z = 3.6



Songaila & Cowie (1996)

The Gunn-Peterson Effect

$$\tau_{\nu=\nu_0/(1+z)} = (g_u / g_l)(1/ 8\pi)\lambda_0^3 \, \Gamma_{ul} \, \langle n_l \rangle / H(z)$$

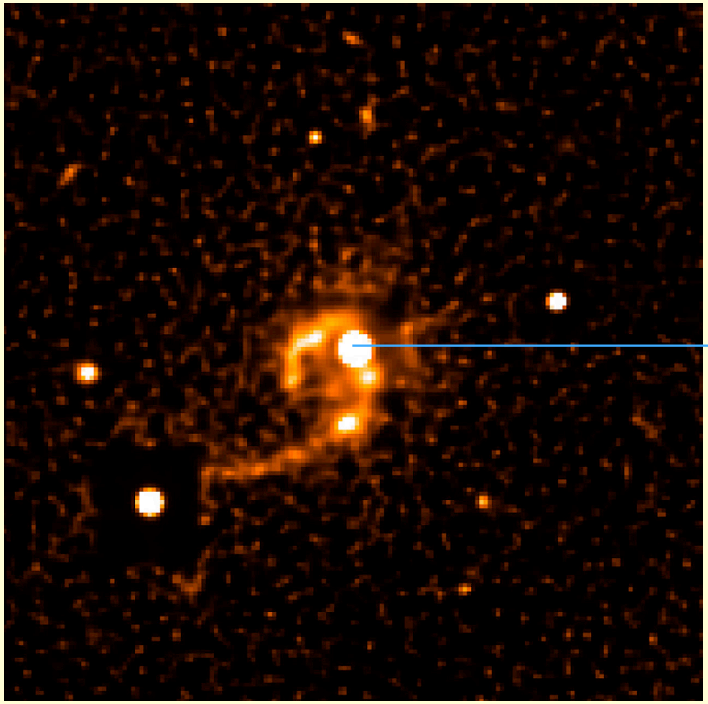
$$\approx 2.2 \times 10^4 \, f_{HI}(z)(f_{lu} \, \lambda_0 / 506A)(1+z)^{3/2}$$

$(\text{for } g_u/g_l = 3)$

Observed QSO $f_\nu = f_\nu^{int} \exp(-\tau_\nu)$

(Gunn & Peterson 1965; Scheuer 1965;
Field 1959 in 21cm EoR context)

The Lyman-α Forest



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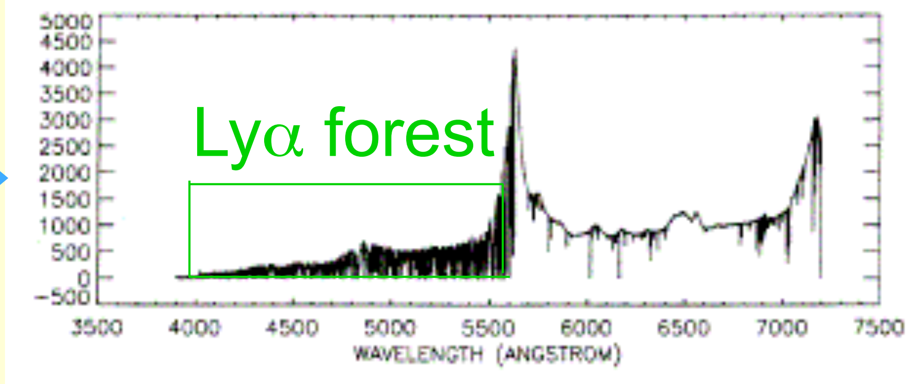


Songaila & Cowie (1996)

The Lyman-α Forest

- Resonance line optical depth

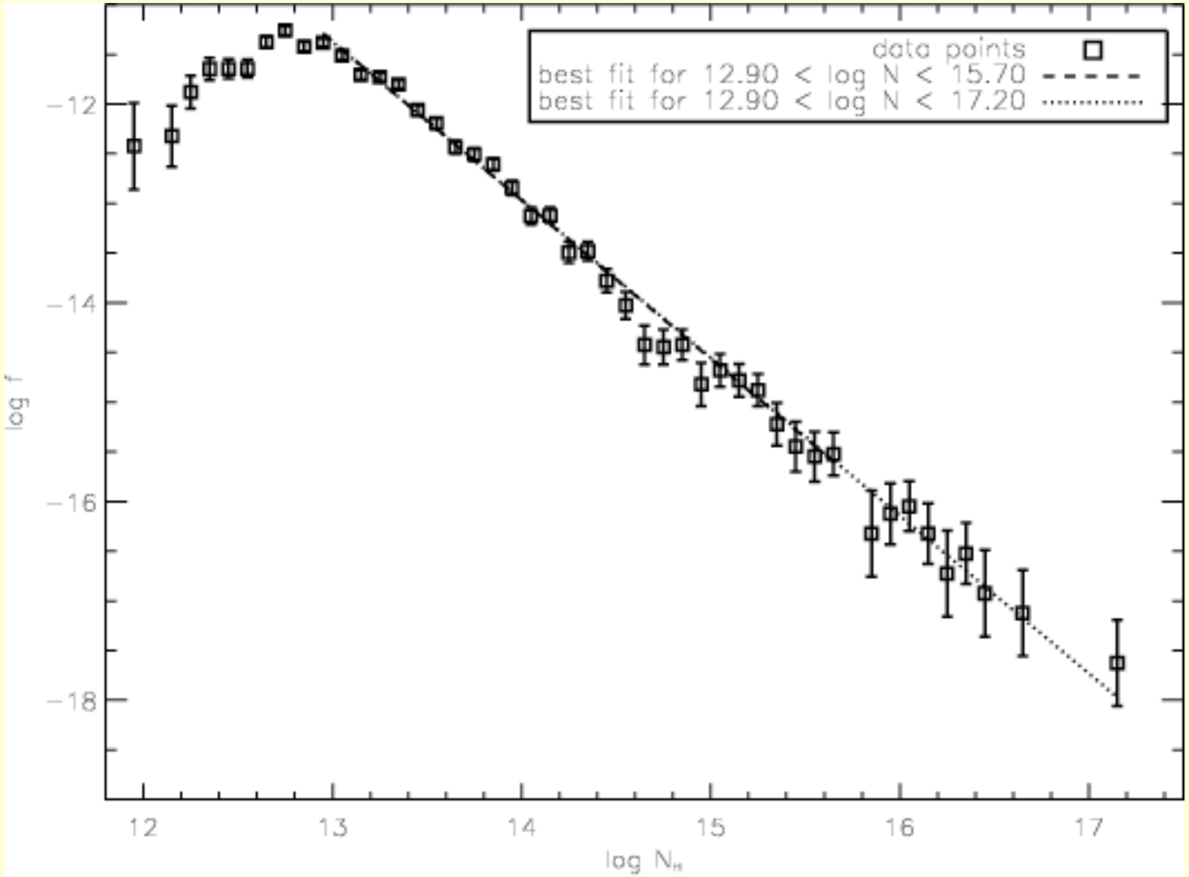
$$\tau_0 = \frac{N\sigma\lambda_{lu}}{\pi^{1/2}b} = \frac{\sqrt{\pi}e^2}{m_e c}\frac{N}{b}\lambda_{lu}f_{lu}$$

$$\simeq 0.38\left(\frac{N_{\rm HI}}{10^{13}\,{\rm cm}^{-2}}\right)\left(\frac{20\,{\rm km\,s}^{-1}}{b}\right)$$

For HI Ly-α, $\lambda_{lu} \simeq 1215.67\,{\rm A}, \quad f_{lu} \simeq 0.4162\ldots.$

Properties of the Lyman-α Forest

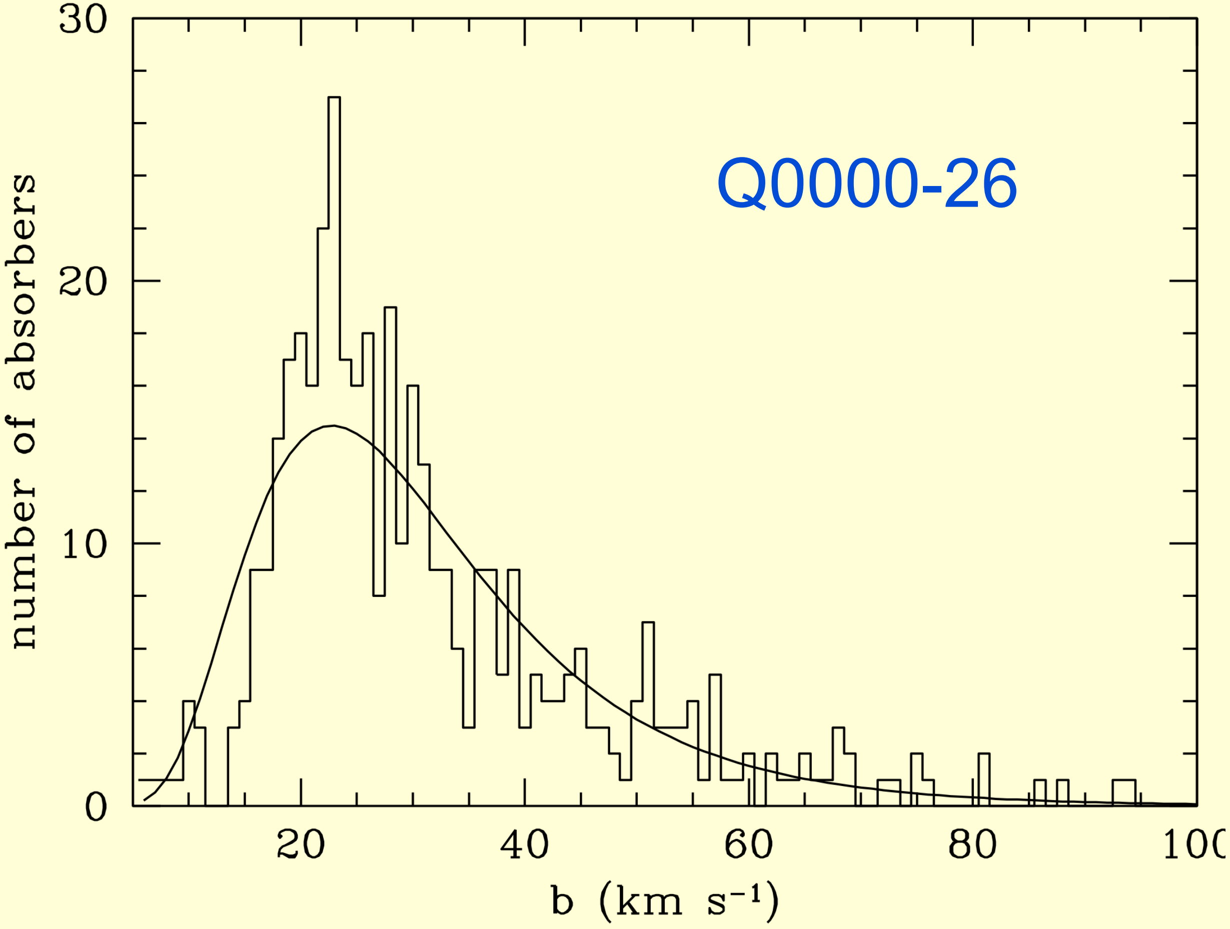
- HI column density distribution



Janknecht et al. (2006)

Properties of the Lyman-α Forest

- HI Doppler parameter distribution

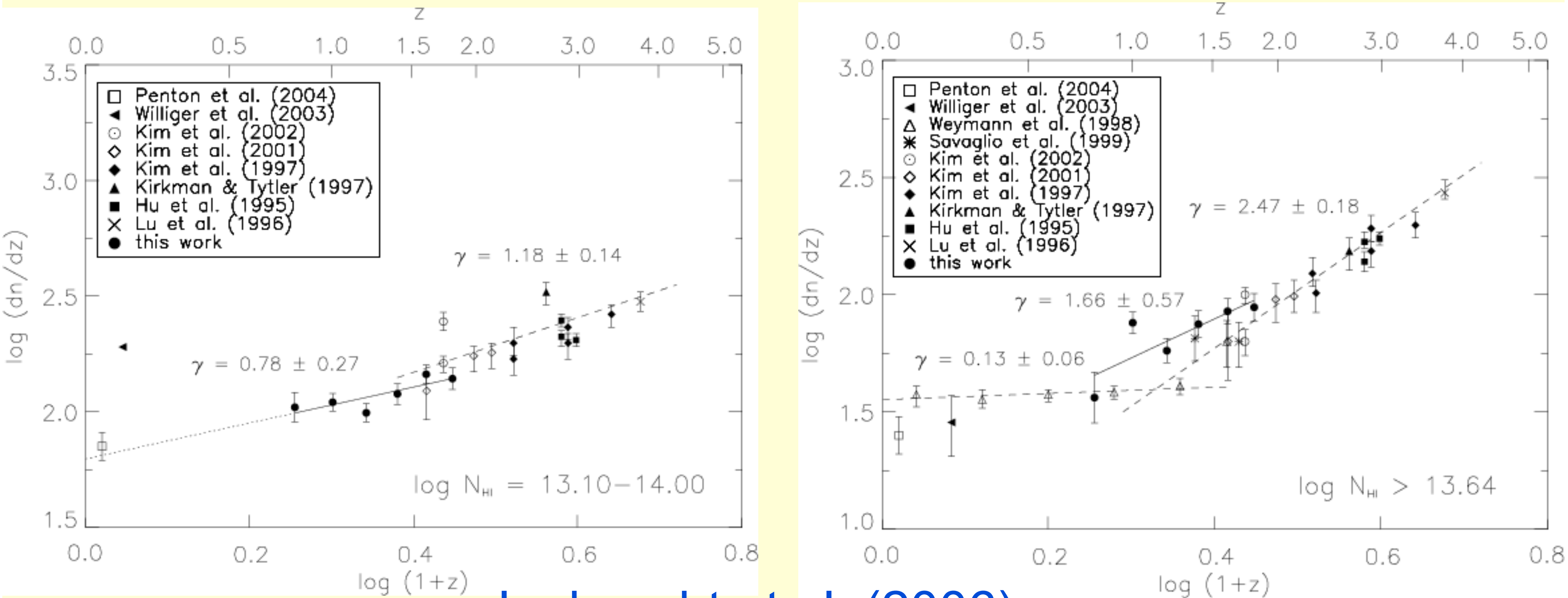


Lognormal distribution provides good fit

Lu et al. (1996)

Properties of the Lyman-α Forest

- Line number evolution depends on HI column density



Janknecht et al. (2006)

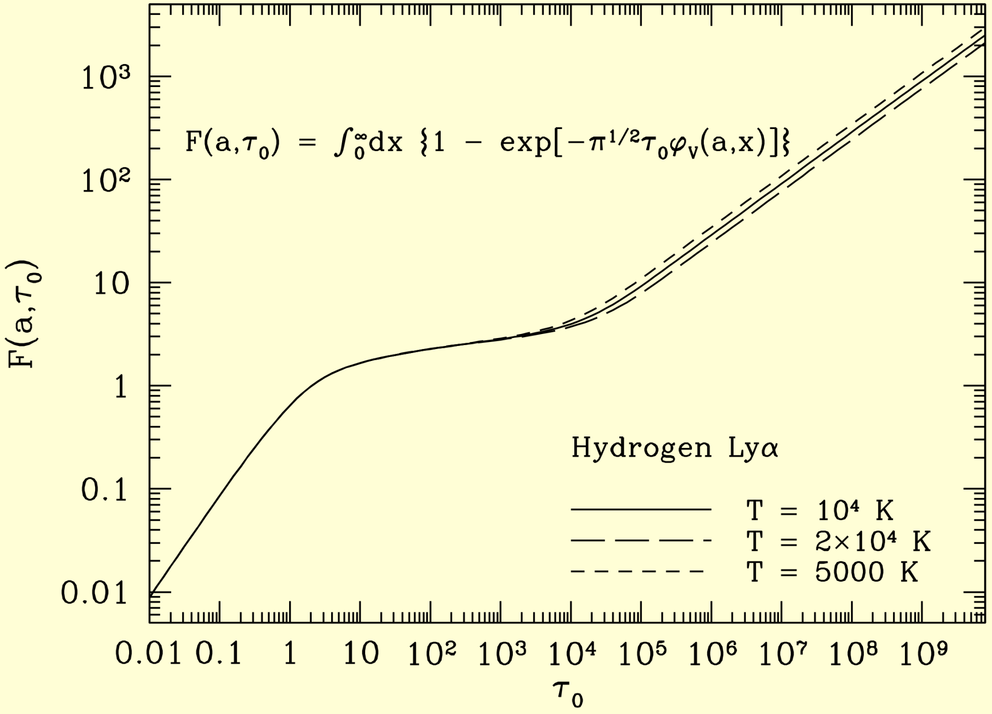
The Lyman-α Forest

Equivalent width:

$$w = \int_0^\infty d\lambda \, \left(1 - e^{-\tau_\lambda}\right) = \frac{\lambda^2}{c} \int_0^\infty d\nu \, \left(1 - e^{-\tau_\nu}\right)$$

$$\frac{w}{\lambda} = 2\frac{b}{c} F(a, \tau_0)$$

$$a = \frac{\Gamma_{ul}}{4\pi \Delta\nu_D}, \quad \Delta\nu_D = \frac{b}{c}\nu_{lu}$$



The Lyman-α Forest

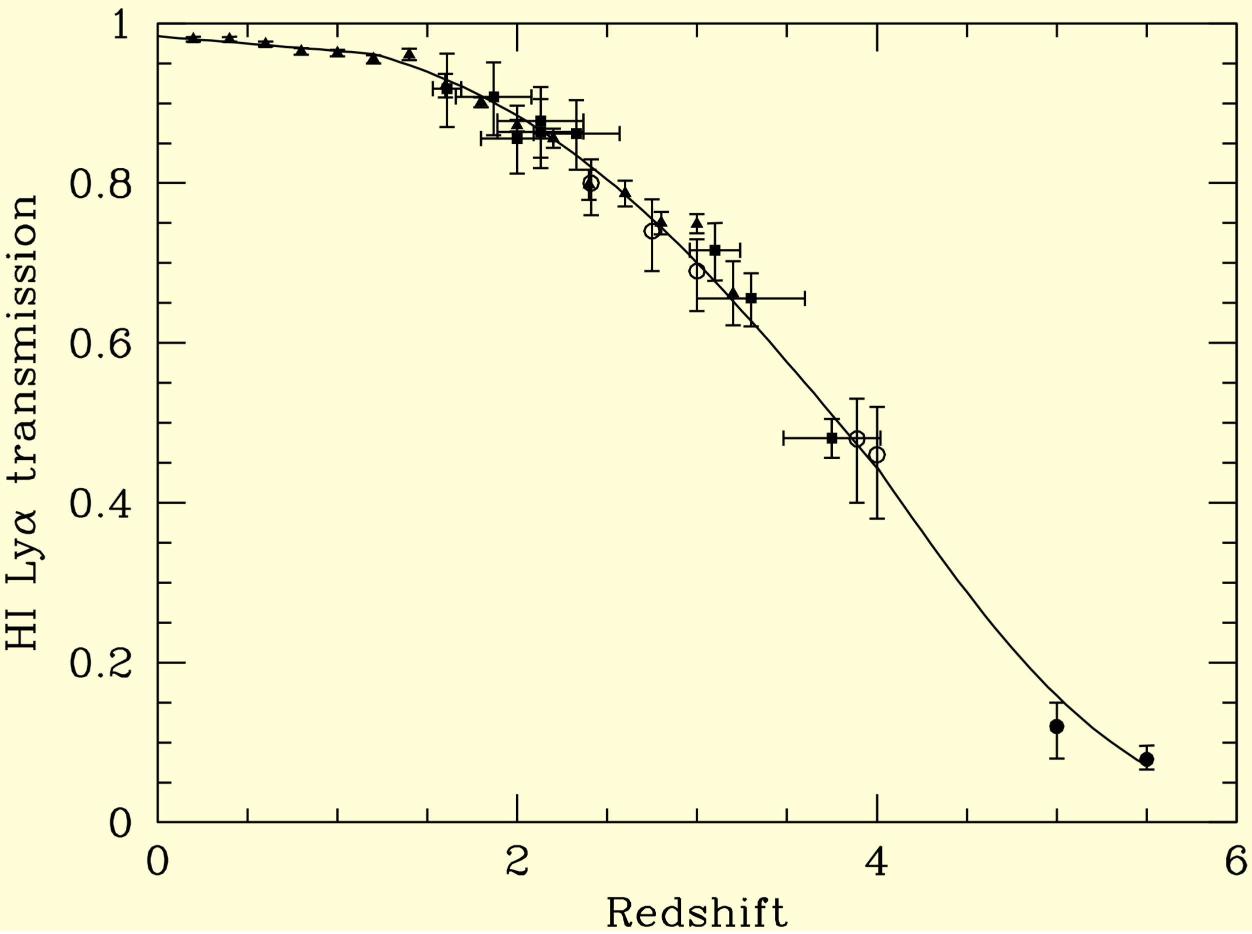
Line-blanketing

$$\begin{aligned}\tau_{\nu=\nu_0(1+z)} &= \int dx\, w(x)\frac{dN(x)}{d\lambda} \\ &= \frac{1+z}{\lambda_0}\int dw\, w\frac{d^2N}{dw\,dz}\end{aligned}$$

(Spitzer 1948; Press et al. 1993)

Properties of the Lyman-α Forest

- Mean transmission exp(-τ) evolution



The Lyman-α Forest

For optically thin absorption systems,

$$\tau_{\nu=\nu_0/(1+z)} = (g_u / g_l)(1/ 8\pi)\lambda_0^3 A_{ul} <n_l>/ H(z)$$

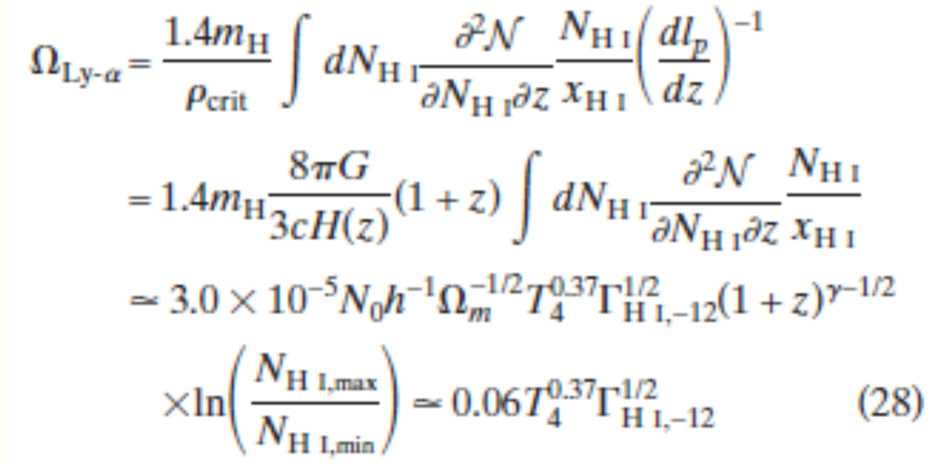
where now $< n_l > = Q_{abs}(z)n_{abs}(z)$

where $Q_{abs}(z)$ is the *porosity* (spatial filling factor) of absorbers of mean internal neutral hydrogen density $n_{abs}(z) \sim \Omega_b^2/ \Gamma_{HI}$.

For optically thick absorption systems,

$$\tau_\nu \approx 3Q_{abs} (z) [b/ H(z)L]$$

The Lyα forest: principal reservoir of all the baryons?



$$
\begin{aligned}
\Omega_{\mathrm{Ly}\text{-}\alpha} &= \frac{1.4 m_{\mathrm{H}}}{\rho_{\mathrm{crit}}} \int dN_{\mathrm{H\,I}} \frac{\partial^2 \mathcal{N}}{\partial N_{\mathrm{H\,I}} \partial z} \frac{N_{\mathrm{H\,I}}}{x_{\mathrm{H\,I}}} \left(\frac{dl_p}{dz} \right)^{-1} \\
&= 1.4 m_{\mathrm{H}} \frac{8\pi G}{3cH(z)} (1+z) \int dN_{\mathrm{H\,I}} \frac{\partial^2 \mathcal{N}}{\partial N_{\mathrm{H\,I}} \partial z} \frac{N_{\mathrm{H\,I}}}{x_{\mathrm{H\,I}}} \\
&\simeq 3.0 \times 10^{-5} N_0 h^{-1} \Omega_m^{-1/2} T_4^{0.37} \Gamma_{\mathrm{H\,I},-12}^{1/2} (1+z)^{\gamma-1/2} \\
&\quad \times \ln\left(\frac{N_{\mathrm{H\,I,max}}}{N_{\mathrm{H\,I,min}}} \right) \simeq 0.067 T_4^{0.37} \Gamma_{\mathrm{H\,I},-12}^{1/2} \qquad (28)
\end{aligned}
$$

Most of baryons in the Lya forest for characteristic absorber size $l \sim \lambda_{\mathrm{Jeans}} \sim 100$ kpc (AM & Madau 1993)

…but not if the systems are sheets with $l_{\mathrm{thick}} \ll \lambda_{\mathrm{Jeans}}$ (Rauch & Haehnelt 1995)

The Lyman-α Forest

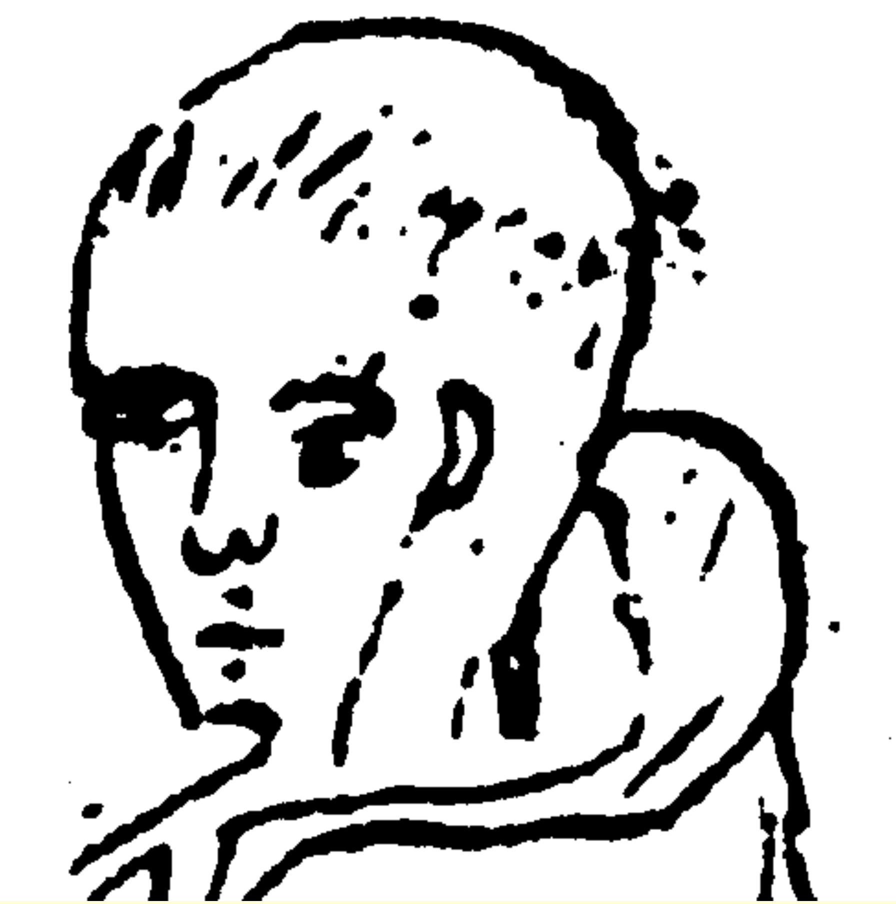
The $64,000 question: What are they?

- Pressure-confined intergalactic gas clouds (Sargent et al. 1980; Ostriker & Ikeuchi 1983)
- Gravitationally-confined dark matter minihalos (Ikeuchi 1986; Rees 1986; but see Bond, Szalay & Silk 1988)
- Caustics and sheets (McGill 1990; Miralda-Escudé & Rees 1993; AM 1994)
- Extended gaseous disks (Salpeter 1993; Charlton et al. 1993, 1994)

Ockham’s razor

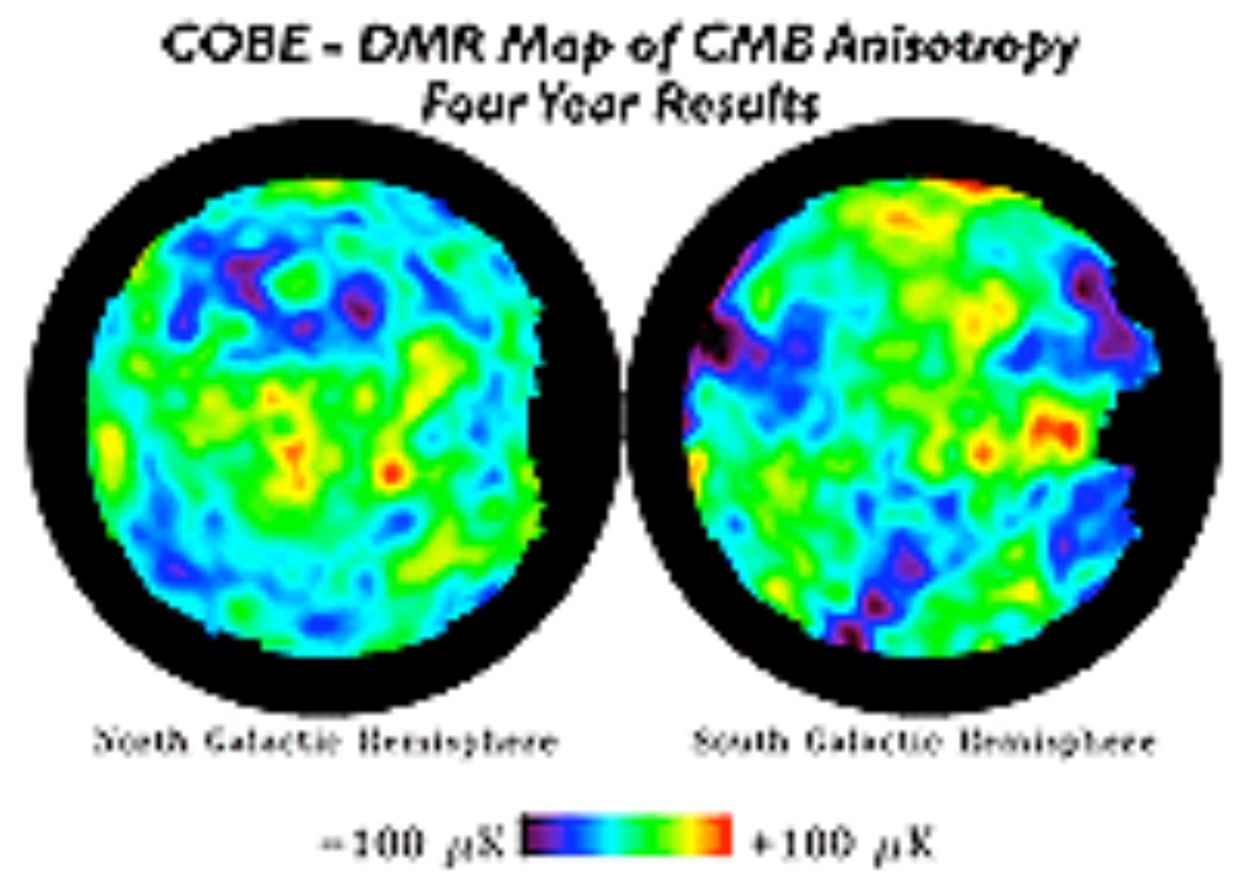
“Plurality should not be posited without necessity.”

William of Ockham
(1285–1347/49)



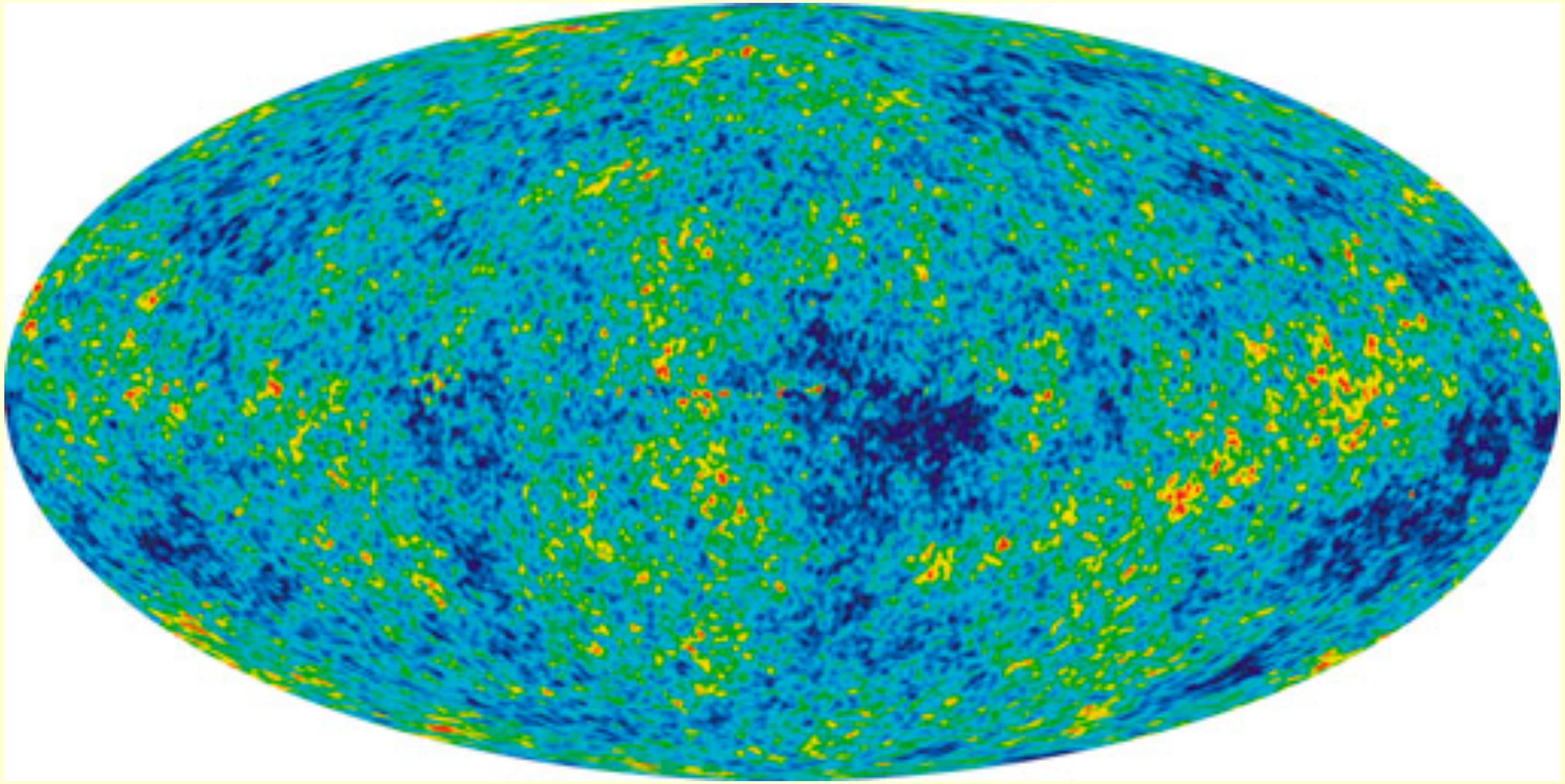
The game changer: detection of Cosmic Microwave Background fluctuations

Smoot et al. (1992)



Cosmic Background Explorer (COBE)

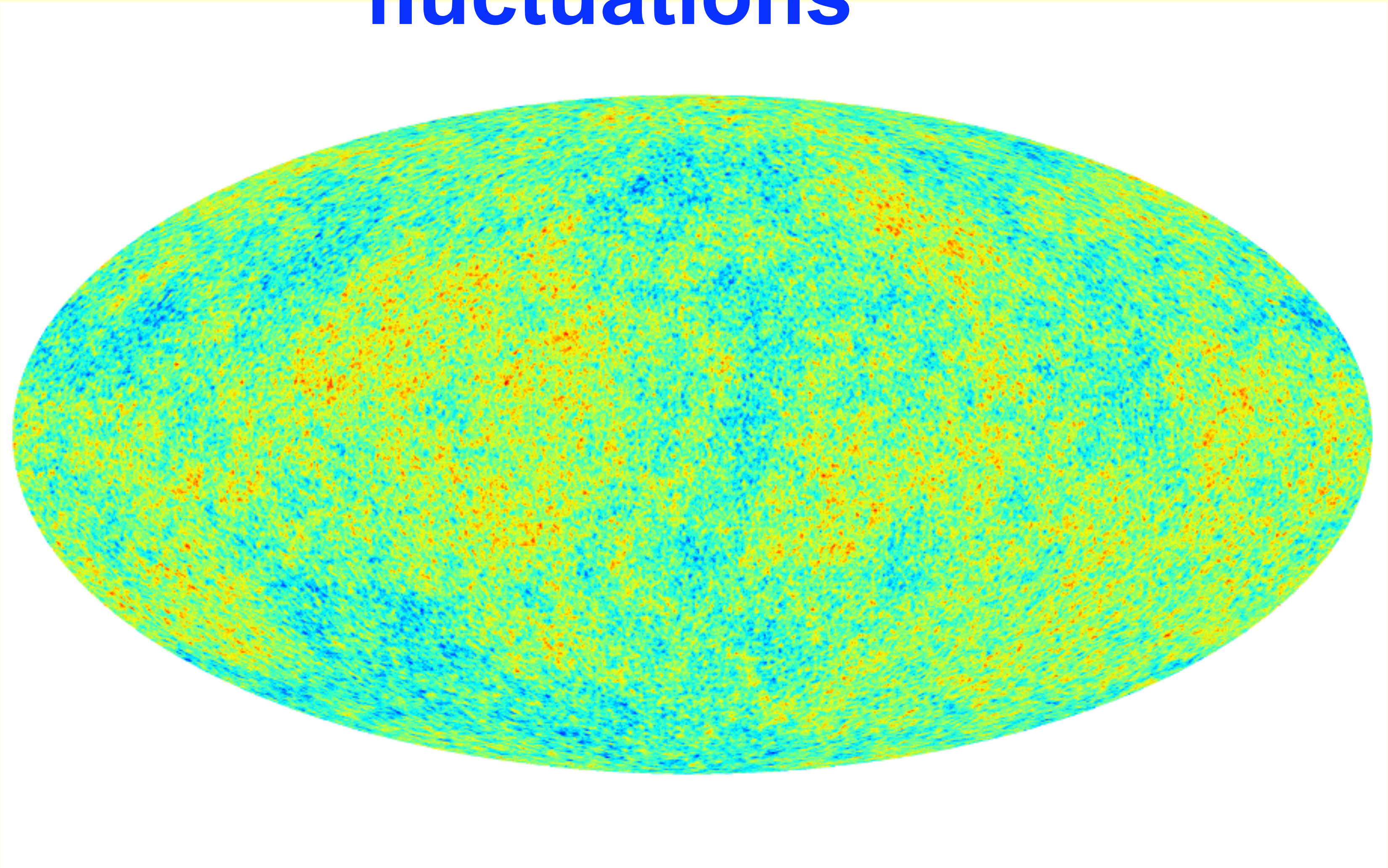
The game changer: detection of Cosmic Microwave Background fluctuations



Bennet et al. (2003)

Wilkinson Microwave Anisotropy Probe (WMAP)

The game changer: detection of Cosmic Microwave Background fluctuations



Planck

Planck Team (2013)

Non-linear initial conditions problem: solve by cosmological simulations

- Combined gravity – hydrodynamics code

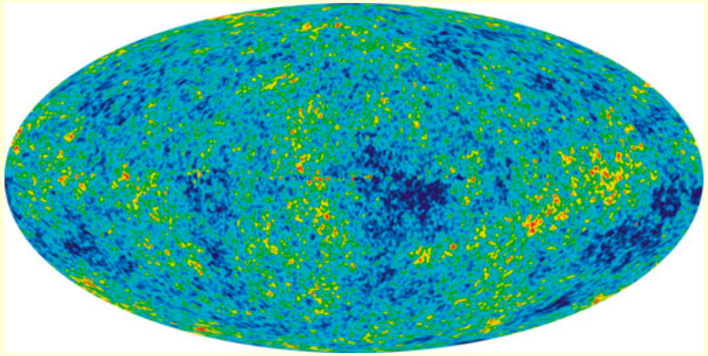
  (treecode/ SPH; PM/ grid hydro)
- Photoionization heating and atomic cooling

  (eg Haardt & Madau 1996)
- “Instantaneous’’ optically thin reionization
- Cosmological world model
- Initial conditions

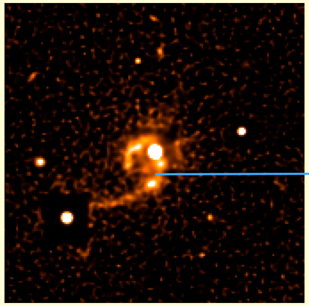
  (CMB normalized Cold Dark Matter P(k): Peebles 1982, 1984; Bond & Szalay 1983)

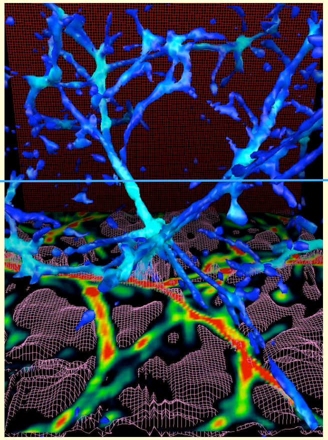
Cen et al. (1994); Zhang et al. (1995, 1997); Hernquist et al. (1996); Miralda-Escudé et al. (1996); Wadsley & Bond (1997)

The Lyman-α Forest

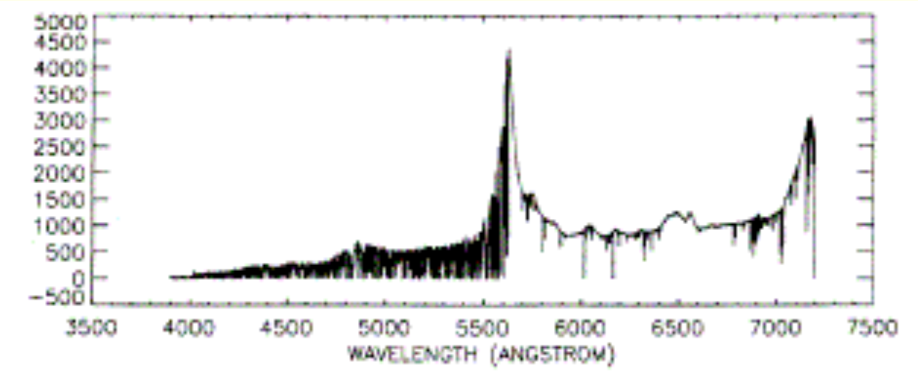


Primordial density fluctuations





Q1422+231; z = 3.6



Songaila & Cowie (1996)

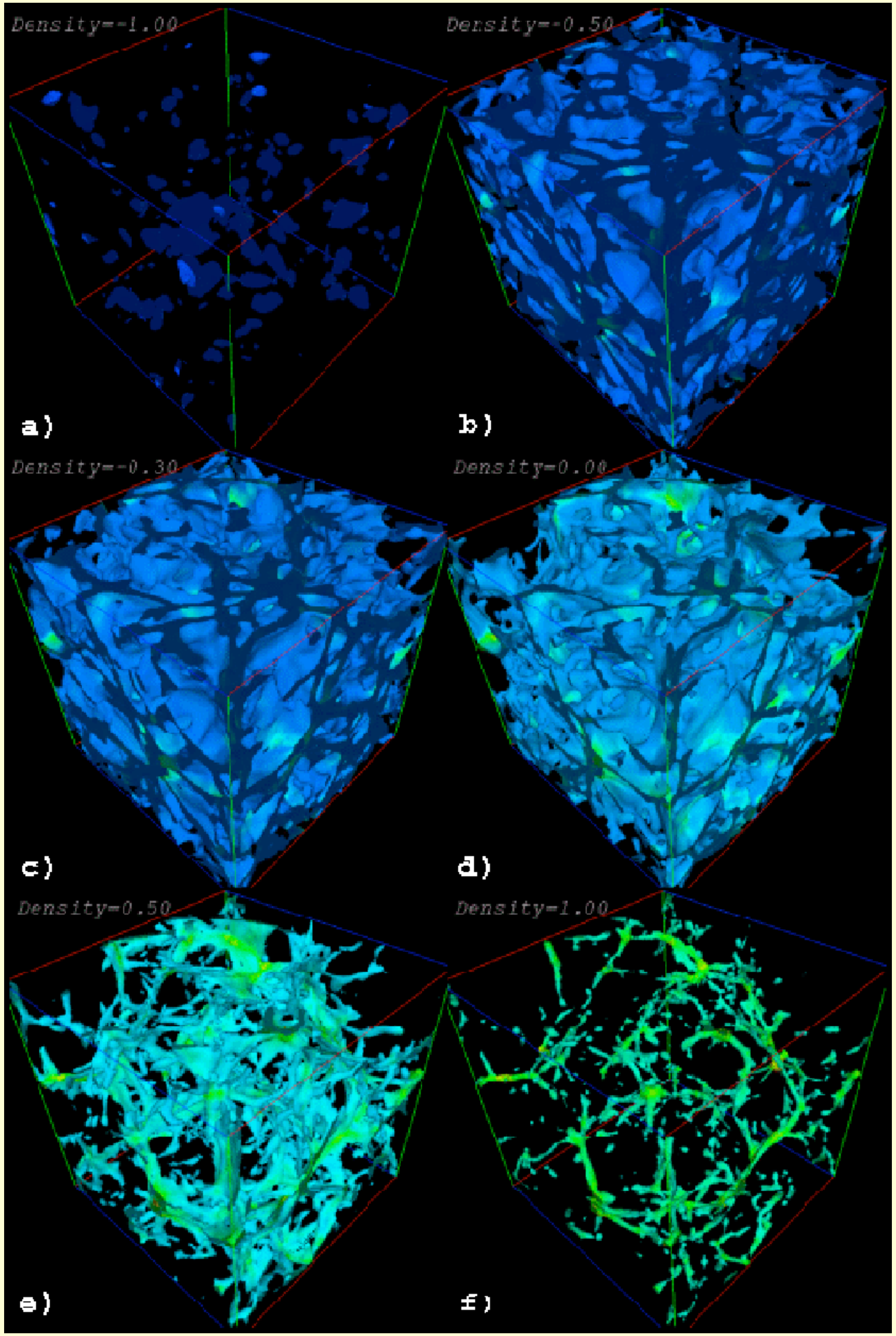
Ockham’s razor vs The principle of plenitude

“Plurality should not be posited without necessity.”

William of Ockham
(1285–1347/49)

‘‘The universe is a *plenum formarum* in which the range of conceivable diversity of *kinds* of … things is exhaustively exemplified.’’

Arthur Lovejoy in
The Great Chain of Being (1936)



New paradigm

Column density correlates with morphology

10^{16} cm^{-2} < N_{HI} : spheroidal (minihaloes) (3D)

$10^{14.5}$ cm^{-2} < N_{HI} < 10^{16} cm^{-2} : filamentary (cosmic web) (1D)

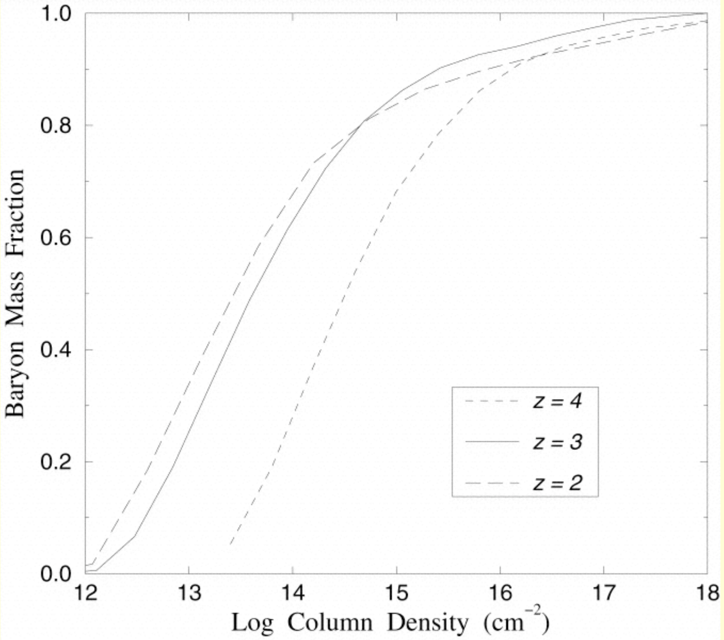
$10^{13.5}$ cm^{-2} < N_{HI} < $10^{14.5}$ cm^{-2} : sheet-like (Zeldovich pancakes)(2D)

N_{HI} < $10^{13.5}$ cm^{-2} : voids

from Zhang, AM, Anninos, Norman (1998)

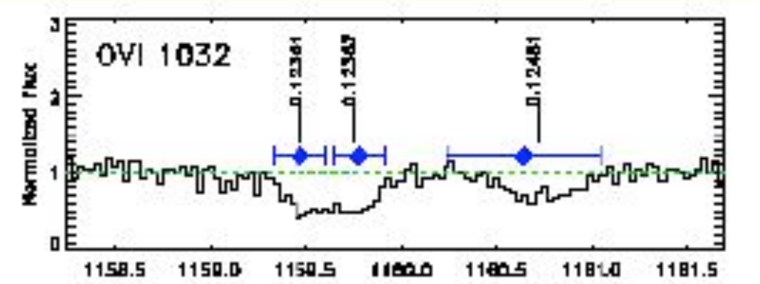
The Lyα forest contains most of the baryons

At high z:



~90% in Lyα forest

Zhang, AM, Anninos &
Norman (1998)
(cf AM & Madau 1993)



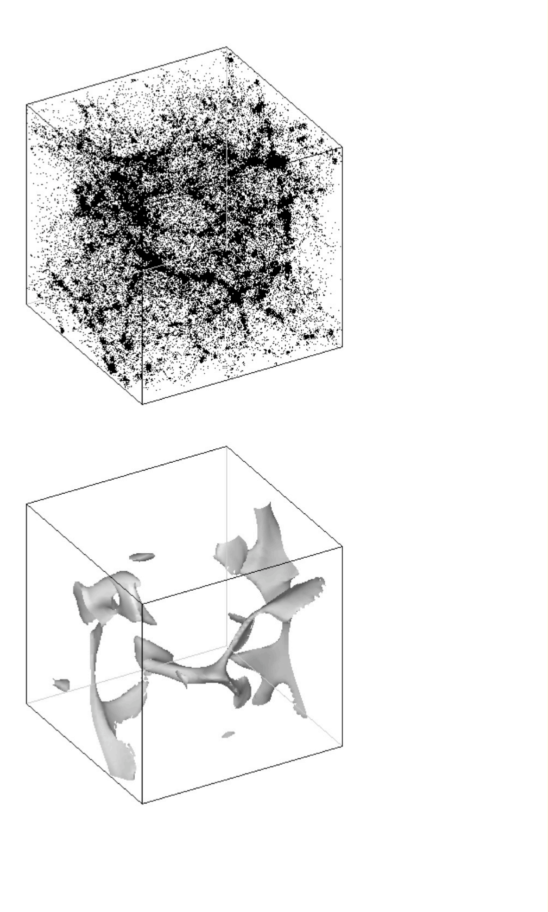
At low z: >40% in IGM:

- >30% in diffuse Lya forest
- >10% in Warm-Hot Intergalactic Medium (WHIM)

Danforth et al. (2014); Werk et al. (2014)

Cosmic web: 3D geometry of gaussian statistics

Bardeen, Bond, Kaiser & Szalay (1986)



N-body simulation

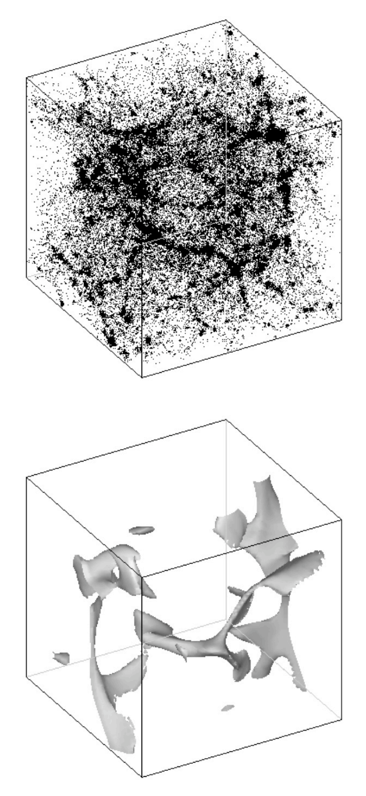
(A. Klypin)

Corresponding Zeldovich map of (Lagrangian) initial conditions

(Bond, Kofman & Pogosyan 1996)

Cosmic web: 3D geometry of gaussian statistics

Bardeen, Bond, Kaiser & Szalay (1986)



N-body simulation

(A. Klypin)

Corresponding Zeldovich map of (Lagrangian) initial conditions

(Bond, Kofman & Pogosyan 1996)

'Precise' statistical predictions of quasi-nonlinear structures

The Lyman-α Forest

- Resonance line optical depth

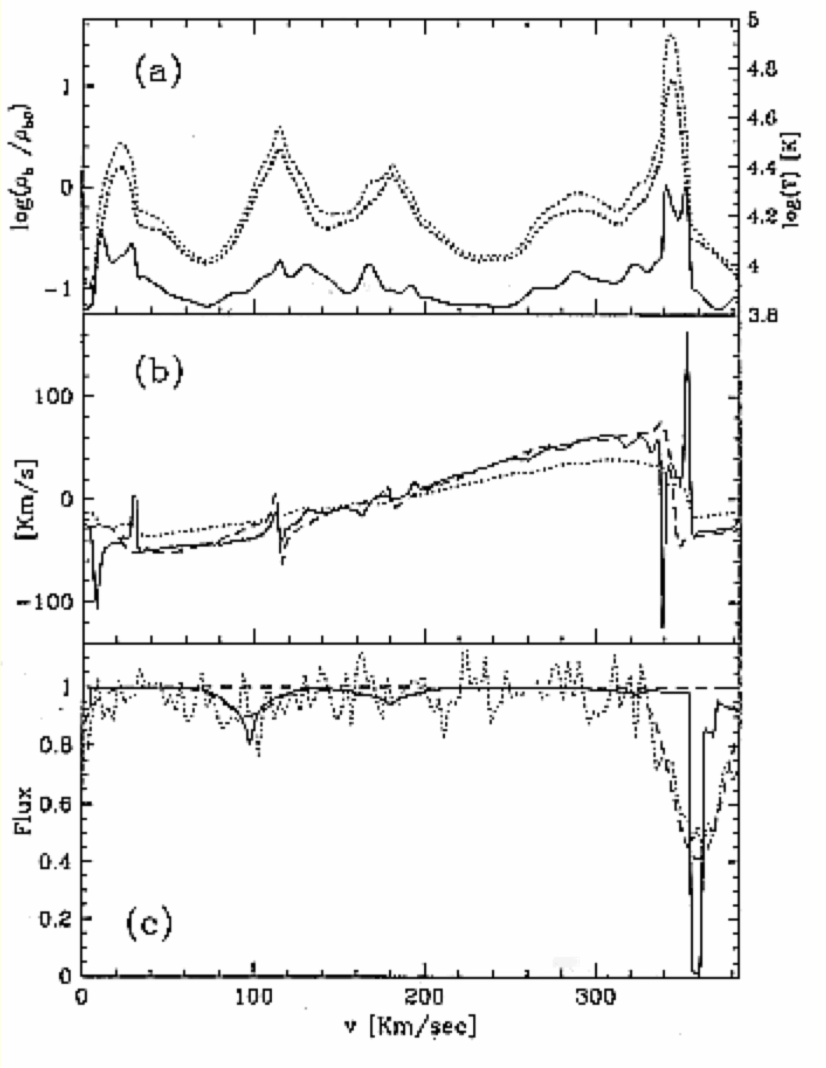
$$\tau(v) = \int dl A(l) \left[\frac{\rho(l)}{\bar{\rho}}\right]^2 T(l)^{-0.7} b^{-1} e^{-(v-v_0)^2/b^2}$$

$$v_0 = Hl + v_{\rm los}, \quad b = \sqrt{2k_{\rm B}T/m_{\rm H}}$$

$$A(l) = 18.0 f_e \left(\frac{\Omega_b h^2}{0.02}\right)^2 \Gamma_{-12}^{-1}(l)(1+z)^6$$

Photoionization rate per HI atom: $\Gamma_{-12} = \Gamma/10^{-12}\,{\rm s}^{-1}$

The Lyman-α Forest



Synthetic spectrum:

gas overdensity

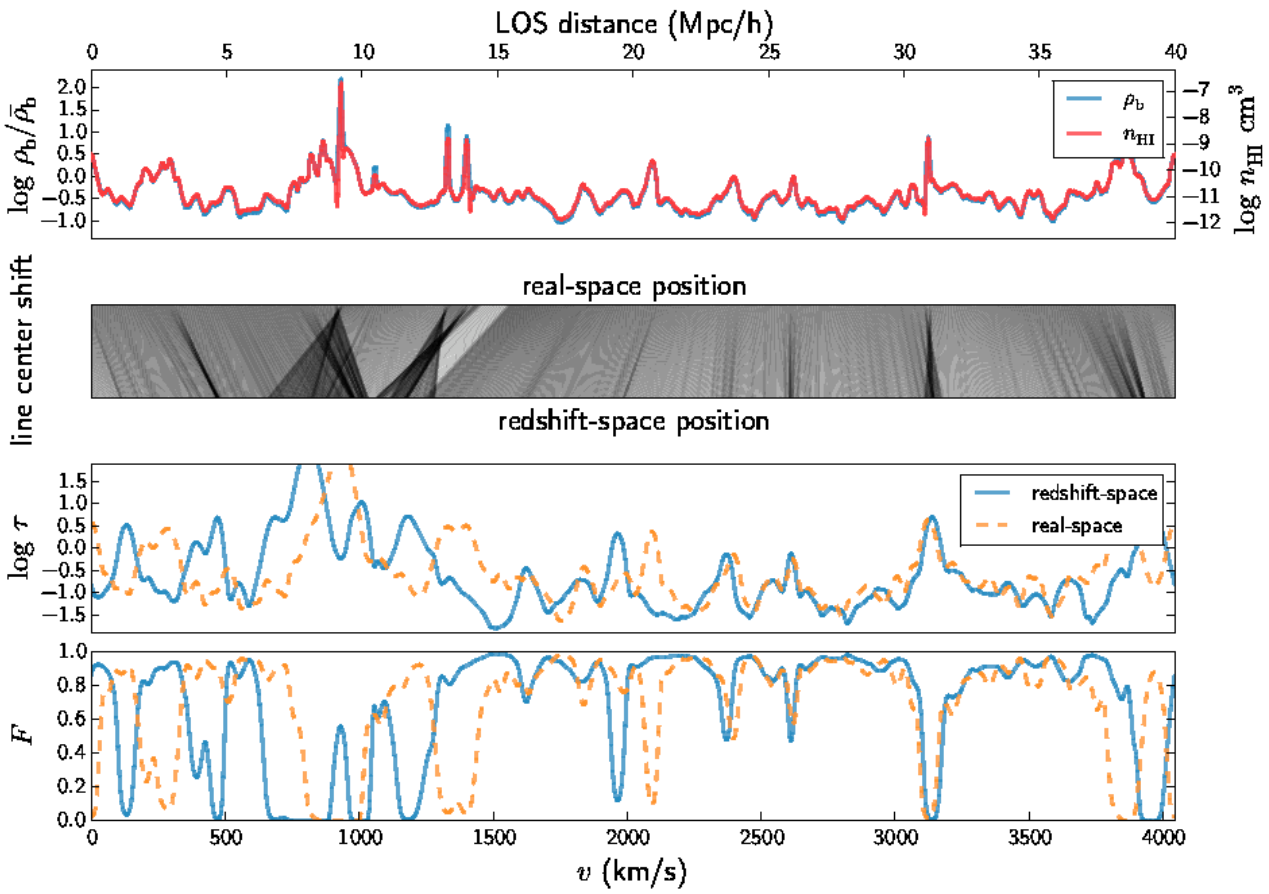
peculiar velocity

spectrum

(Cen et al. 1994)

ΛCDM: 3 h^{-1} Mpc; 288^3

The Lyman-α Forest



Synthetic spectrum:

gas overdensity

peculiar velocity:
velocity caustics

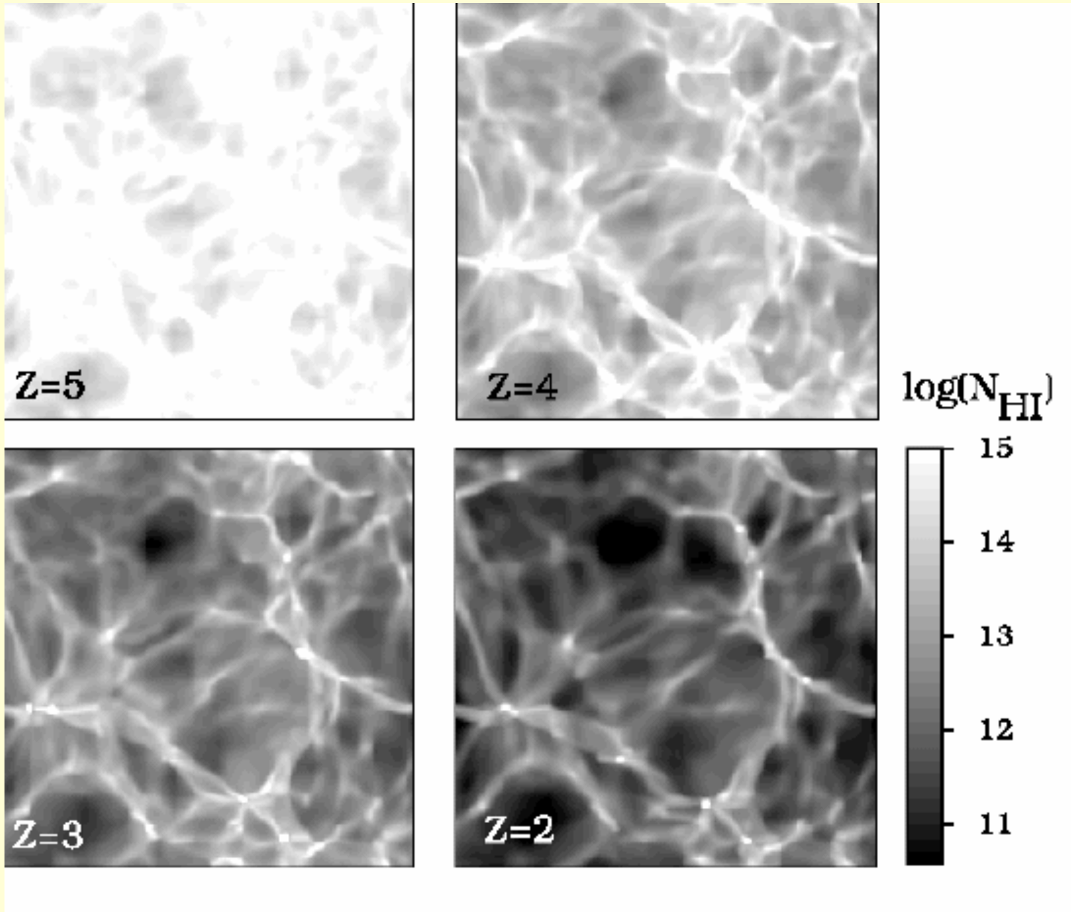
optical depth

spectrum

(Lukić et al. 2014, in prep.)

ΛCDM: 40 h^{-1} Mpc; 2048^3

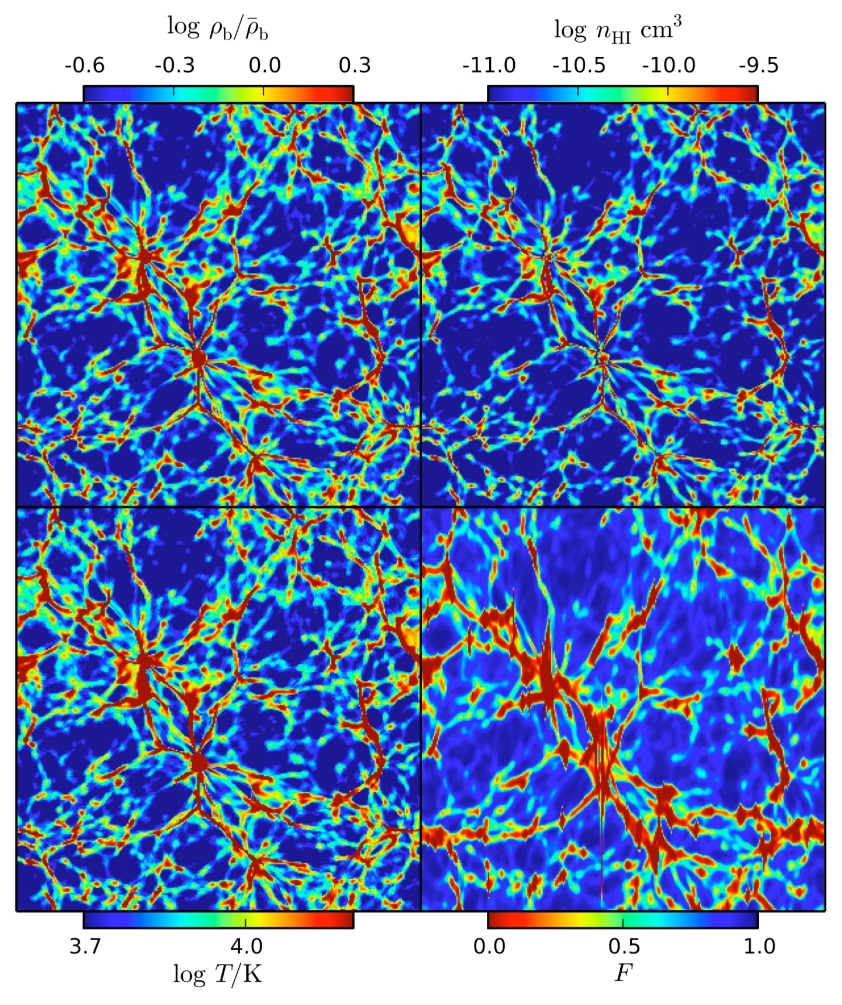
The Lyman-α Forest



(Zhang, AM, Anninos & Norman 1998)

Evolution mainly an effect of the expansion of the Universe

The Lyman-α Forest



The gas properties trace the dark matter

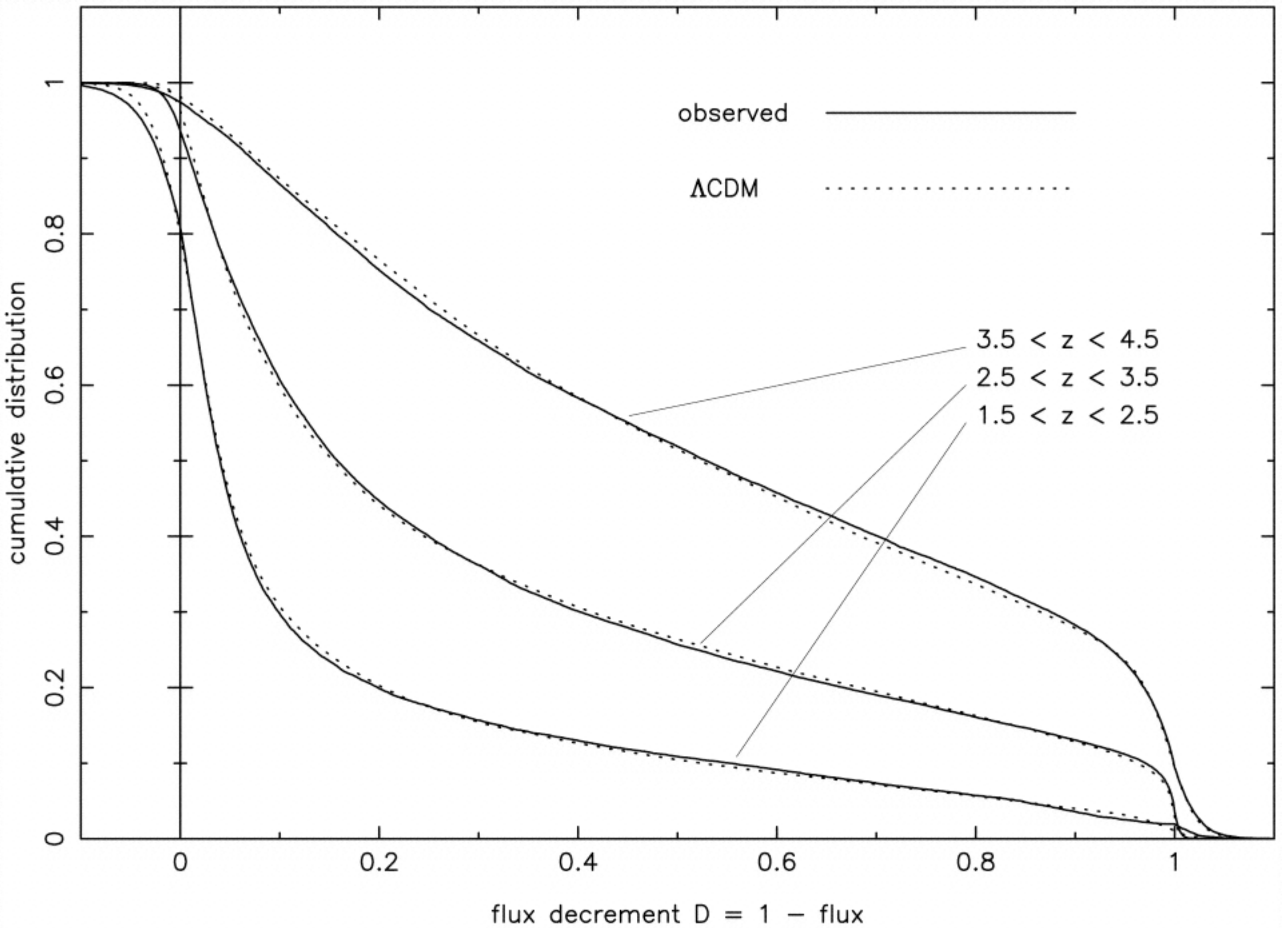
2048^3, 20 h^{-1} Mpc
z = 2.5

(Lukić et al. 2014, in prep.)

What does the Lyα forest tell us?

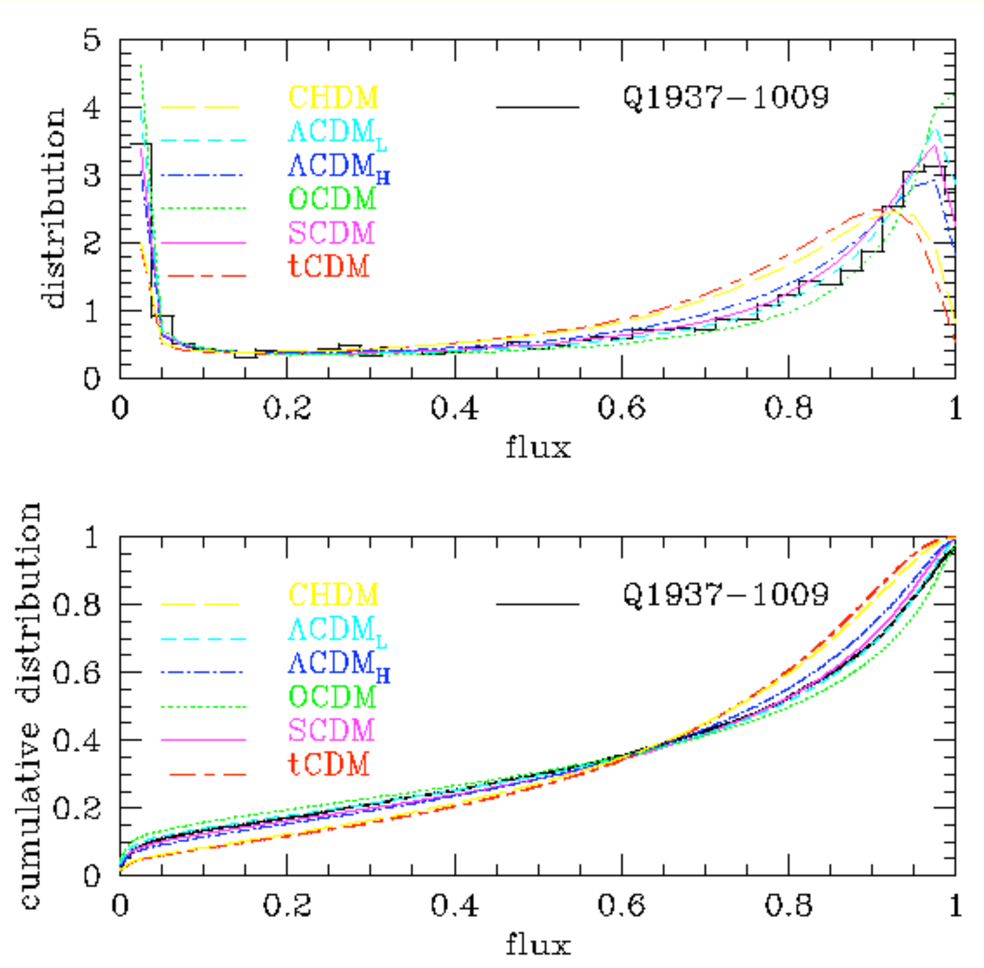
- Constraints on cosmological parameters

Statistics of the Lyα forest: pixel flux distribution function



Rauch et al. (1997)

Statistics of the Lyα forest



Best fit: ΛCDM_L

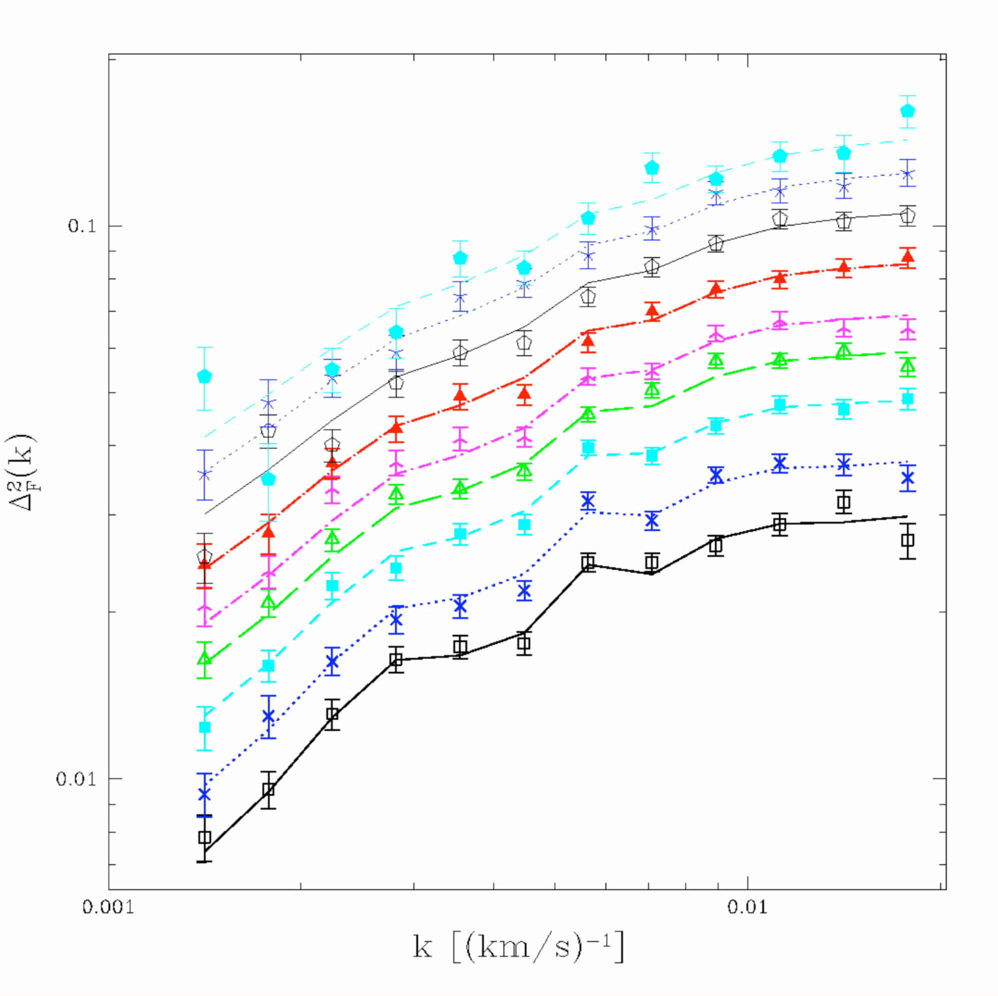
$d_{KS}=0.022$, $P_{KS}=0.1-0.3$

Mostly constraining σ_{Jeans}

AM, Bryan & Machacek (2001)

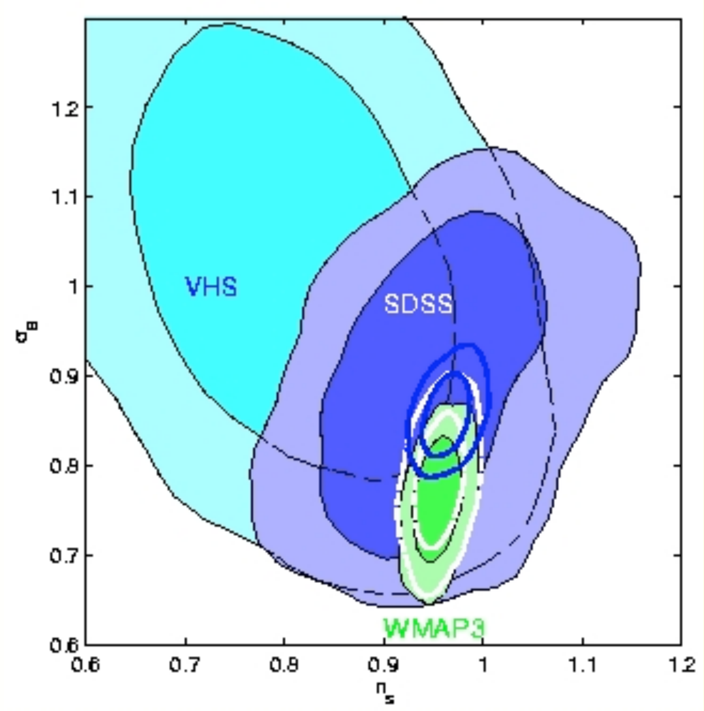
(Data from Burles & Tytler 1997)

Lyα forest flux power spectrum



McDonald et al. (2006) using SDSS data

Combined constraints: CMB + Lyα forest



σ_8 = 0.78±0.05, n_s = 0.96±0.02
WMAP3 + hi-res Lyα forest data

σ_8 = 0.86±0.03, n_s = 0.96±0.02
WMAP3 + low-res Lyα forest data
(Viel, Haehnelt, Lewis 2006)

σ_8 = 0.80±0.04
low-res Lyα forest data + hydro simulations (Viel & Haehnelt 2006)

WMAP-9: σ_8 = 0.82±0.03, n_s = 0.96±0.01 (Hinshaw et al. 2013)

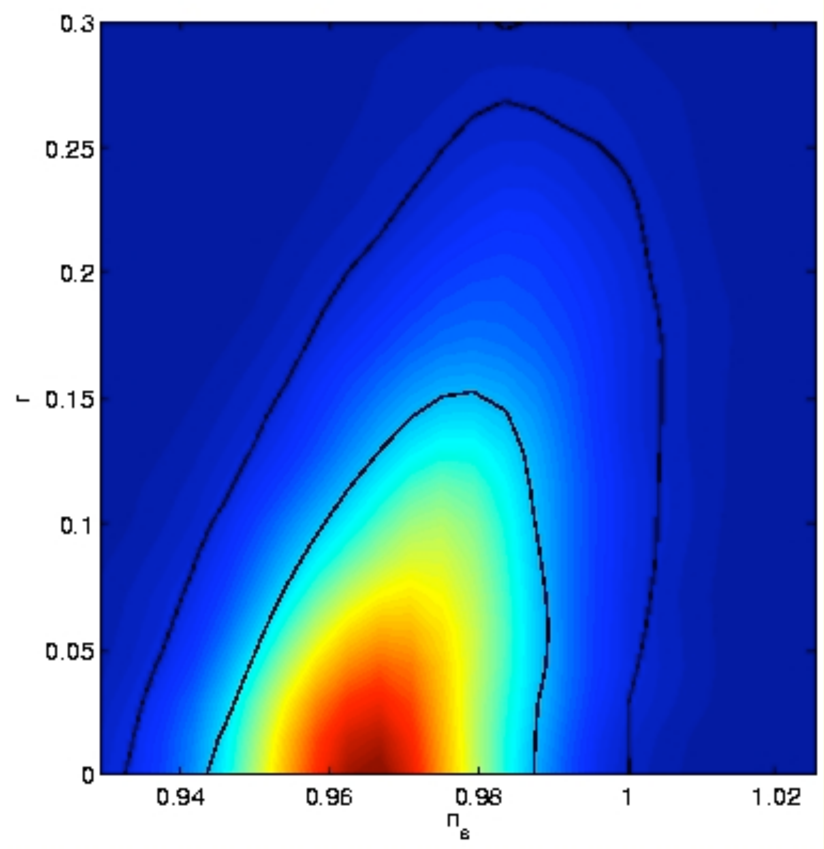
Planck: σ_8 = 0.834±0.027, n_s = 0.962±0.009 (Planck Team 2013)

Combined analyses: CMB, $\xi(r)$, SNe, Lyα

Seljak, Slosar, McDonald (2006)

Running coupling constant analysis

$n_s(k) = n_s(k_0) + \alpha \log(k/k_0)/2, \; k_0 = 0.05/\mathrm{Mpc}$



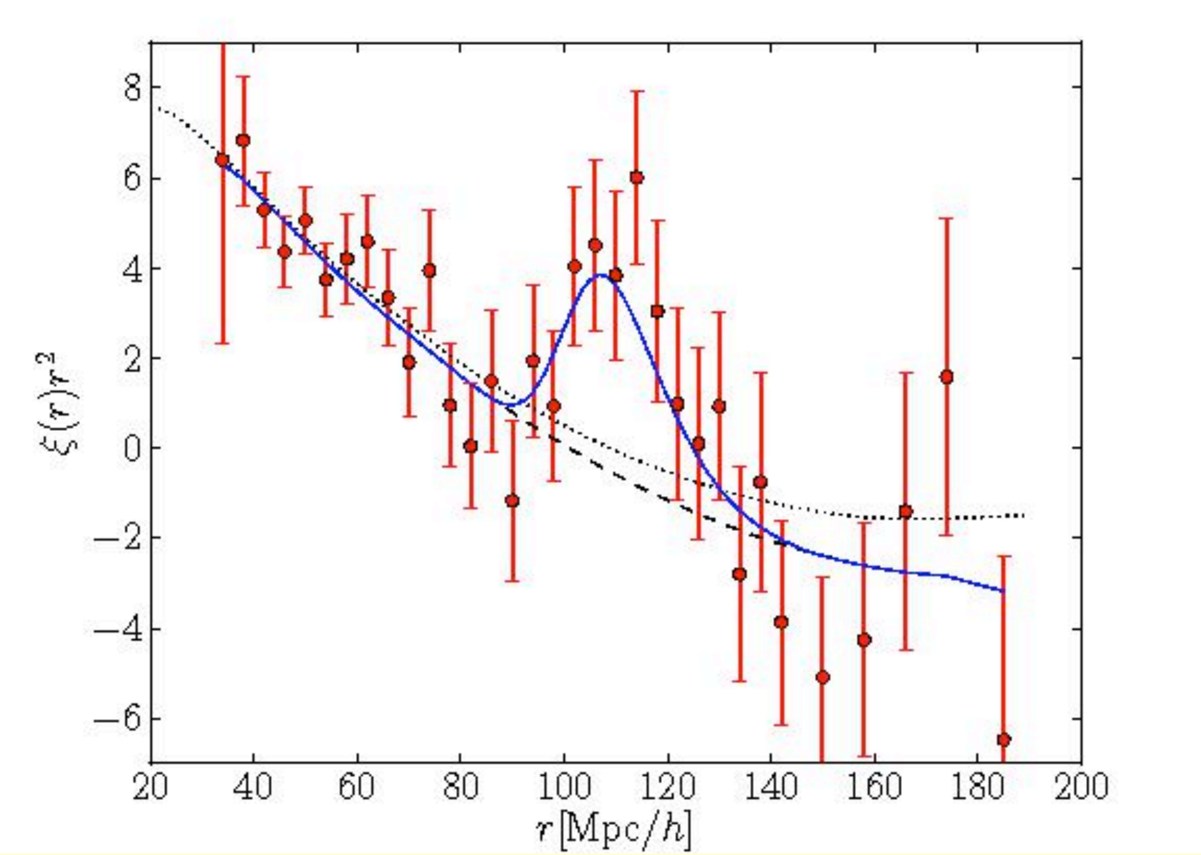
marginalised

$n_s = 0.965 \pm 0.012$

$\alpha = -0.015 \pm 0.012$

Lyα forest flux power spectrum: include transverse-to-los data

Baryon Oscillation Spectroscopic Survey/ SDSS-III



Slosar et al. (2013)
(also Busca et al. 2013)

$$100 \times (\alpha_{iso} - 1) = -1.6^{+2.0\ +4.3\ +7.4}_{-2.0\ -4.1\ -6.8}\ \text{(stat.)} \pm 1.0\ \text{(syst.)} \quad @\ z = 2.4$$

What does the Lyα forest tell us?

- Constraints on cosmological parameters
- Nature of sources of photoionization

What are the sources of ionization?

Galactic stars vs accreting black holes (QSOs)

Mass density of black holes: 3 x 10^5 $M_\odot$ Mpc^{-3}
Mass density of stars: 3 x 10^8 $M_\odot$ Mpc^{-3}
Mass-to-energy conversion efficiencies of
ε_{accr} = $0.1-0.3$ for black holes (Yu & Tremaine 2002)
ε_{nucl} = 0.007 for stars (hydrogen fusion), f_{esc} = 0.05

→ comparable ionizing photon rates

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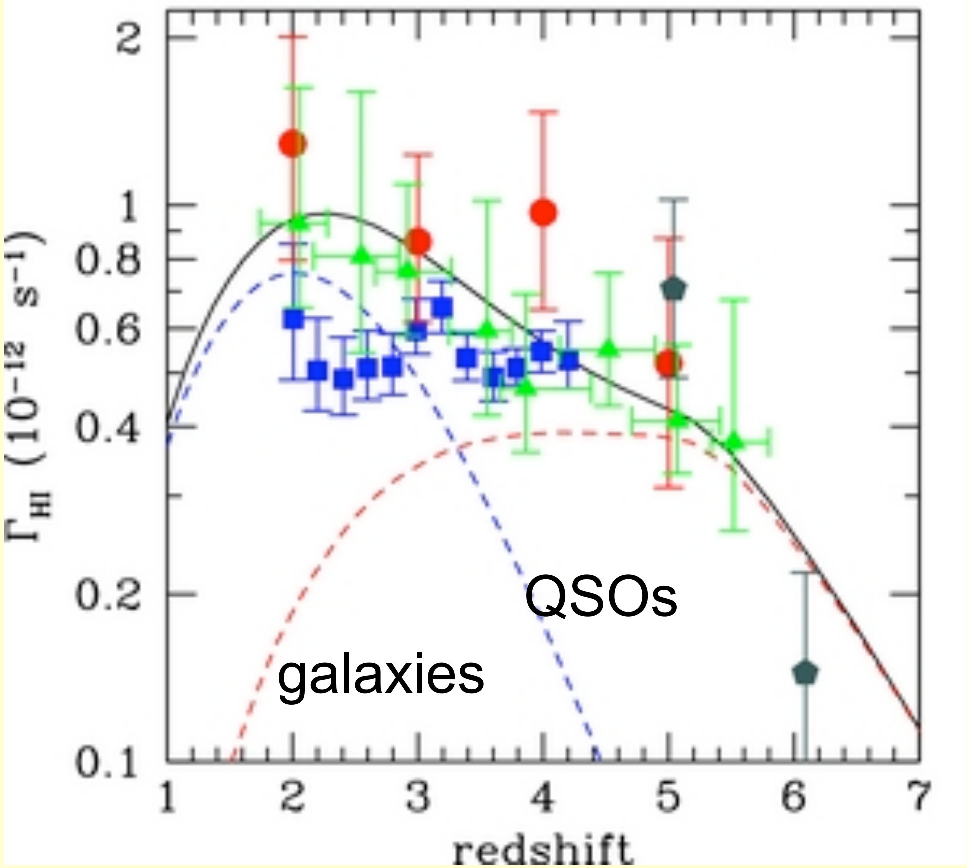
→ comparable ionizing photon rates

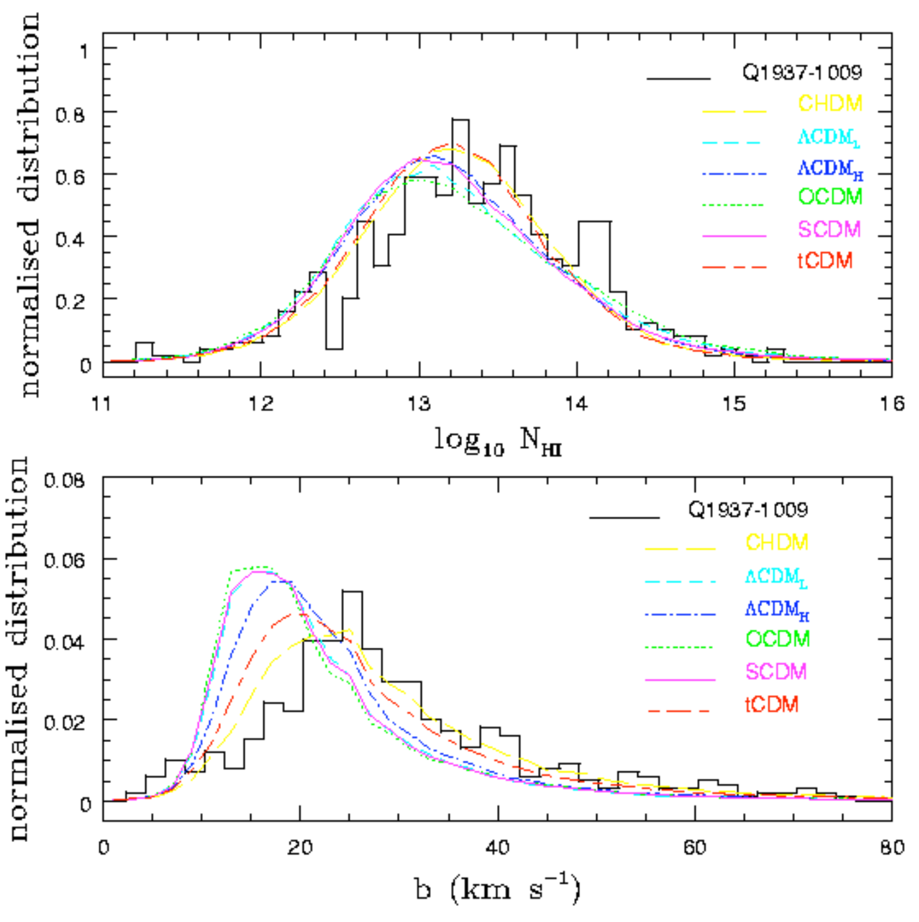
Cf Principle of plenitude

Metagalactic HI ionization rate Γ_{HI}



Haardt & Madau (2012)

Statistics of the Lyα forest

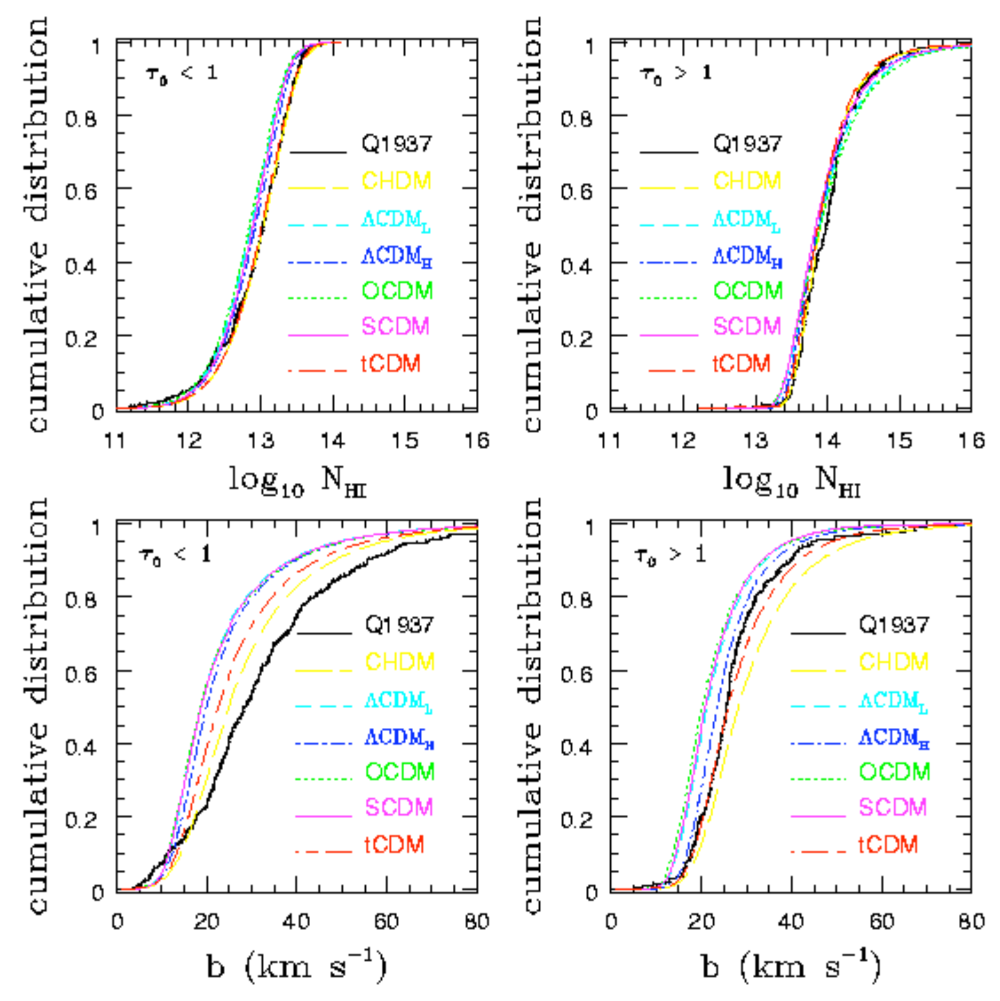


(AM, Bryan & Machacek 2001)

Predicted line widths too narrow.

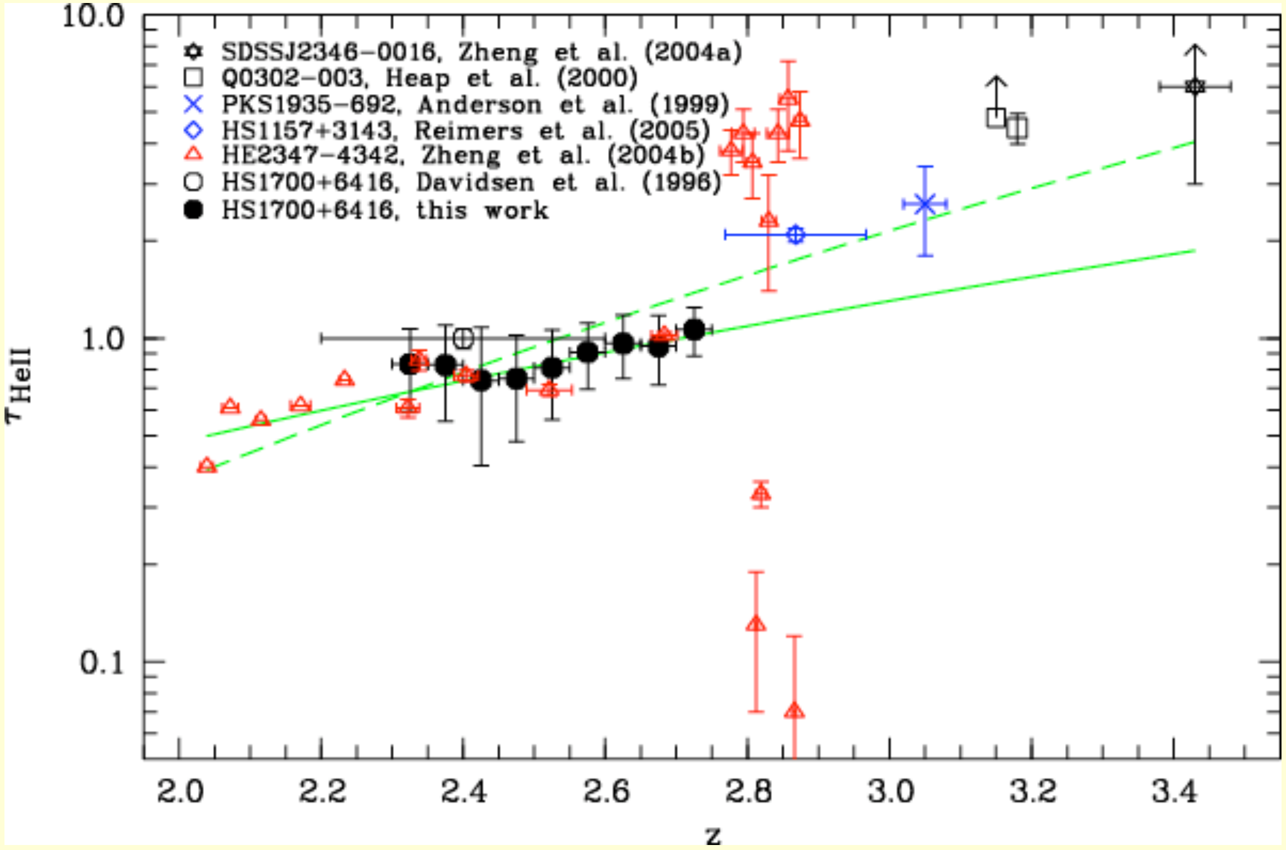
Theuns et al. (1998); Bryan, Machacek, Anninos & Norman (1999); AM, Bryan & Machacek (2001)

Statistics of the Lyα forest



AM, Bryan & Machacek (2001)

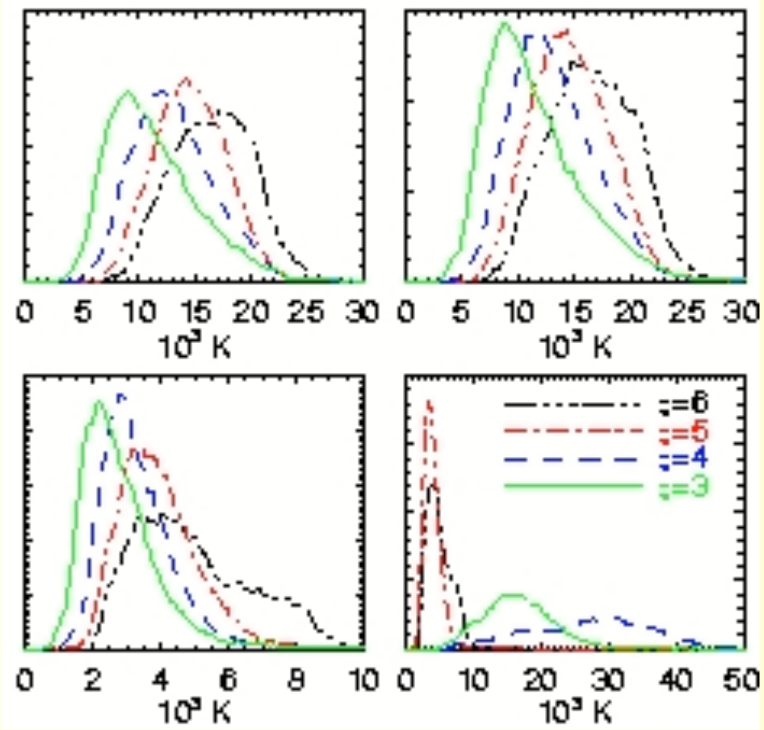
HeII Lyman-α Optical Depth



Fechner et al. (2006)

Temperature predictions

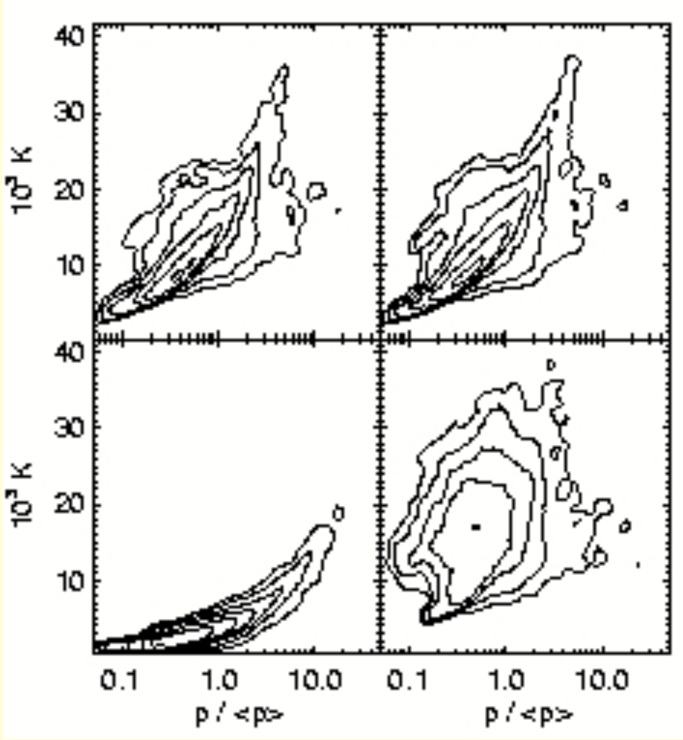
PL MQ



SB HY

Temperature evolution

PL MQ



SB HY

Temperature vs density

Tittley & AM (2007)

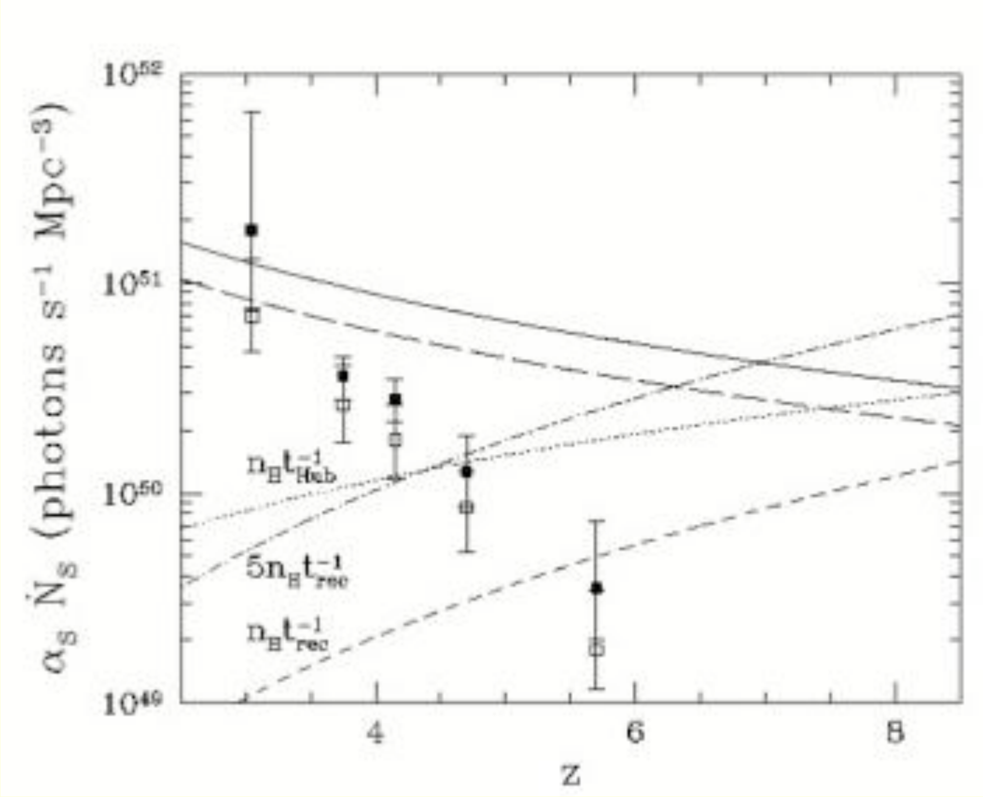
What does the Lyα forest tell us?

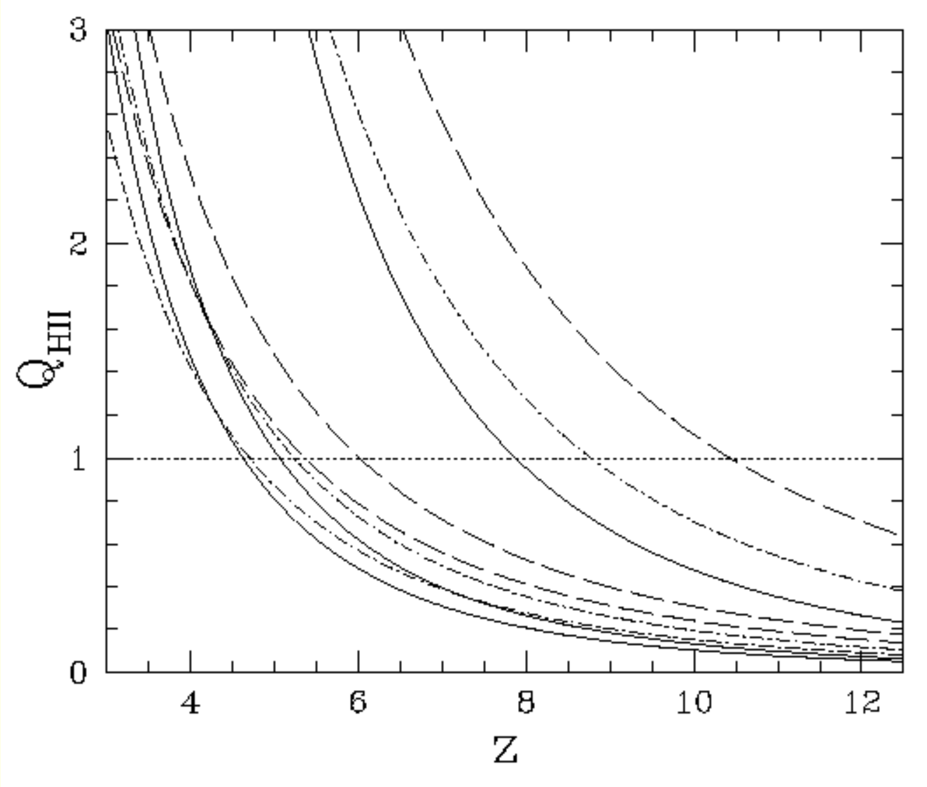
- Constraints on cosmological parameters
- Nature of sources of photoionization
- Nature of sources of reionization (EoR)

Epoch of Reionization

Inferred Γ_{HI} $\longrightarrow$ only a few photons/ H atom over Hubble time

Miralda-Escudé (2003), AM (2005), Bolton & Haehnelt (2007)



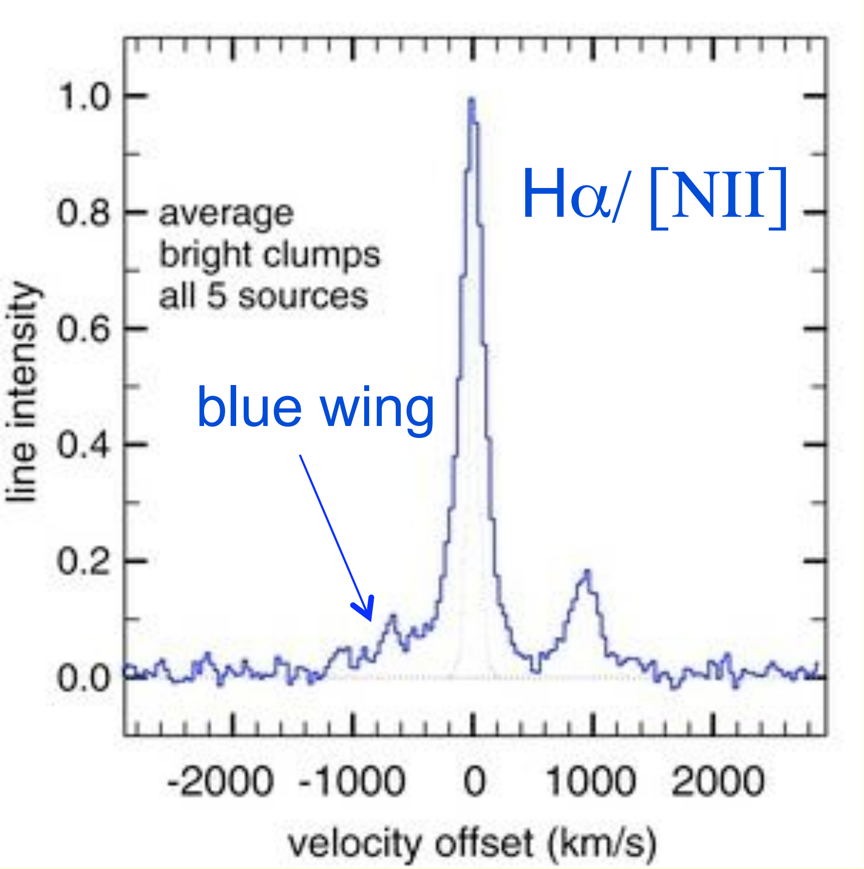


AM (2005)

What does the Lyα forest tell us?

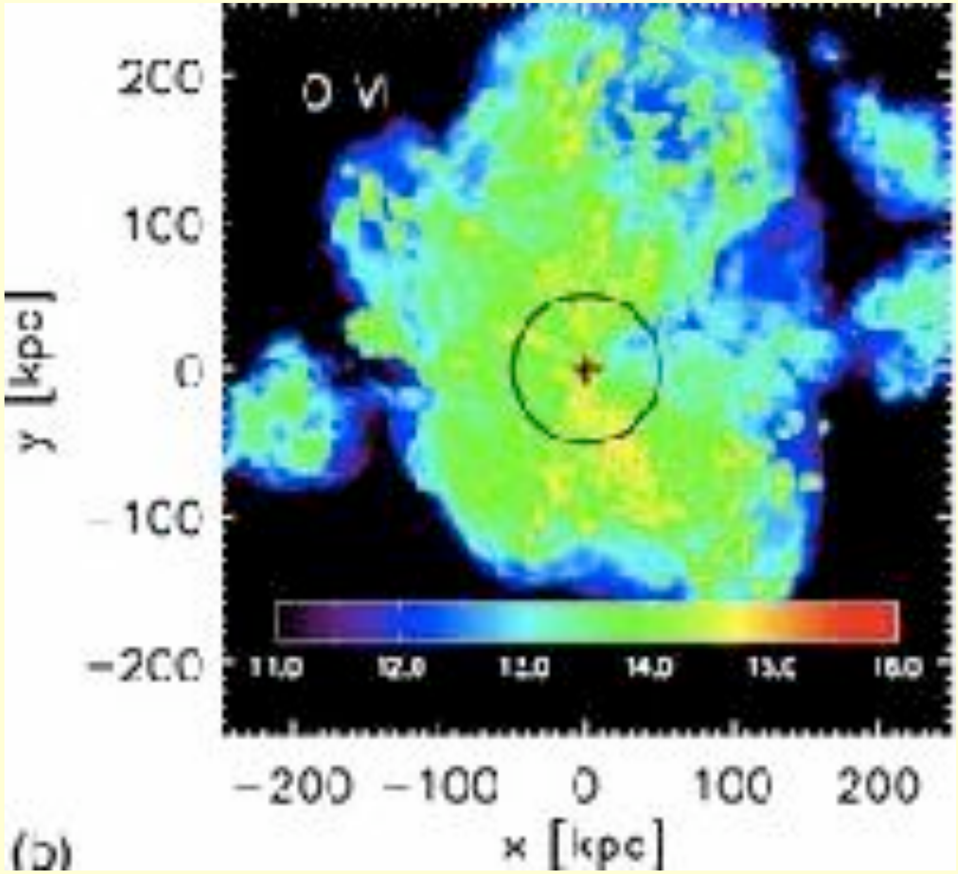
- Constraints on cosmological parameters
- Nature of sources of photoionization
- Nature of sources of reionization (EoR)
- Impact of forming galaxies: winds and metals

Galactic winds



$380 < v_{wind} < 1000$ km s^{-1}

Genzel et al. (2011)



WHIM

Shen et al. (2013)

Conclusions

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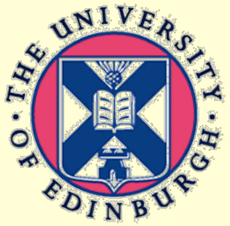
- Proving ground for feedback models of galaxies and QSOs: photoionization, reionization, winds and metals.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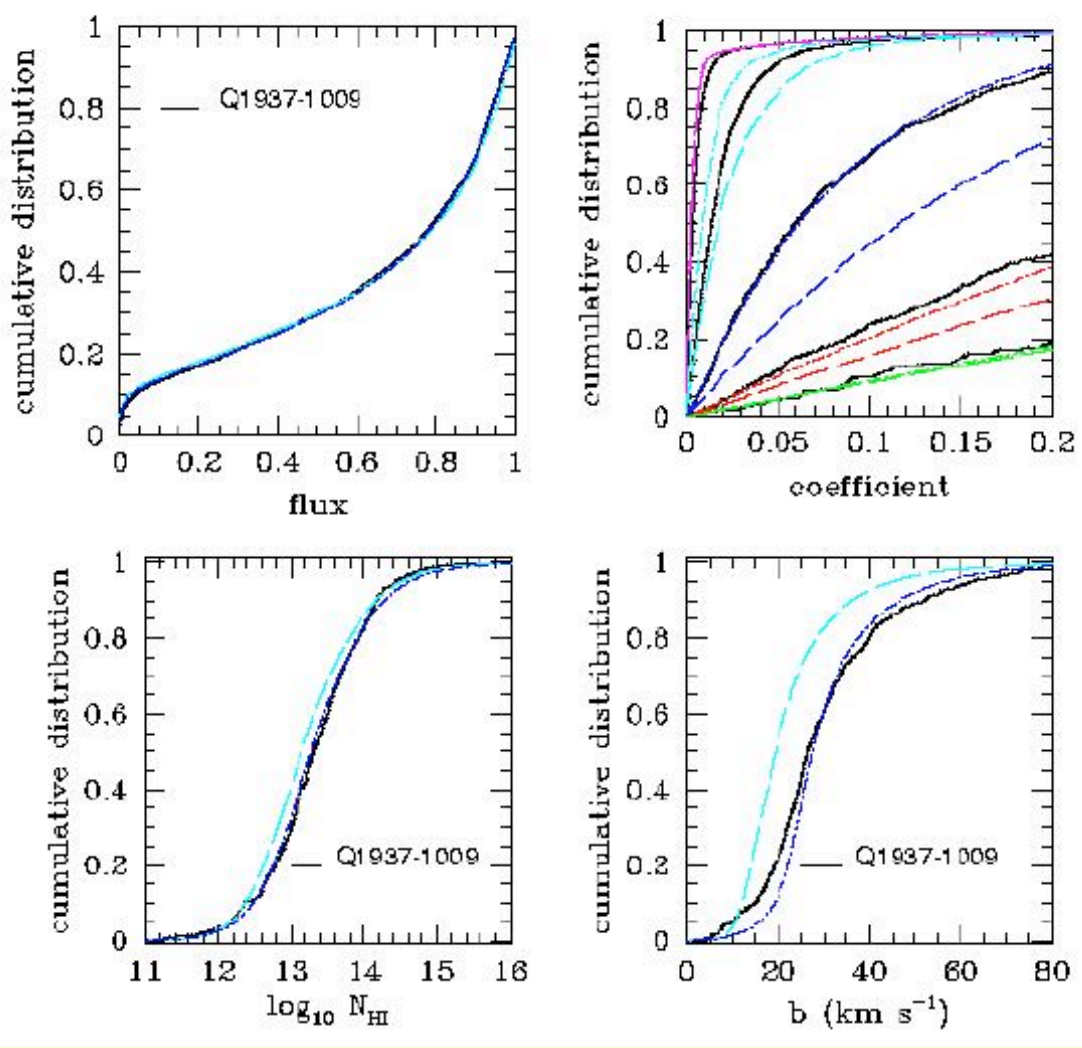
Effect of heat input



AM, Bryan & Machacek (2001)

ΔT = 9,000K added to Doppler widths of ΛCDM$_L$ model results → late HeII reionization?