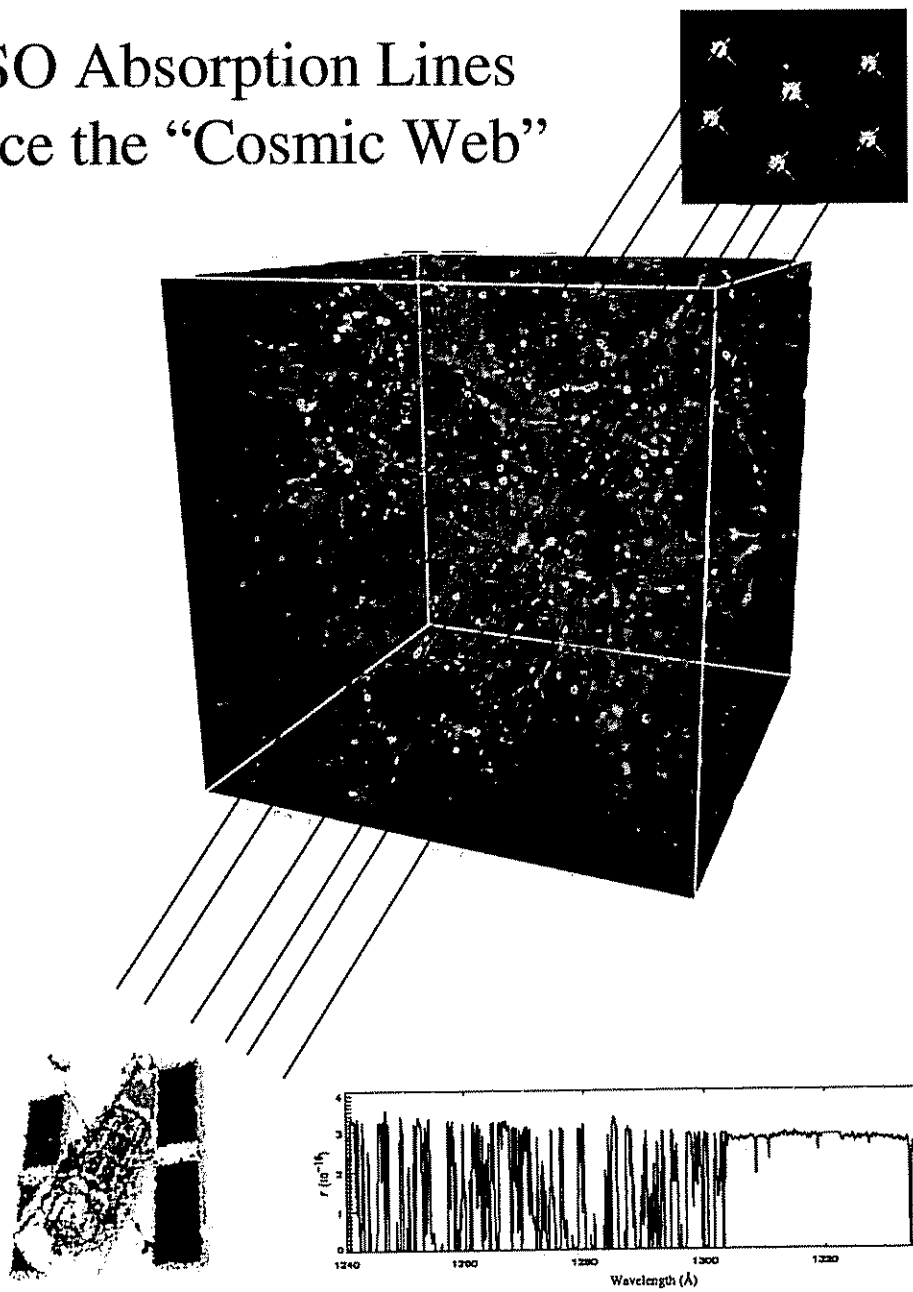
Large-scale Structure and the IGM

QSO Absorption Lines trace the "Cosmic Web"



- Visualization concept from Schiminovich & Martin
- Numerical simulation from Cen & Ostriker (1998)
- Songaila et al. (1995) Keck spectrum adapted by Lindler & Heap

Lyα Forest [Q 0302-003]

$z_{em} = 3.29$

Keck 10^m tel.

[Songaila, Hu, Cowie Nature 1995]

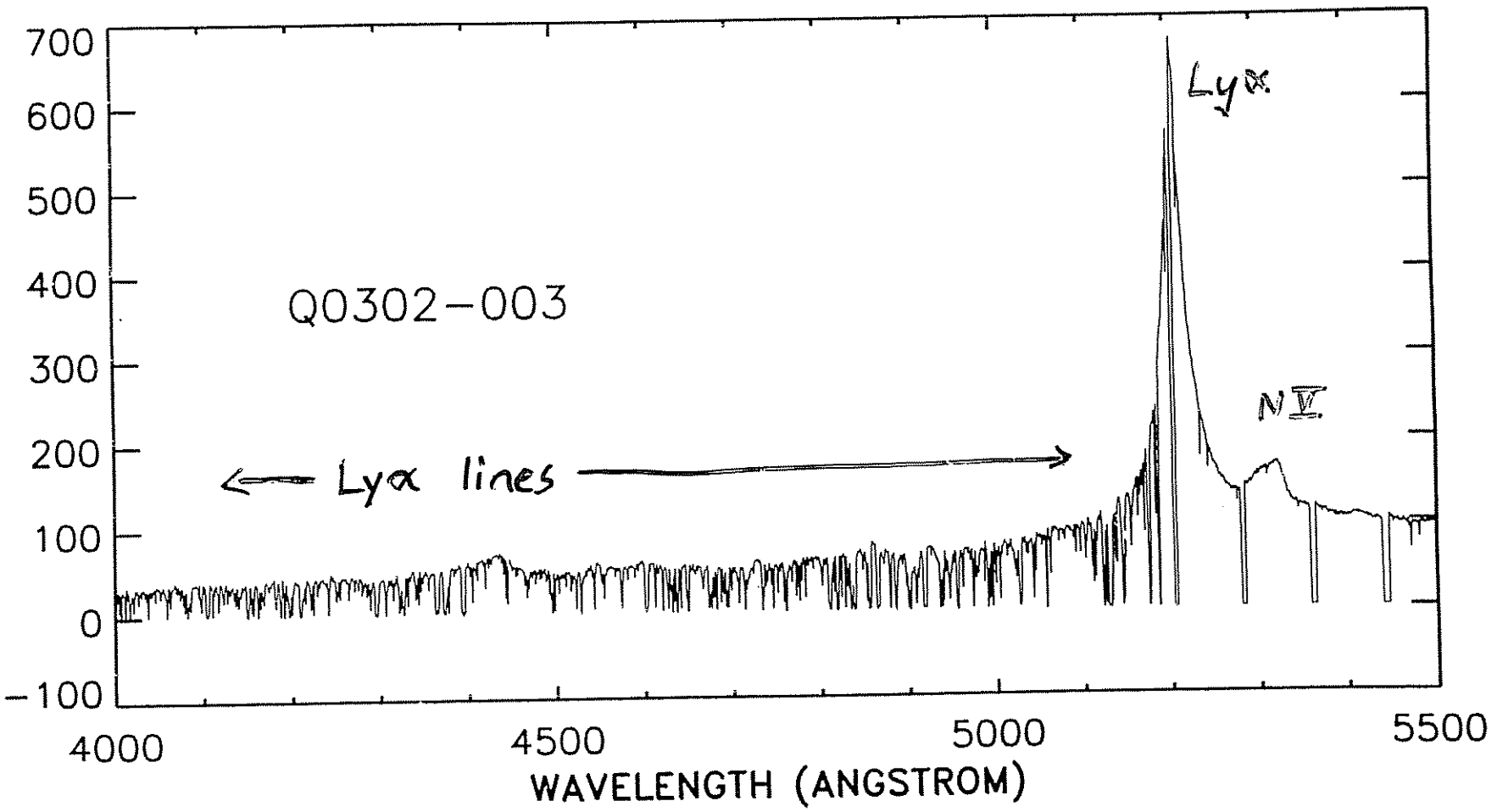
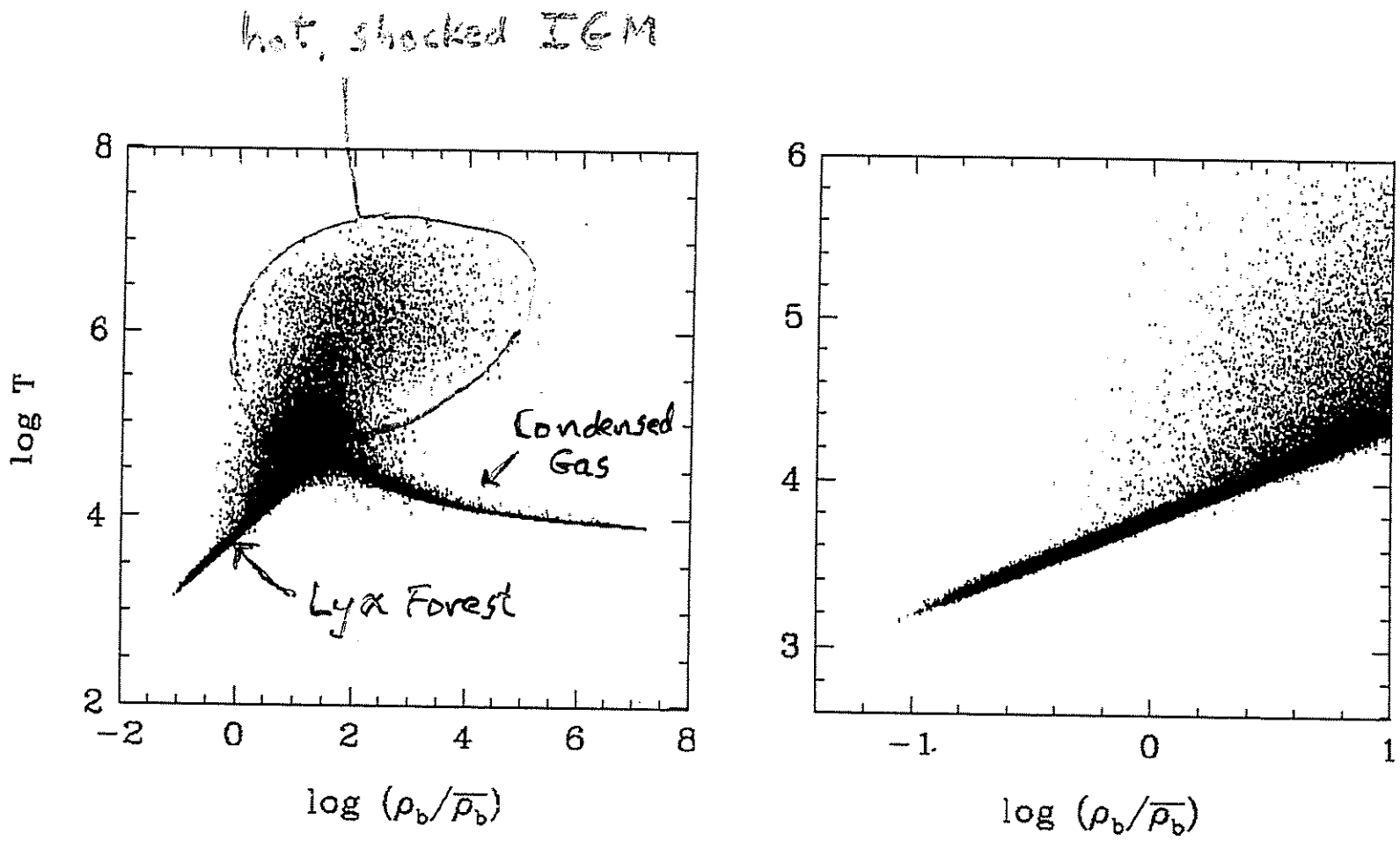
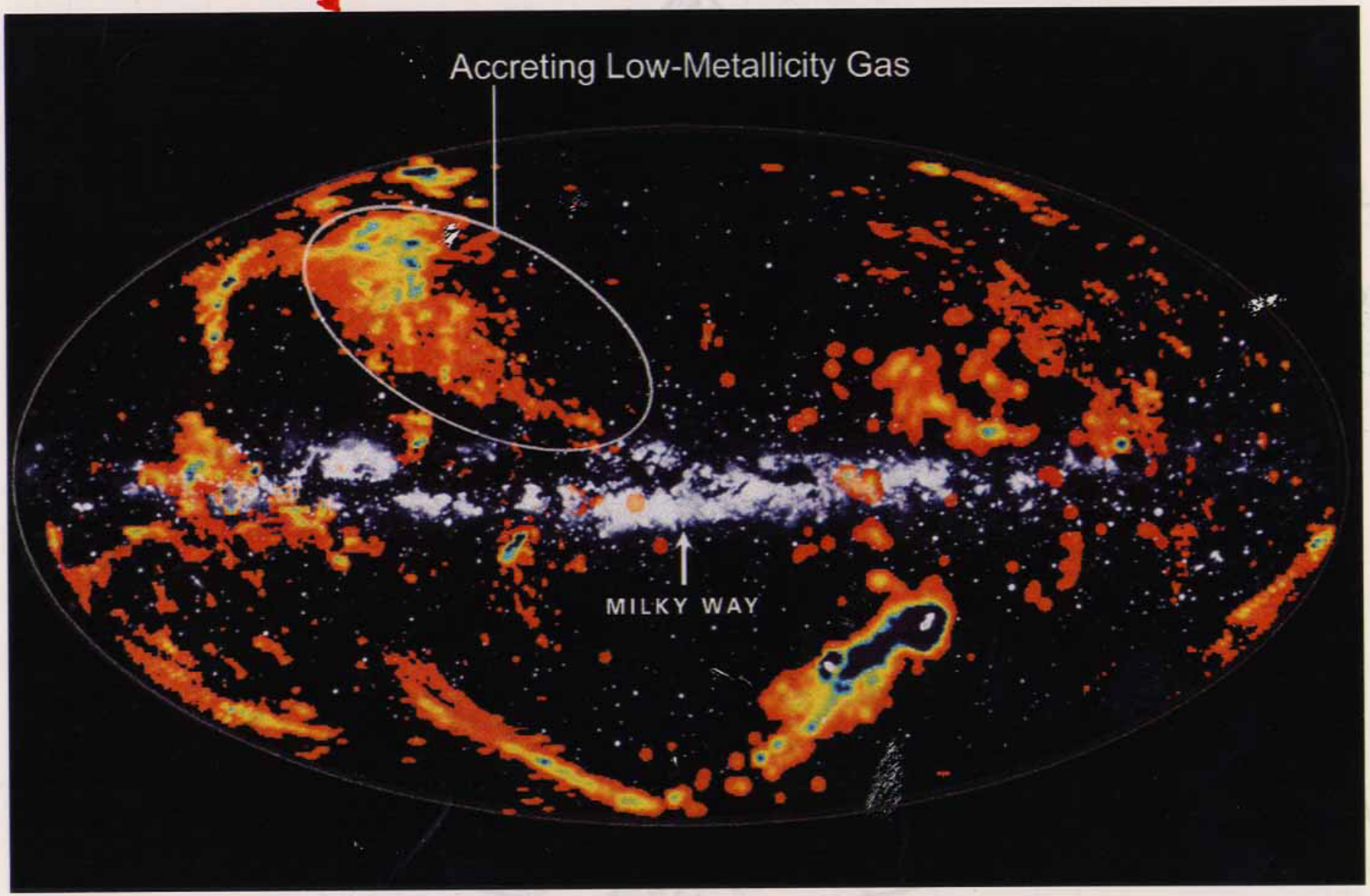


Fig. 1

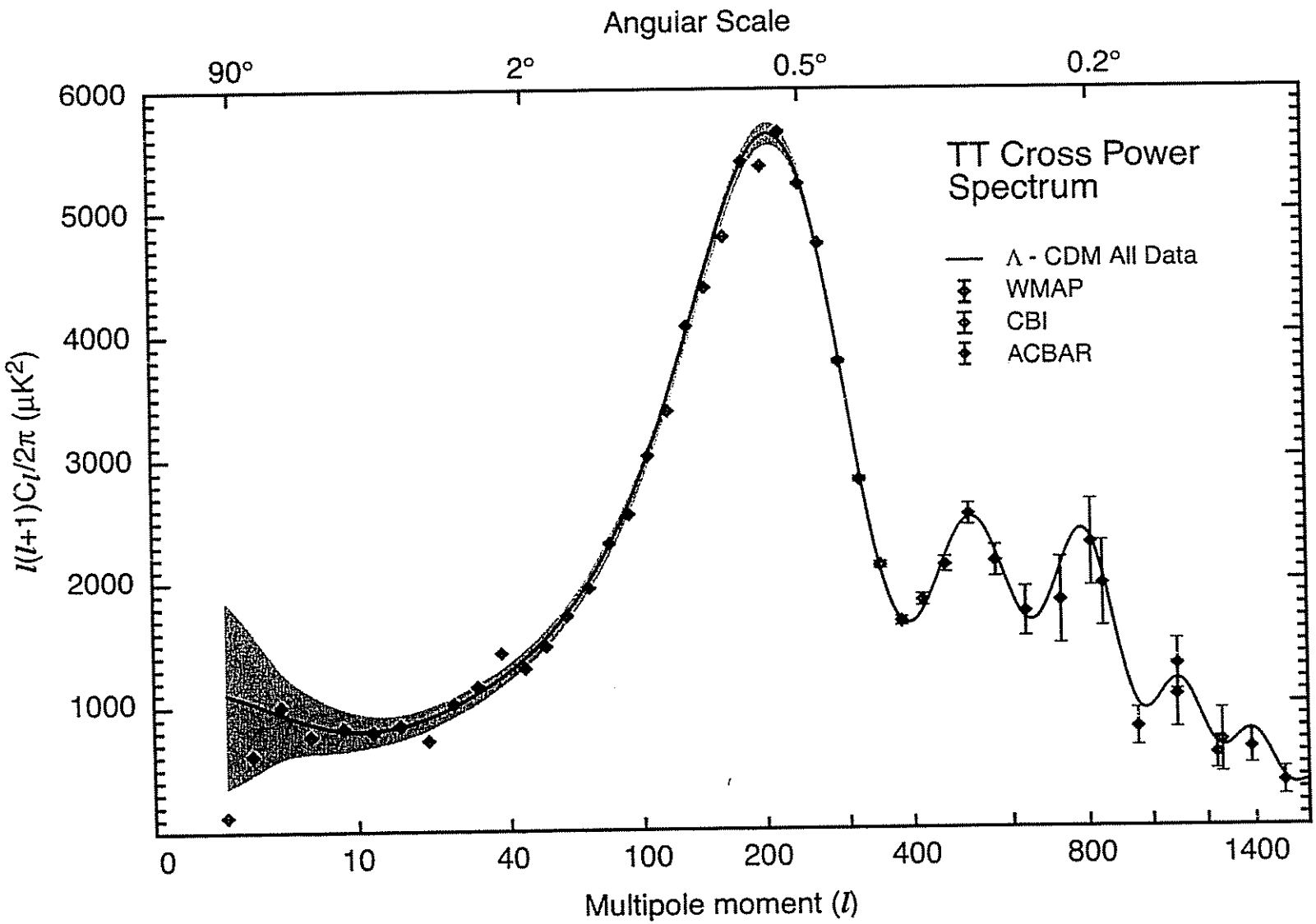

hot, shocked IGM
Condensed Gas
Ly α Forest
log T
log $(\rho_b/\overline{\rho_b})$
log $(\rho_b/\overline{\rho_b})$

HVC - Complex C

Fig. from Wakker

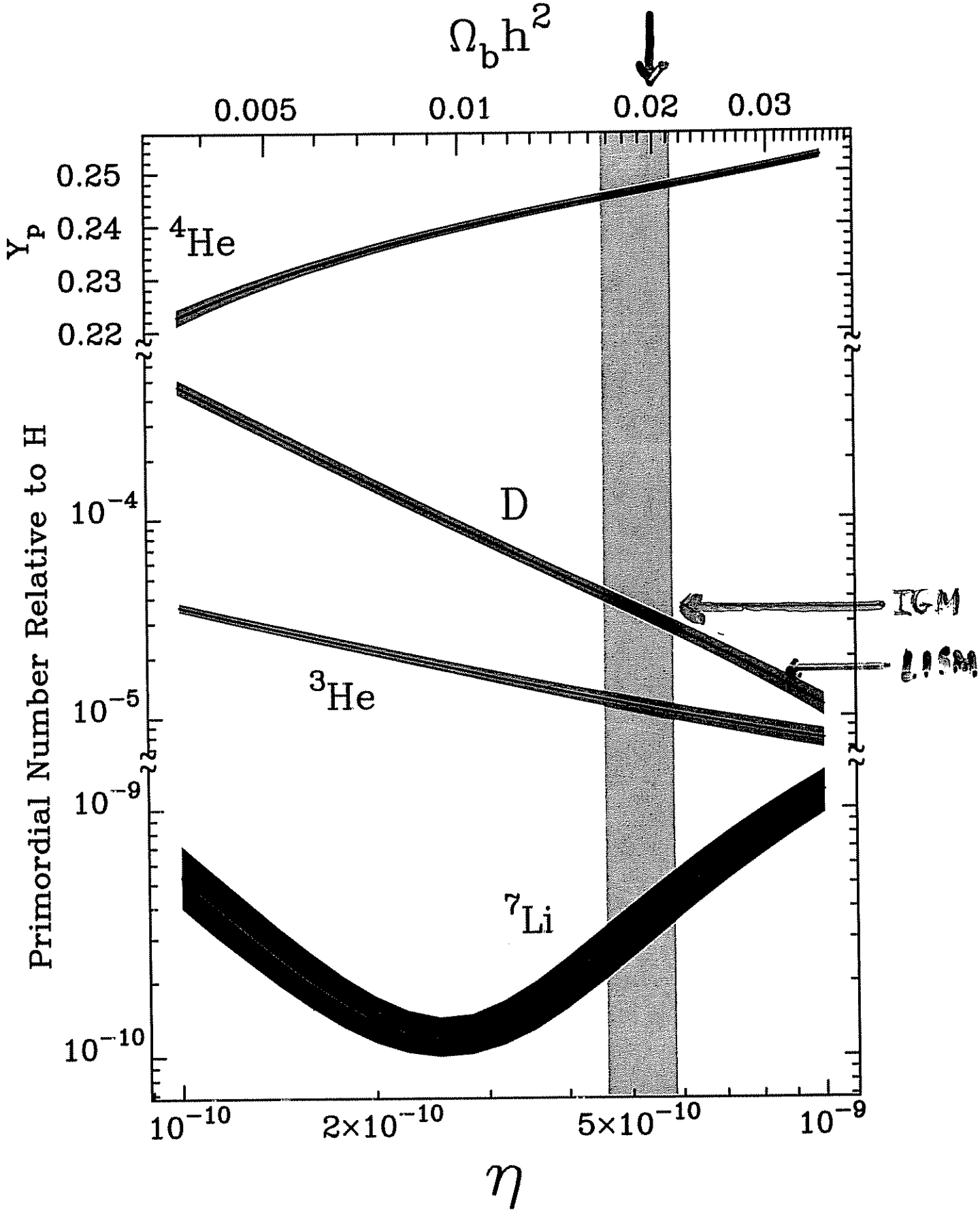


CMB Data and Best Fit Power Law ΛCDM Model



DEUTERIUM

$\Omega_b = 0.04\, h_{70}^{-2}$



Reionization and the "Dark Ages"

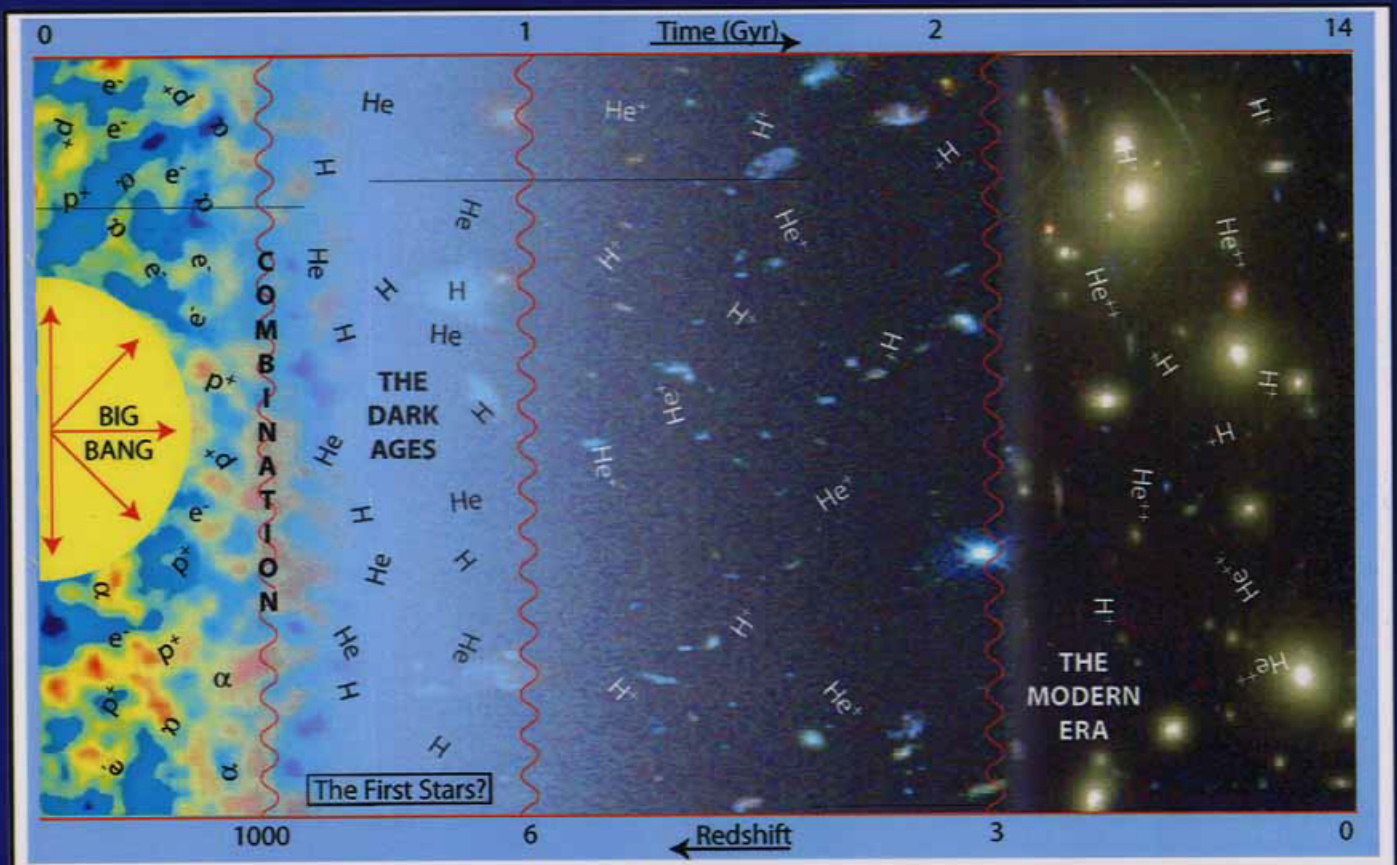
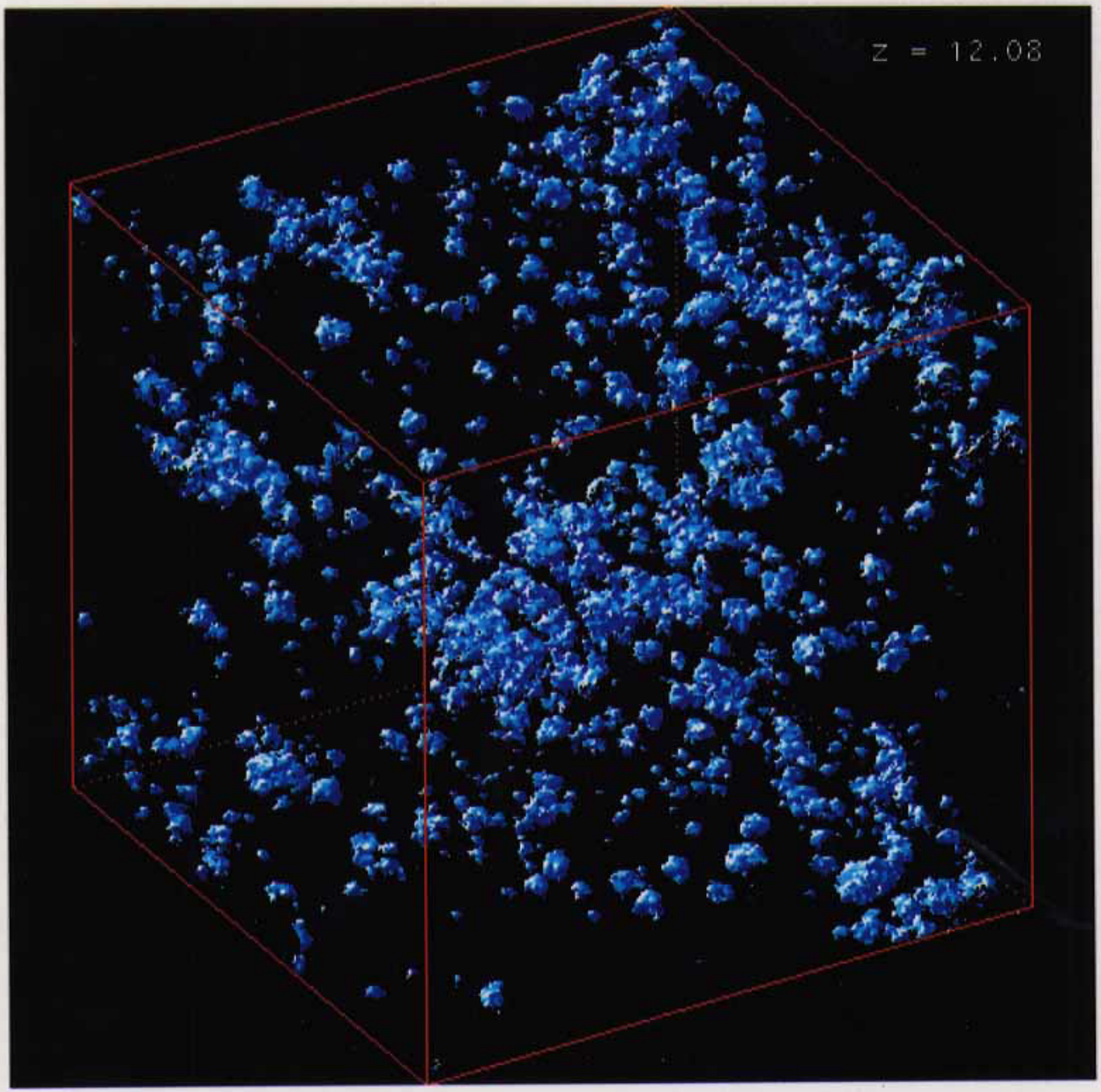


Photo Credits (L to R): BOOMERanG, Hubble Deep Field, STScI

The period between the "combination" and the H reionization at $z \sim 6$ is known as the "dark ages" - before the formation of galaxies and stars.

In the common picture, H reionization is accomplished by stars at $z > 6$.

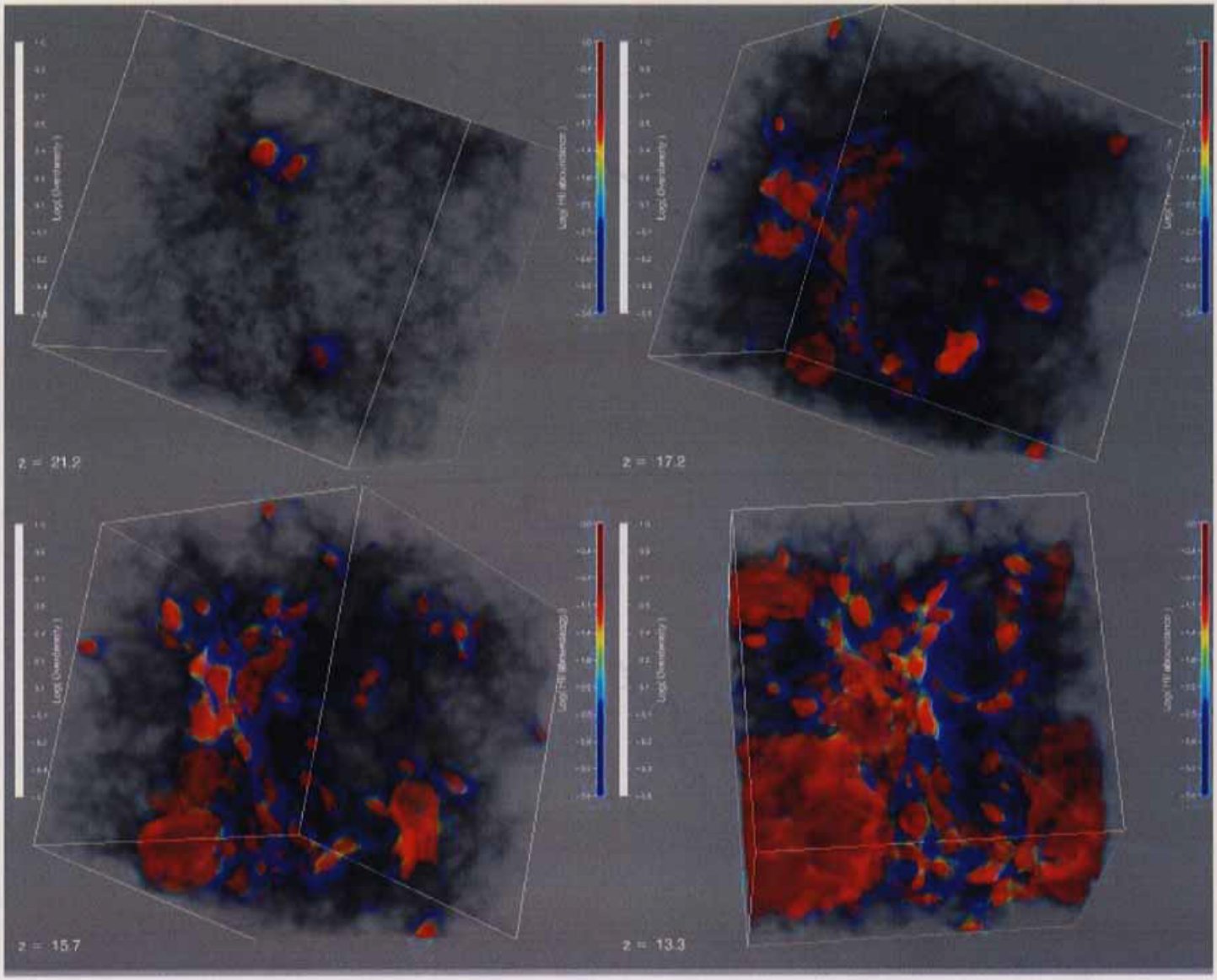
The reionization of He is attributed to QSOs, which have harder ionizing spectra and reach a peak number density at $z = 3$.

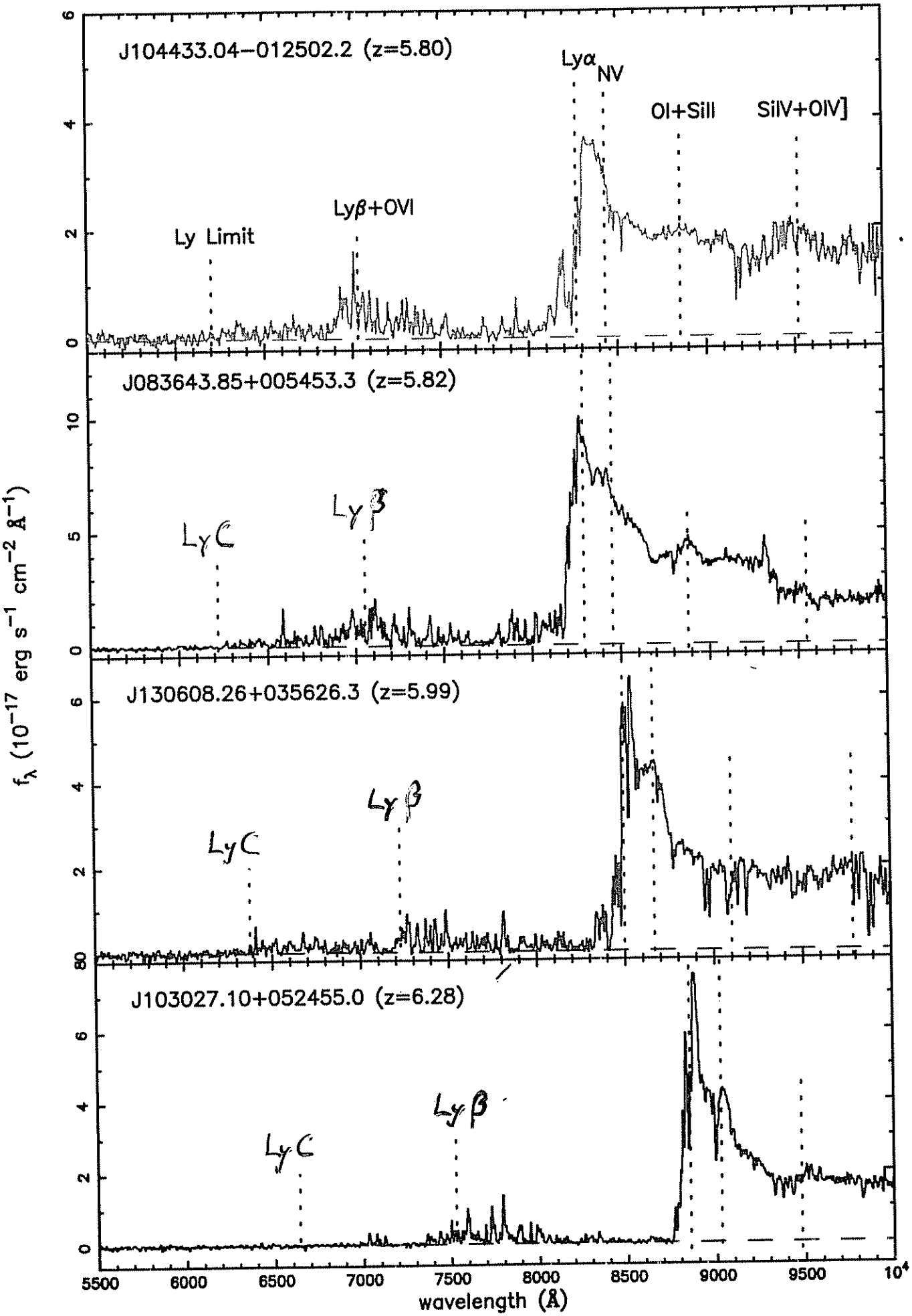

z = 12.08

Ionization Fronts (First Starbursts)

($z \approx 10-15$) Ricotti et al. (2002)

astro-ph/0210832



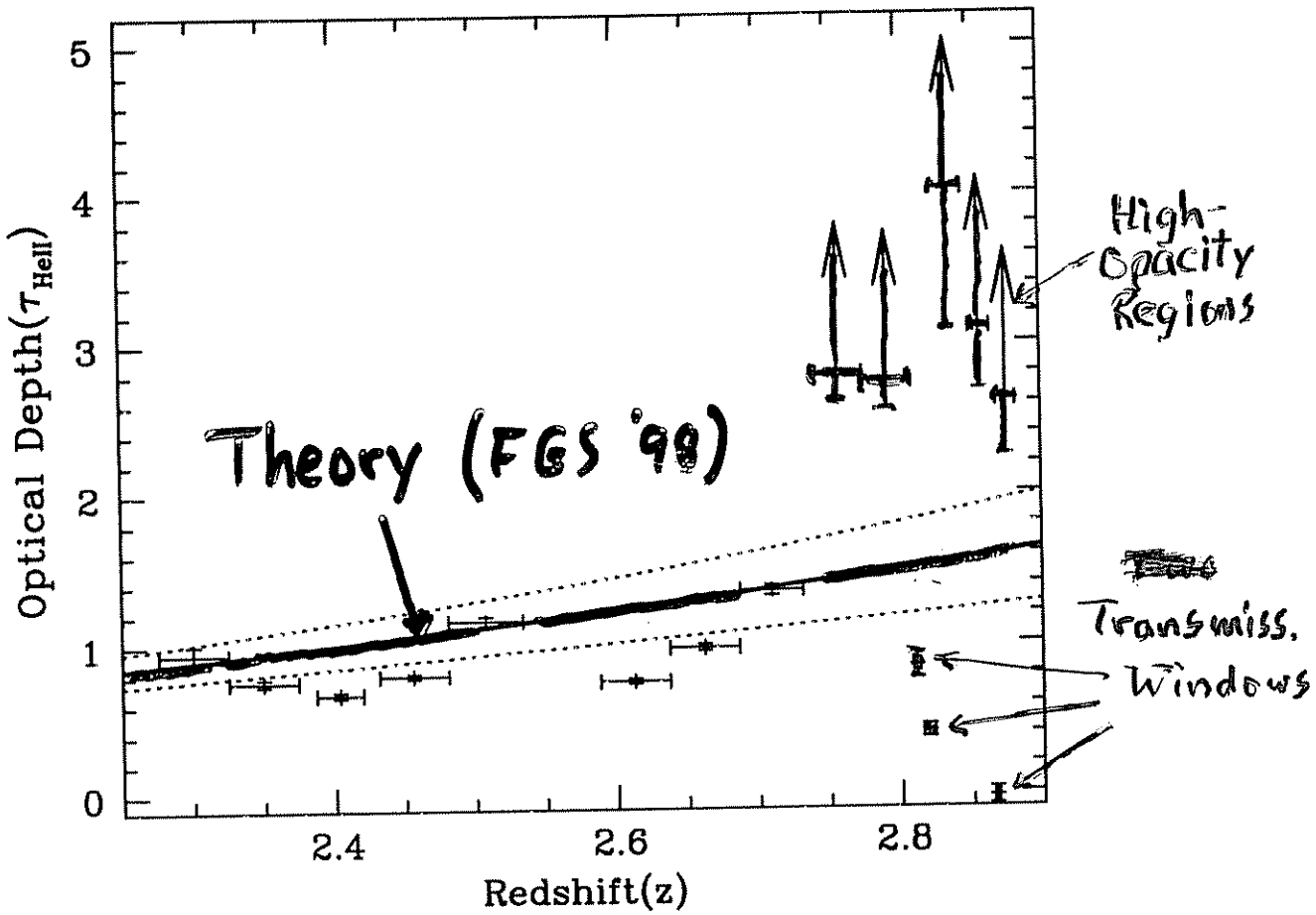

J104433.04−012502.2 (z=5.80)
Lyα
NV
OI+SiII
SiIV+OIV]
Lyβ+OVI
Ly Limit
J083643.85+005453.3 (z=5.82)
LyC
Lyβ
J130608.26+035626.3 (z=5.99)
LyC
Lyβ
J103027.10+052455.0 (z=6.28)
LyC
Lyβ
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
wavelength (Å)
5500
6000
6500
7000
7500
8000
8500
9000
9500
10^4

He^+ Optical Depth [He II Lyα 304 Å]

(toward HE 2347-4342)

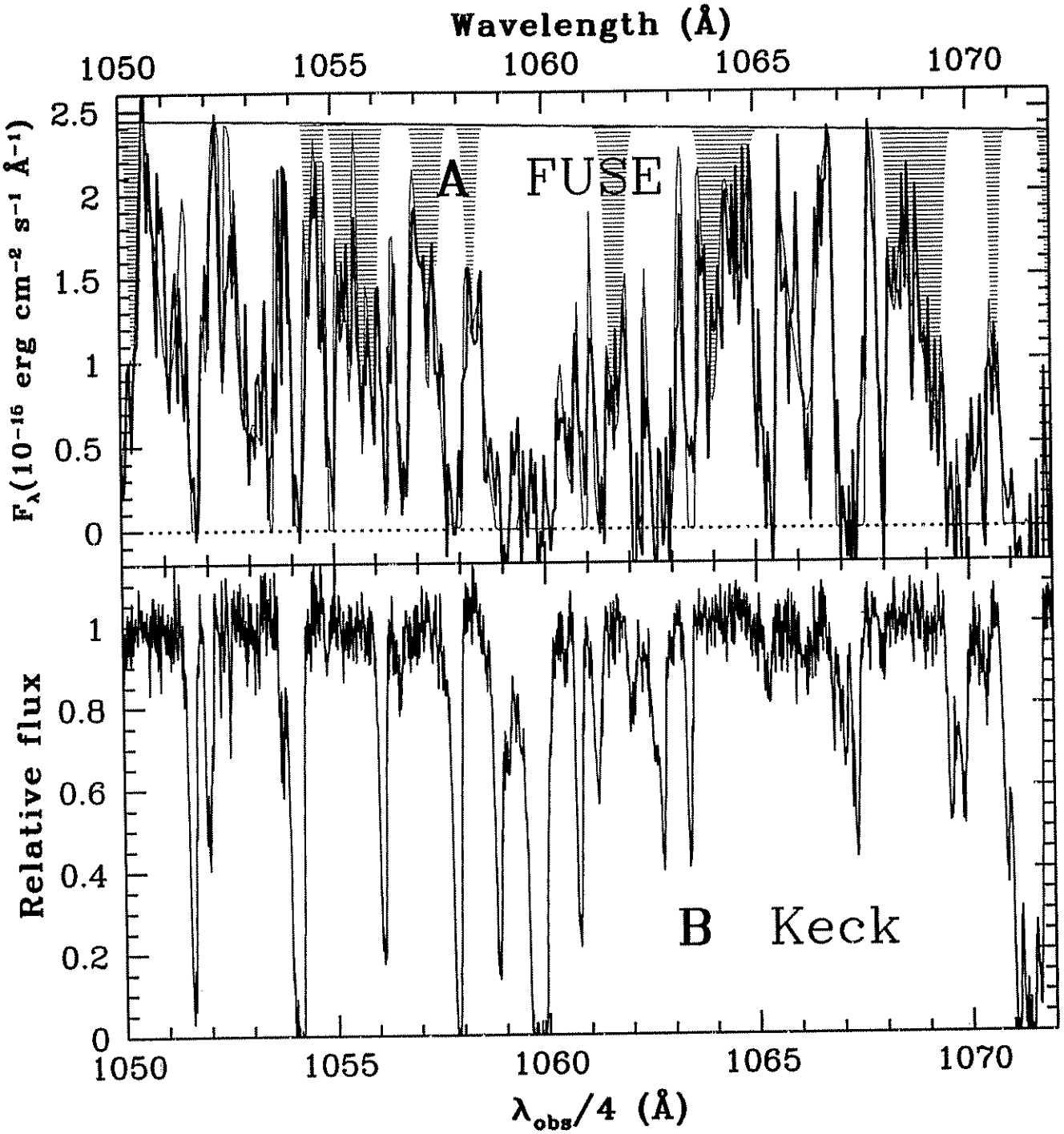
Kriss et al. 2001

Science



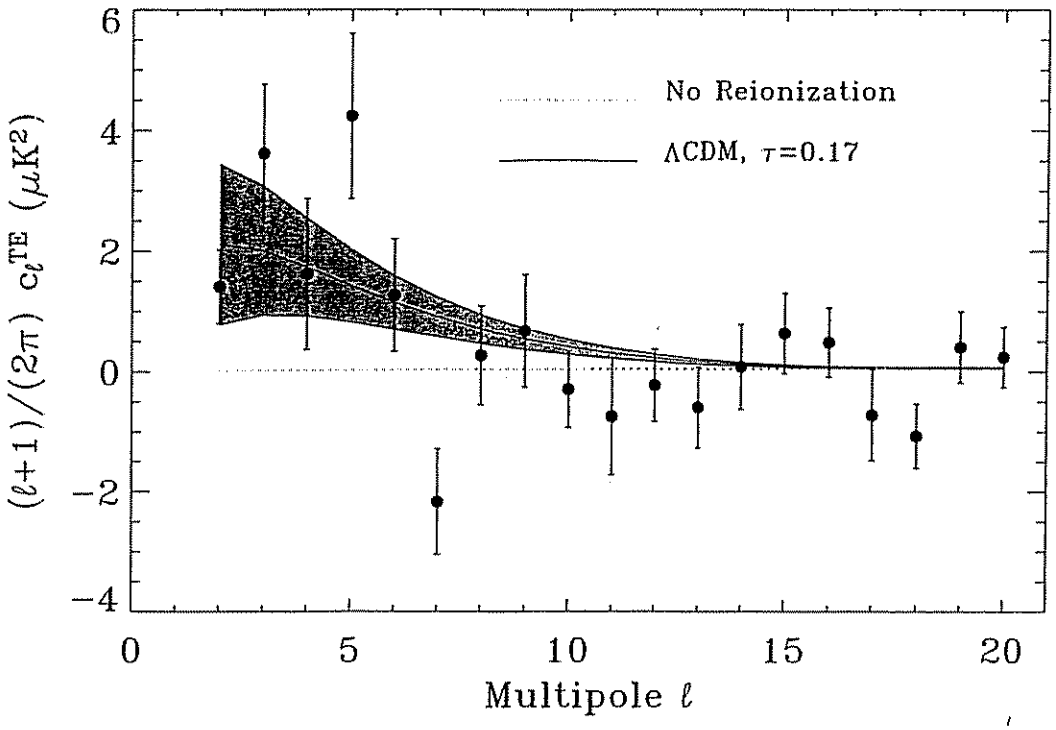
$$z_r^{He^+} \approx 2.8 \pm 0.2$$

He II Lyα (z = 2.45 - 2.55)



CMB opt. depth

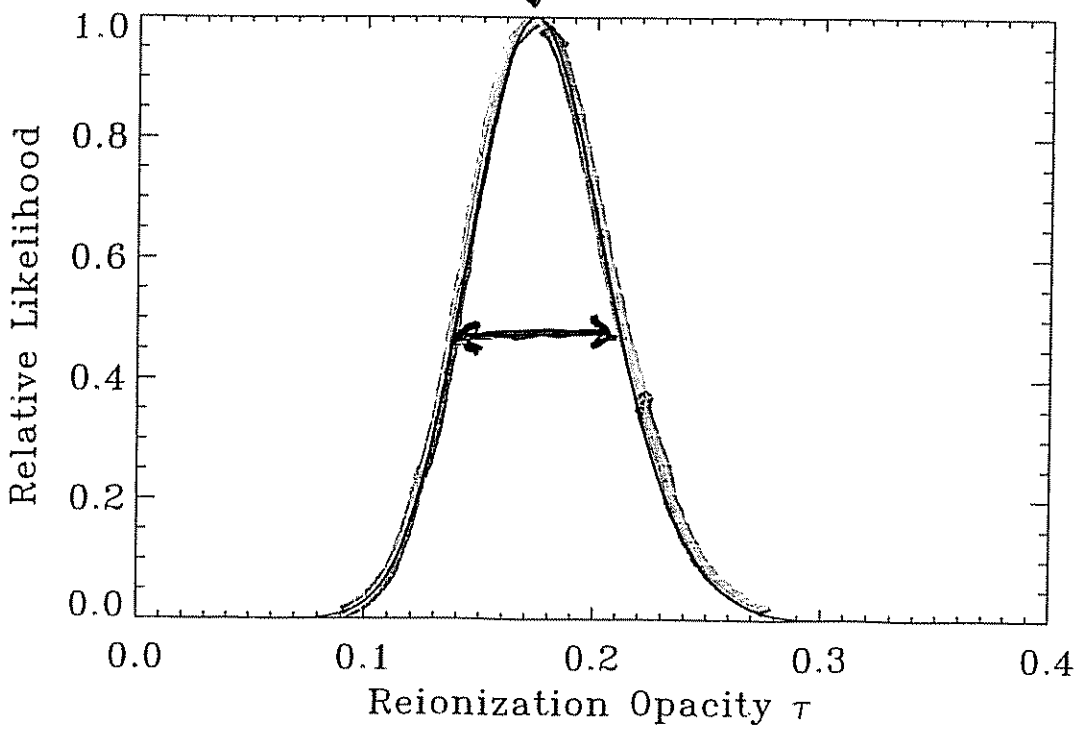
Kogut et at.



Bad χ^2

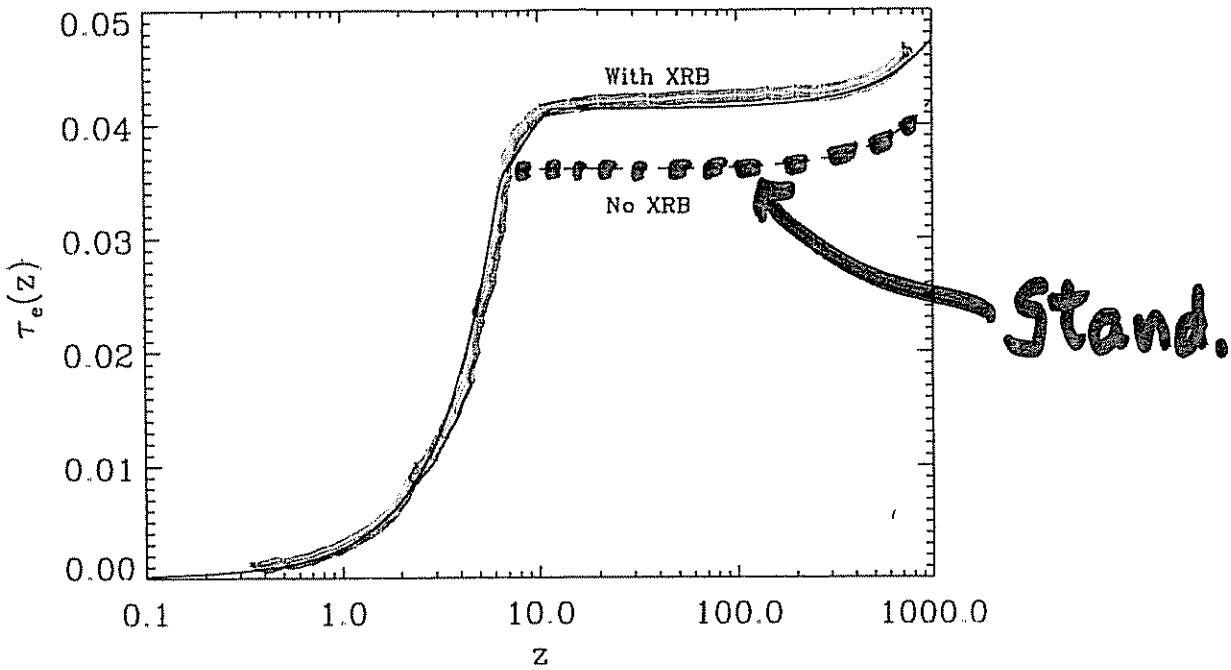
Hype!

$\tau_c = 0.17$



HEATING AND IONIZATION OF THE INTERGALACTIC MEDIUM BY AN EARLY X-RAY BACKGROUND

APARNA VENKATESAN, MARK L. GIROUX,[1] AND J. MICHAEL SHULL

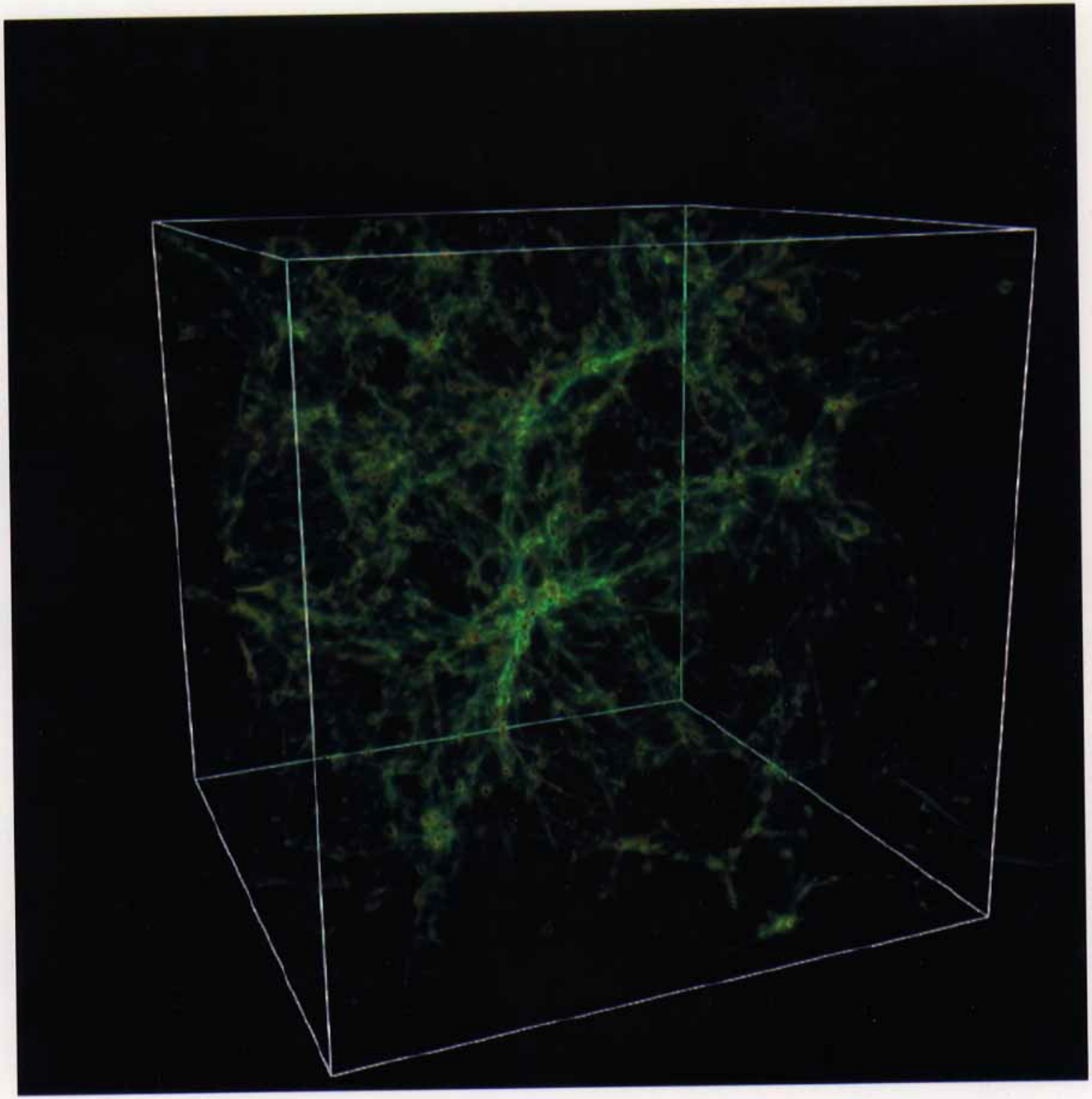


$\tau_e \approx 0.04 - 0.05$

[could be 0.09 with pop III massive stars]

Cen & Ostriker (1998)

"Hot IGM" at $z \ll 1$



Low-Redshift IGM (Lyα)

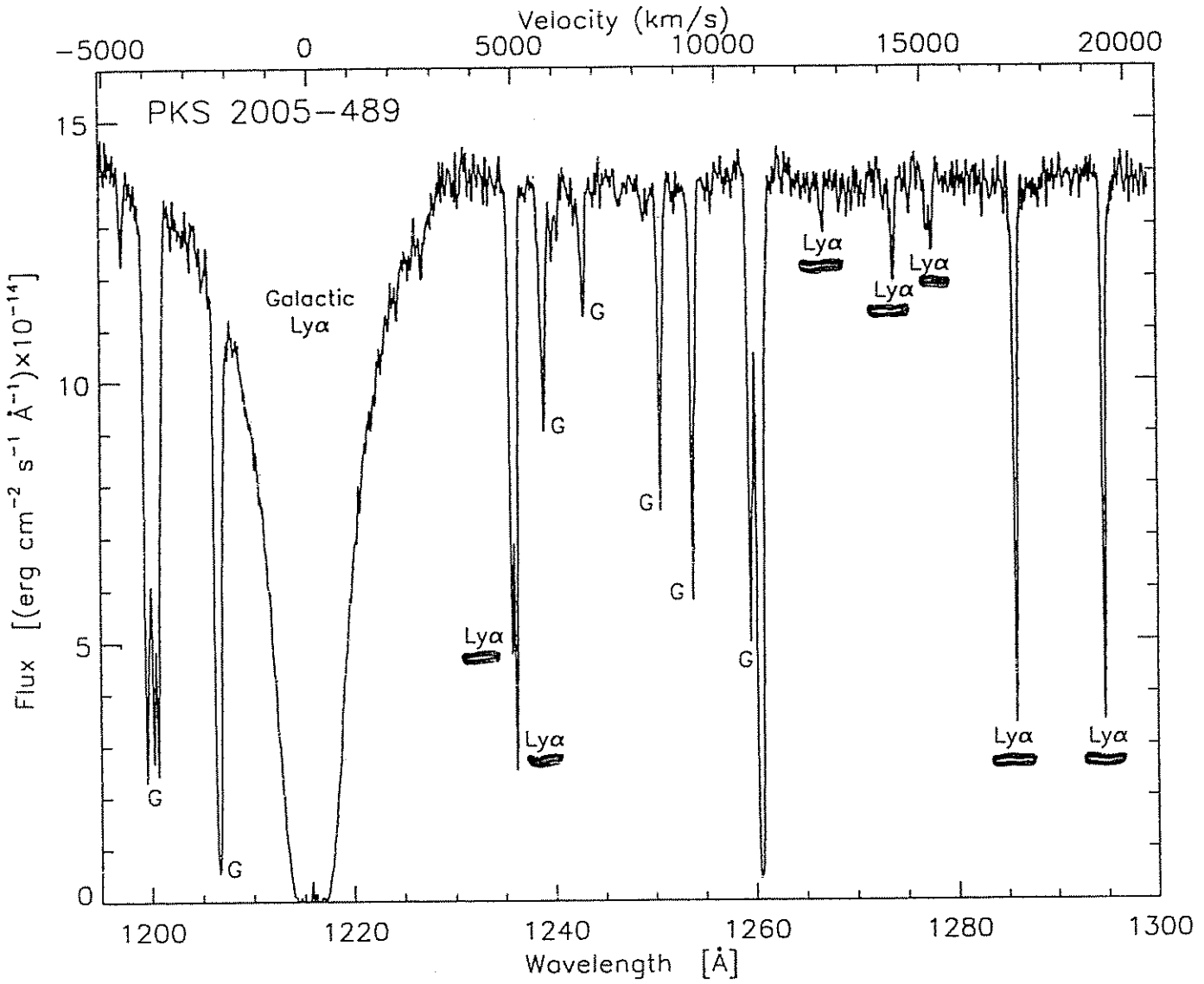
HST/STIS

(Penton, Stocke, Shull)

Still contains 20-30% of baryons

$\left(\frac{dN}{dz} \sim 200\right)$

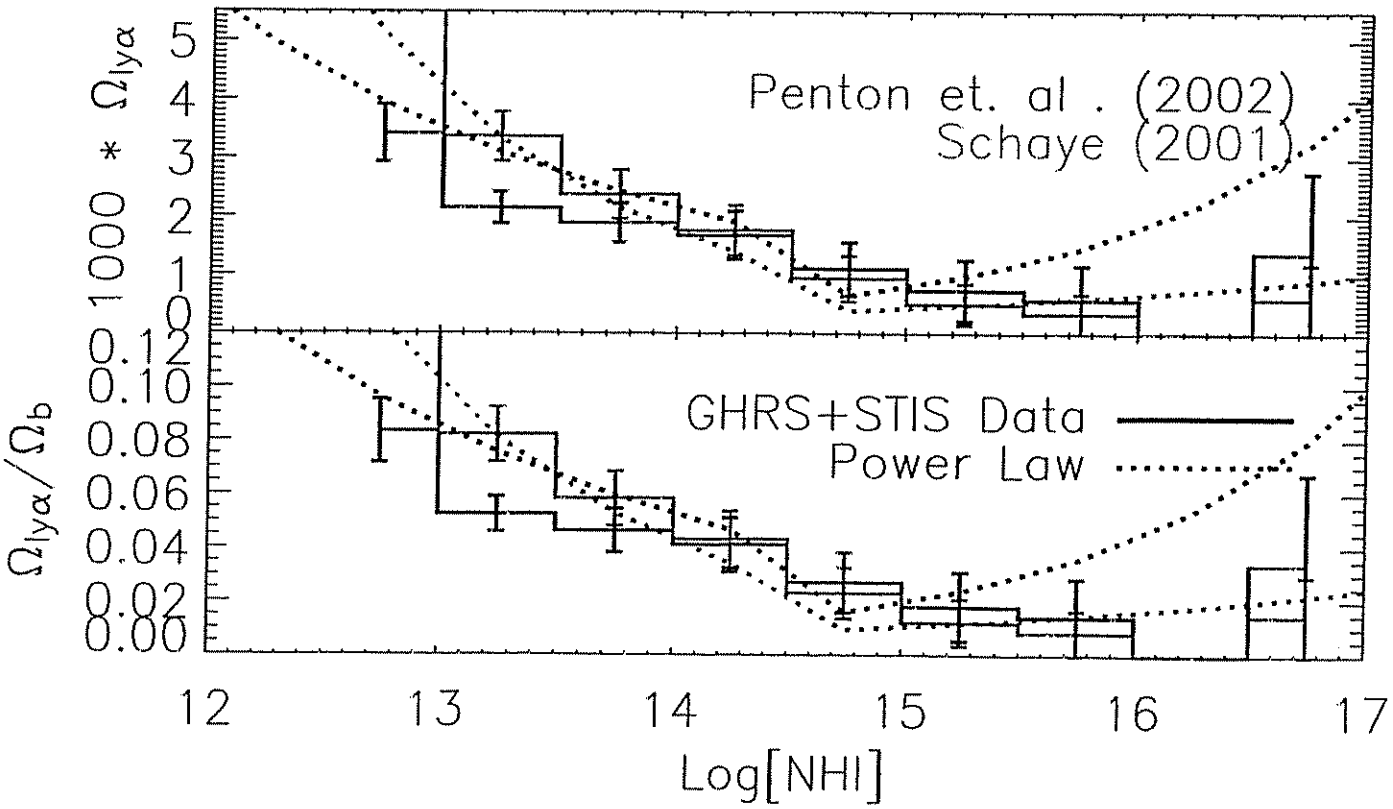
to $N_{HI} = 10^{12.6}\ cm^{-2}$

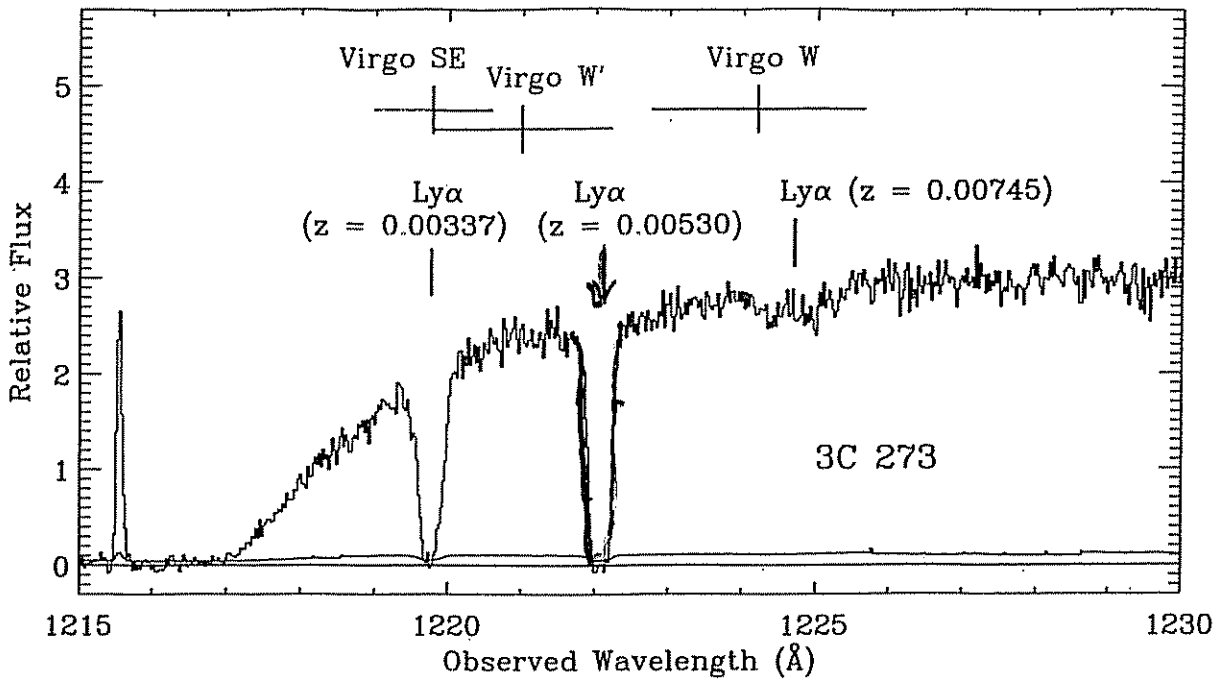


Lyα Forest ($z \lesssim 0.1$)

$$12.5 \leq \log N_{HI} \leq 17.0$$

$$\boxed{\frac{\Omega_{Ly\alpha}}{\Omega_b} \approx 0.32 \pm 0.06}$$



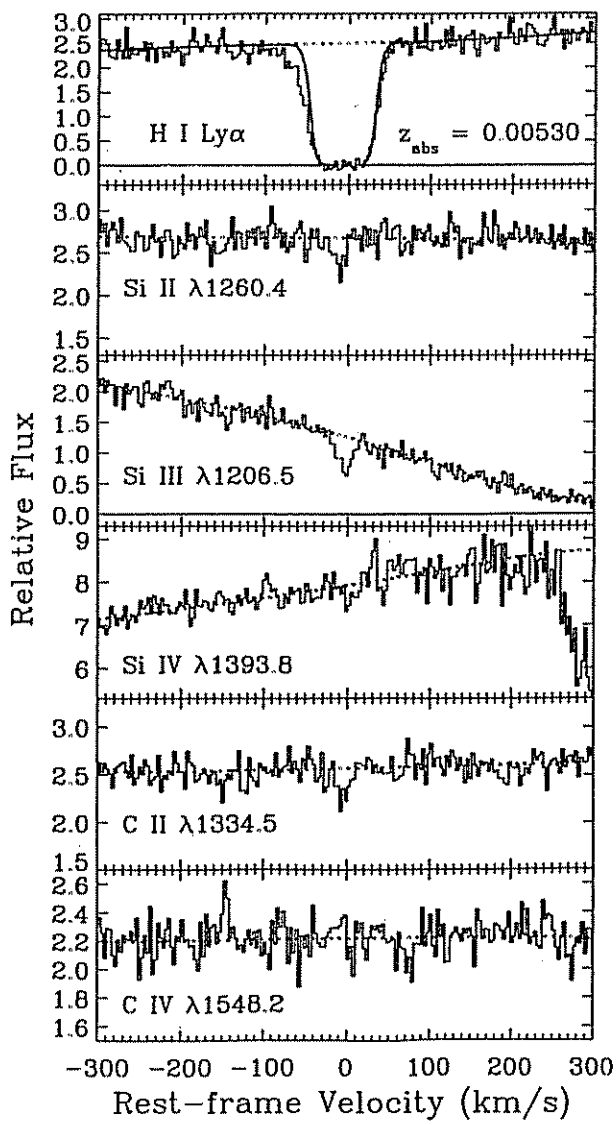


Tripp et al. (2002)
[HST/STIS echelle]

<u>abundances</u>:

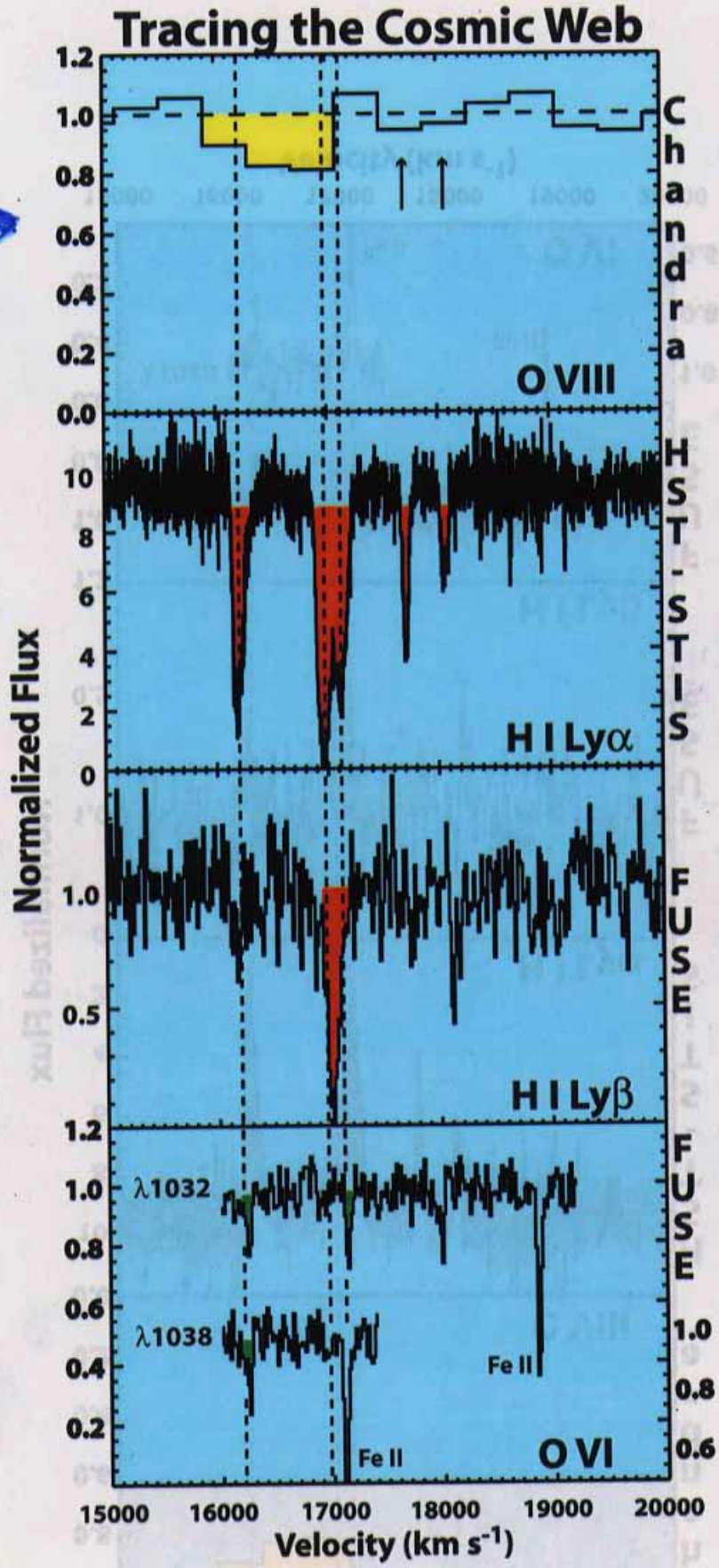
$$[C/H] = -1.2^{+0.3}_{-0.2}$$

$$[Si/C] = +0.2 \pm 0.1$$



Fang et al. (2002) ApJL

Shull, Tumlinson & Giroux (2003)



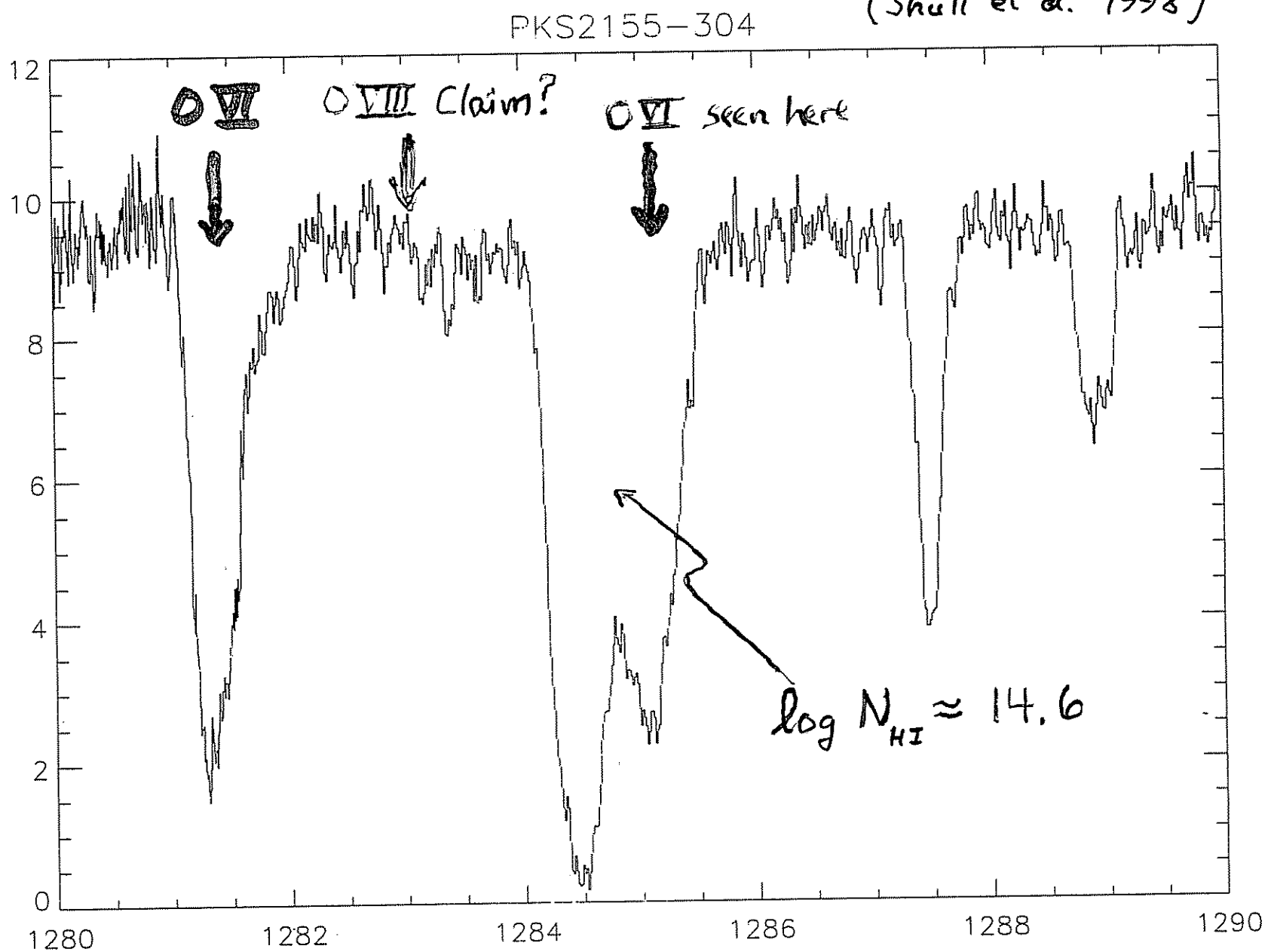
Chandra

HST

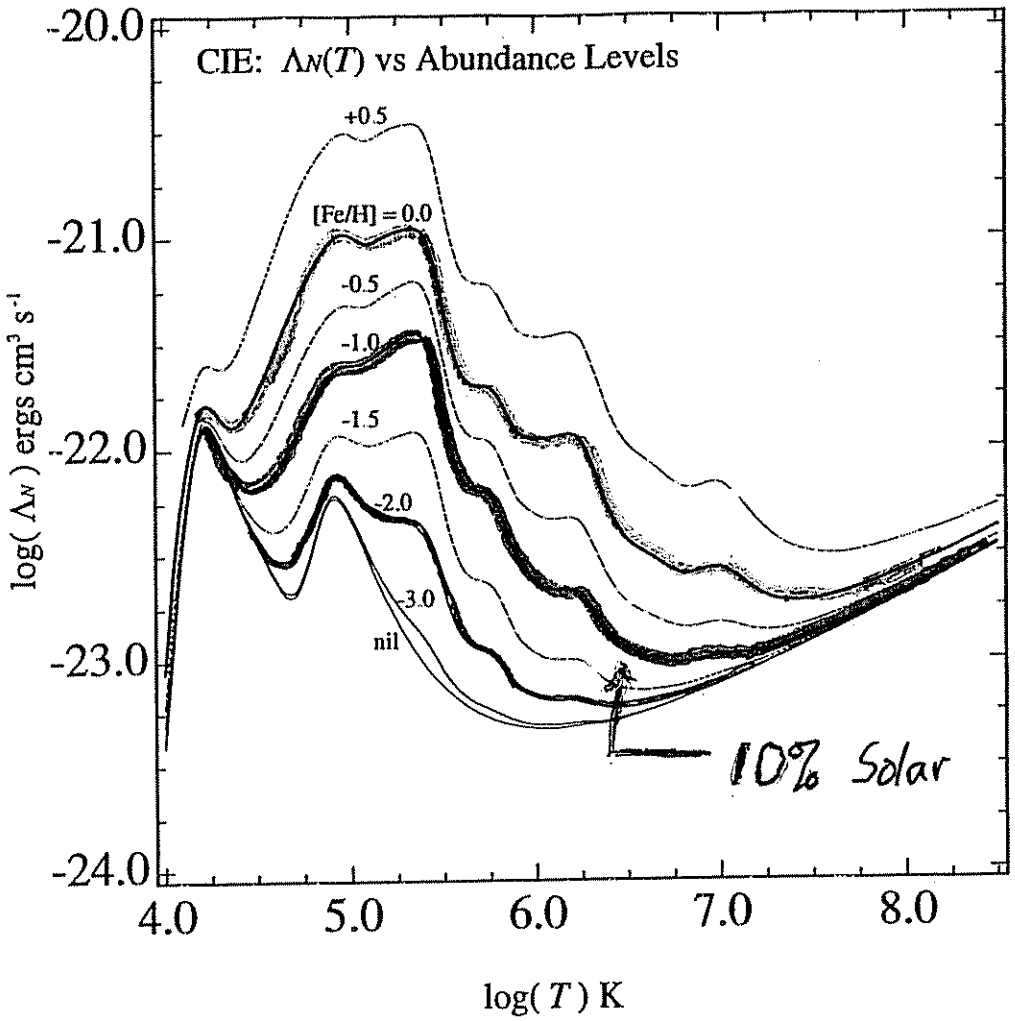
FUSE

FUSE

"Cluster" of Lyα Absorbers
(Shull et al. 1998)



SUTHERLAND & DOPITA



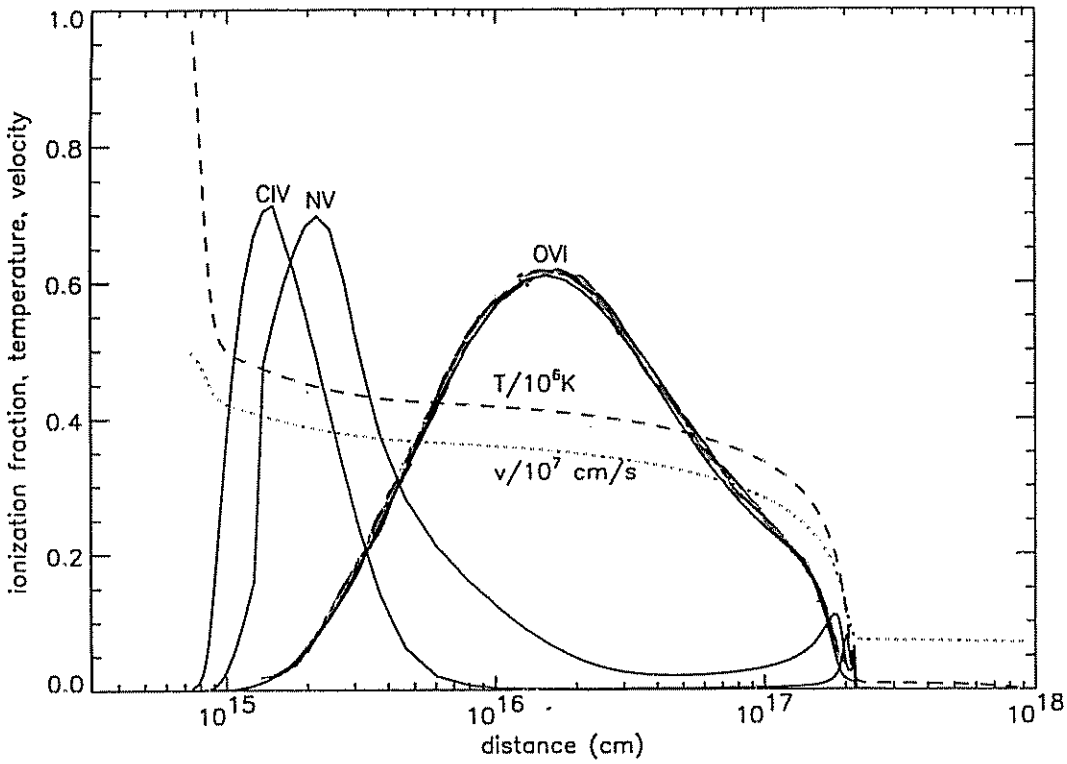
$$t_{cool} \equiv \frac{\frac{3}{2} k T}{n_e \Lambda} \cong \boxed{(2 \times 10^{10}\ \text{yrs}) \frac{T_{6.5}^2}{n_{-4}\, \Lambda_{-23}}}$$

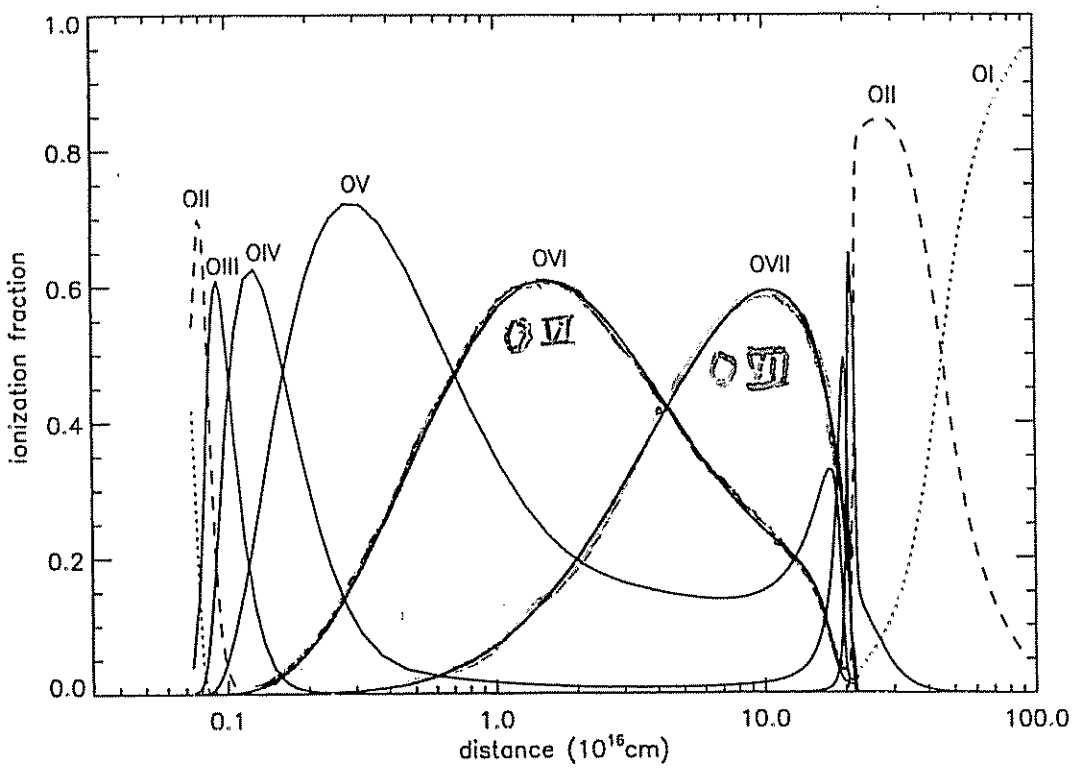
$(\delta \approx 600)$

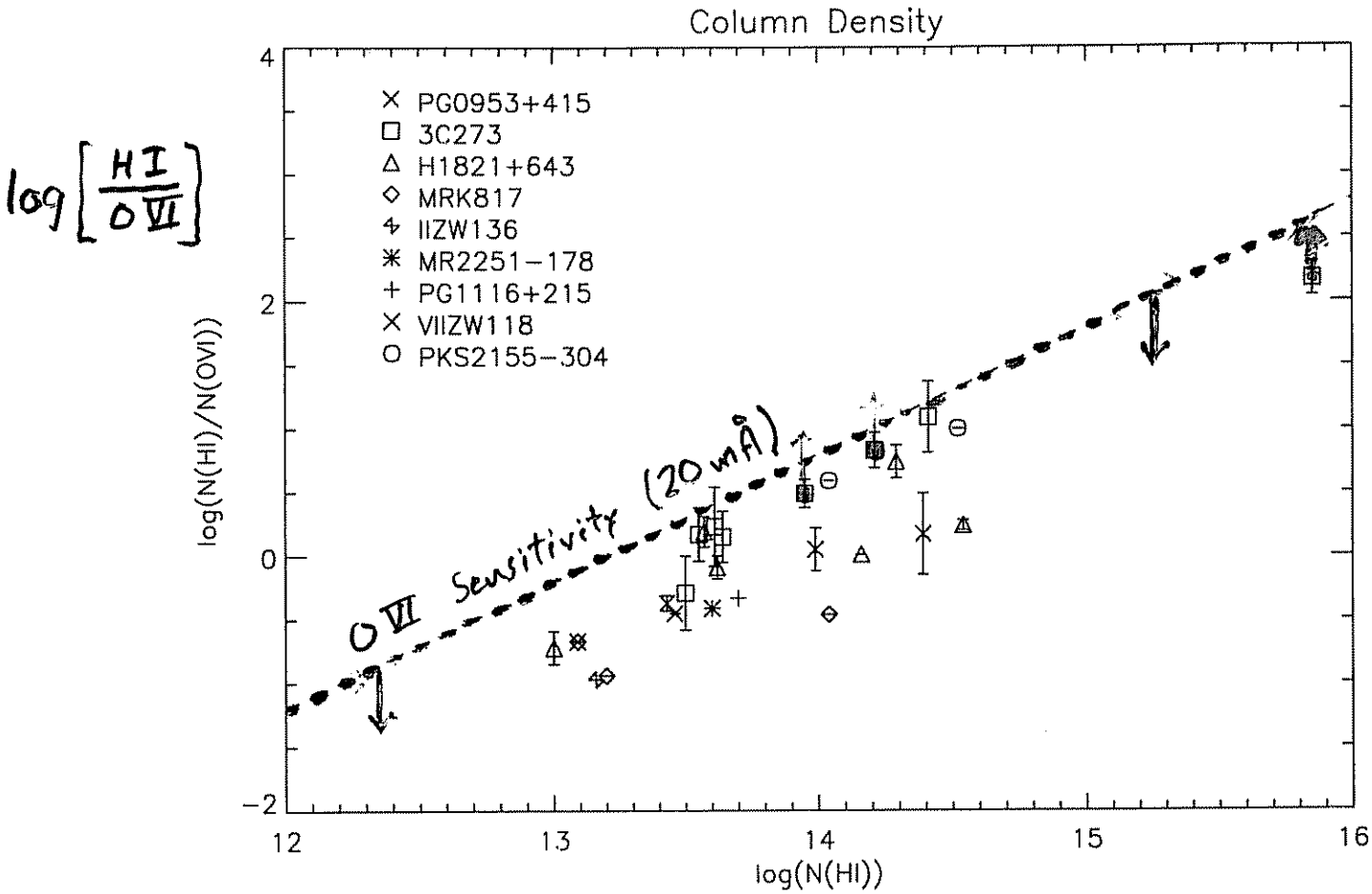
Halo gas can't cool without a shock/compression trigger.

[and radiative cooling]

200 km/s Shock







- OVI and HI Kinematic Assoc.
- Typical ratio $\left[\frac{HI}{OVI}\right] = 0.1 - 10$

BARYONS AT REDSHIFT $z = 0$

Baryon Content:

- $\Omega_b = 0.041 h_{70}^{-2}$ (D/H and CMB)
- $\langle \rho_{b,0} \rangle = (3.8 \pm 0.2) \times 10^{-31}$ g cm^{-3}
- $\langle n_{H,0} \rangle = 1.7 \times 10^{-7}$ cm^{-3}
- Baryon $f_b = \Omega_b / \Omega_m = 0.14 \pm 0.01$

Major Baryon Repositories:

- $\Omega_{\rm Gal} = [0.003 \pm 0.001] h_{70}^{2}$ ← 7 ± 3%
- $\Omega_{\rm 21cm} = [0.00039 - 0.00063] h_{70}^{-1}$ ← 1%
- $\Omega_{Ly\alpha} = [0.008 - 0.012] h_{70}^{-1}$ ← 30% ?
- $\Omega_{OVI} = [0.003 - 0.008] h_{70}^{-1}$ ← 5-10% ?
- $\Omega_{OVIII} = [???] h_{70}^{-1}$ ← TBD (X-ray spectra)

O VII and O VIII