Reionization and the "Dark Ages"

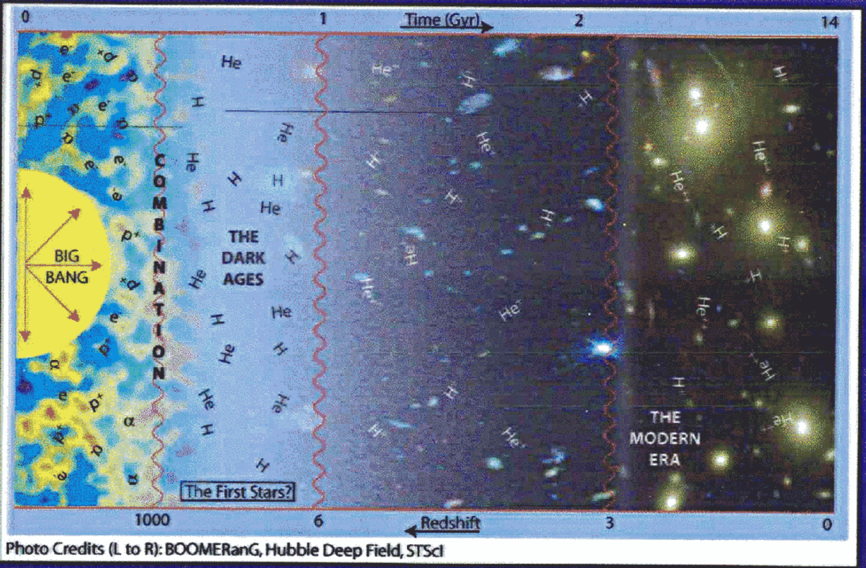


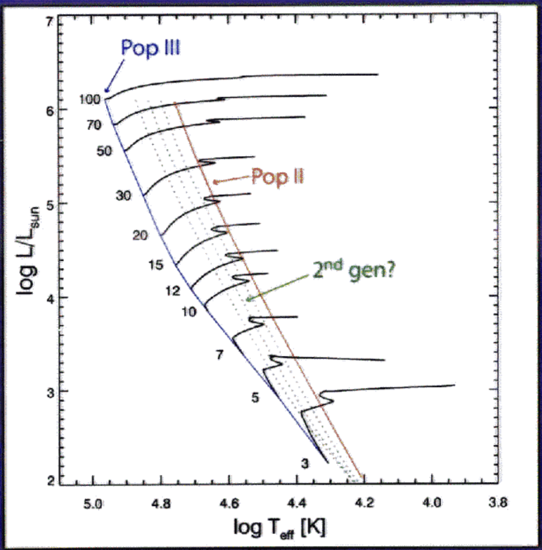
Photo Credits (L to R): BOOMERanG, Hubble Deep Field, STScI

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 $z = 3$.

Evolving Models of Population III

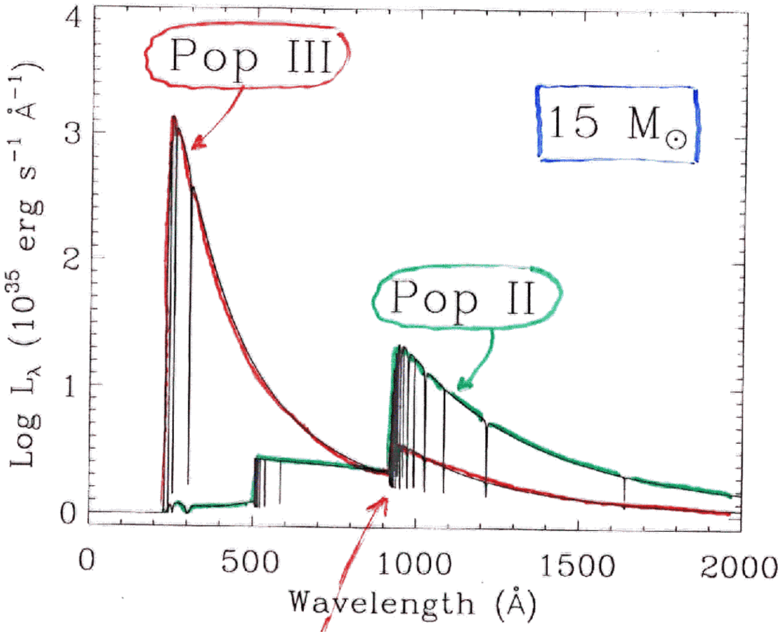


- → Metal-free stars are 2x hotter and 5x smaller than their Pop II counterparts.
- → In general, stars evolve off the MS to lower T_{eff} and higher L.
- → Zero-age models with $Z_C = 10^{-8}, 10^{-7}$, and 10^{-6} lie between Pop III and Pop II (green). These may represent the 2nd generation.

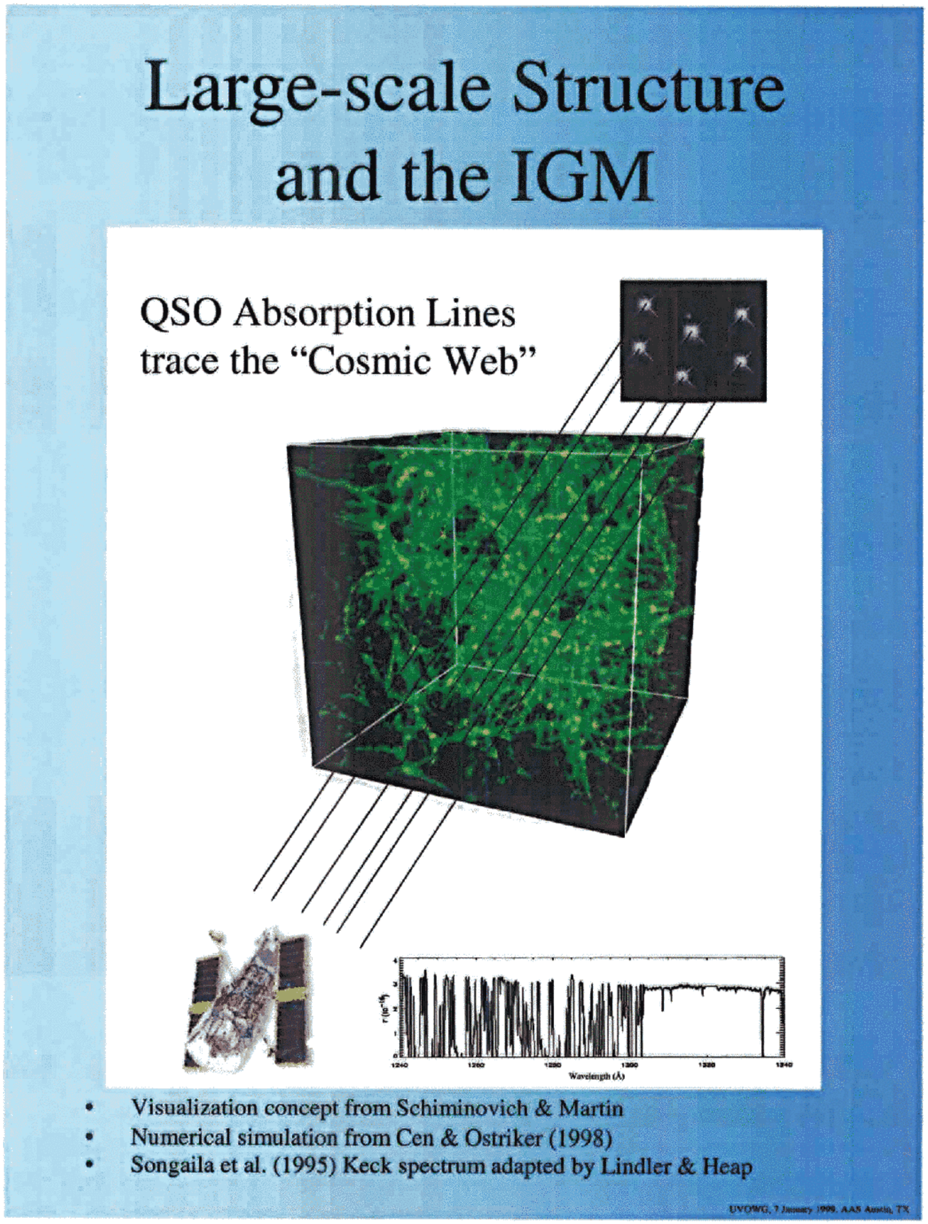
ZERO-METALLICITY STARS AND THE EFFECTS OF THE FIRST STARS ON REIONIZATION

JASON TUMLINSON AND J. MICHAEL SHULL[1]

THE ASTROPHYSICAL JOURNAL, 528:L65–L68



Note The difference in Lyman breaks (T_{eff} larger in Pop III)



Large-scale Structure and the IGM

QSO Absorption Lines trace the "Cosmic Web"

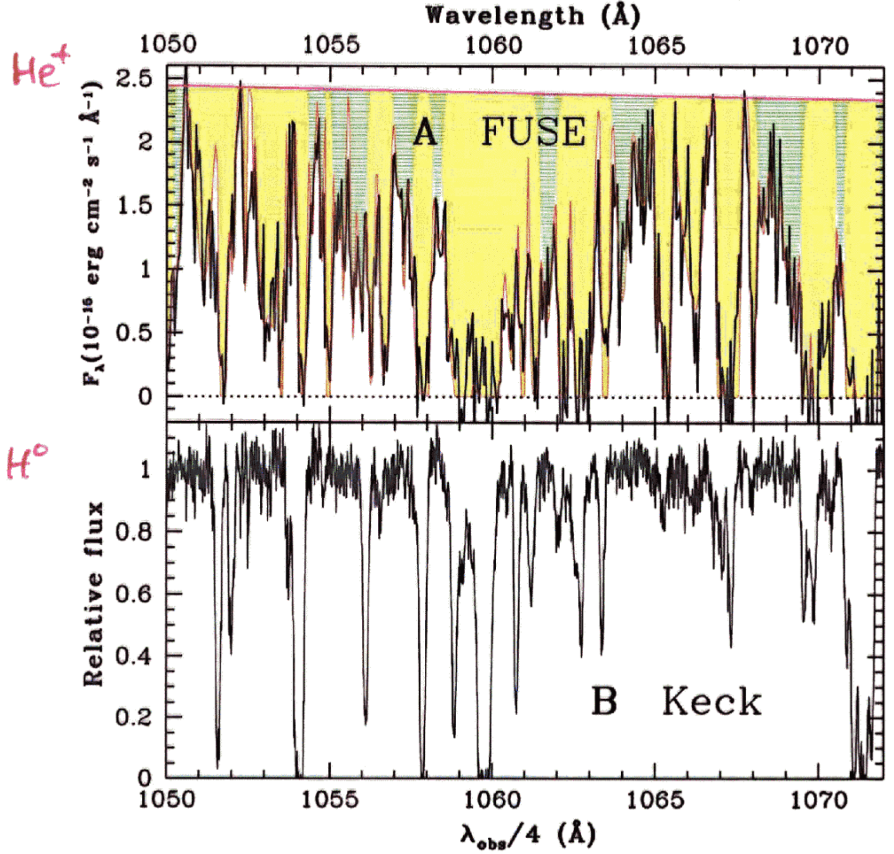
- Visualization concept from Schiminovich & Martin
- Numerical simulation from Cen & Ostriker (1998)
- Songaila et al. (1995) Keck spectrum adapted by Lindler & Heap

UVOWG, 7 January 1999, AAS Austin, TX

He II and H I Lyman α Forests

[$2.3 \leq z \leq 2.9$]

Kriss et al. 2001
Shull et al 2004
Zheng et al 2004



Fine-grained Variation

$\Delta z \sim 10^{-3}$
(Mpc-scale)

$$\eta = \frac{N(He\,II)}{N(H\,I)} = \frac{4\,\tau_{HeII}}{\tau_{HI}}$$

Shull et al. (2004) ApJ

– 22 –

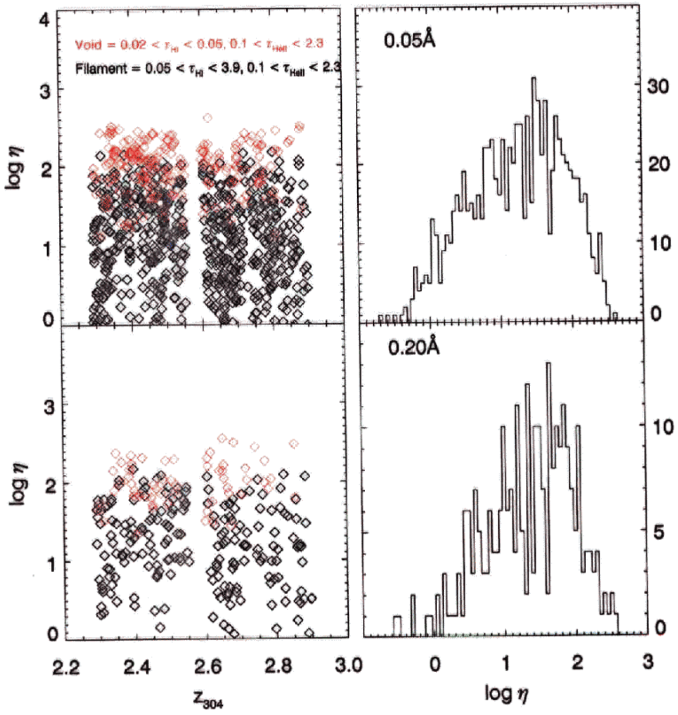
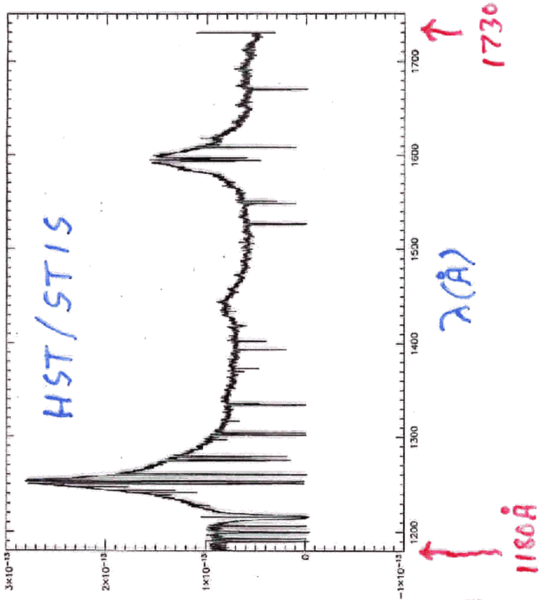
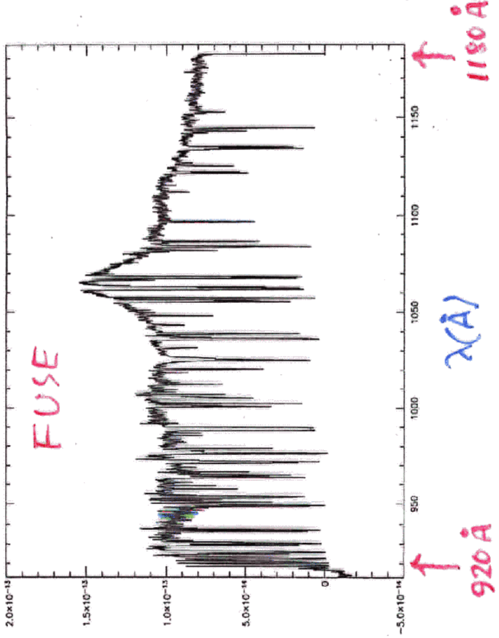
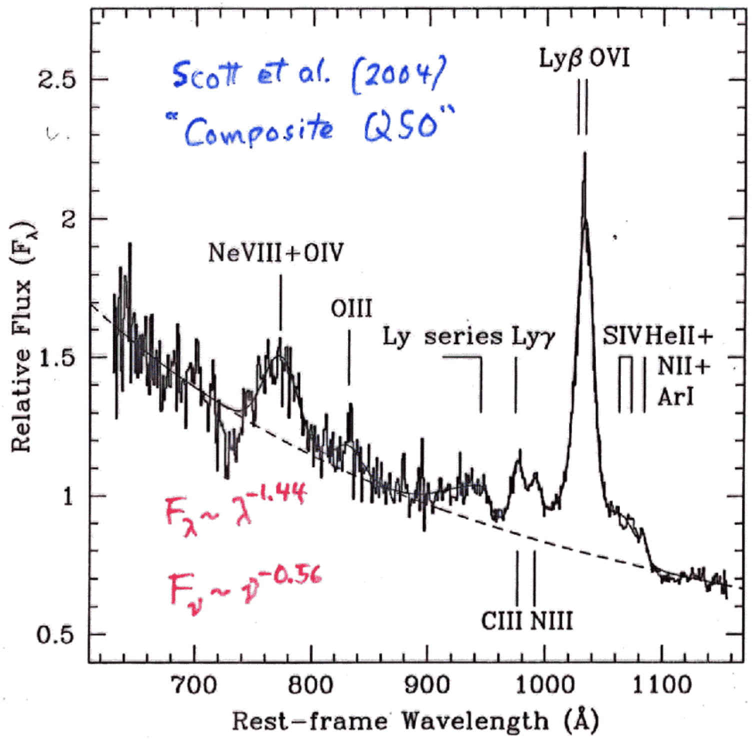
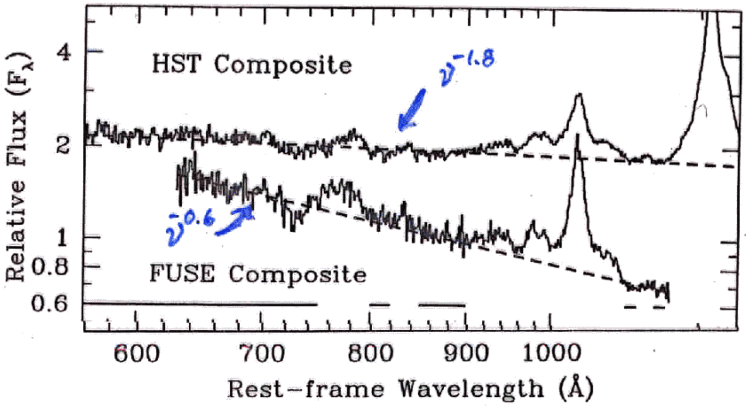


Fig. 3.— Left panels show the distribution with redshift of $\eta = N(\mathrm{He\ II})/N(\mathrm{H\ I})$, determined here as $\eta = 4\tau_{\mathrm{HeII}}/\tau_{\mathrm{HI}}$, in wavelength bins of 0.05 Å (top panels) and 0.20 Å (bottom panels). The distribution of η, integrated over $2.3 < z < 2.9$ is shown in the right panels. With the accuracy of these data, we can reliably measure optical depths in the ranges $0.1 < \tau_{\mathrm{HeII}} < 2.3$ and $0.02 < \tau_{\mathrm{HI}} < 3.91$. Gap at $z = 2.6$ lies between the LiFa and LiF1b FUSE detector segments. "Filaments" in the Lyα forest are plotted in black ($\tau_{\mathrm{HI}} > 0.05$), while "voids" have $0.02 < \tau_{\mathrm{HI}} < 0.05$ and are plotted in red, some as lower limits. The large fluctuations in η suggest wide variation in the spectra of the ionizing sources, density fluctuations, or significant effects of radiative transfer in the IGM.

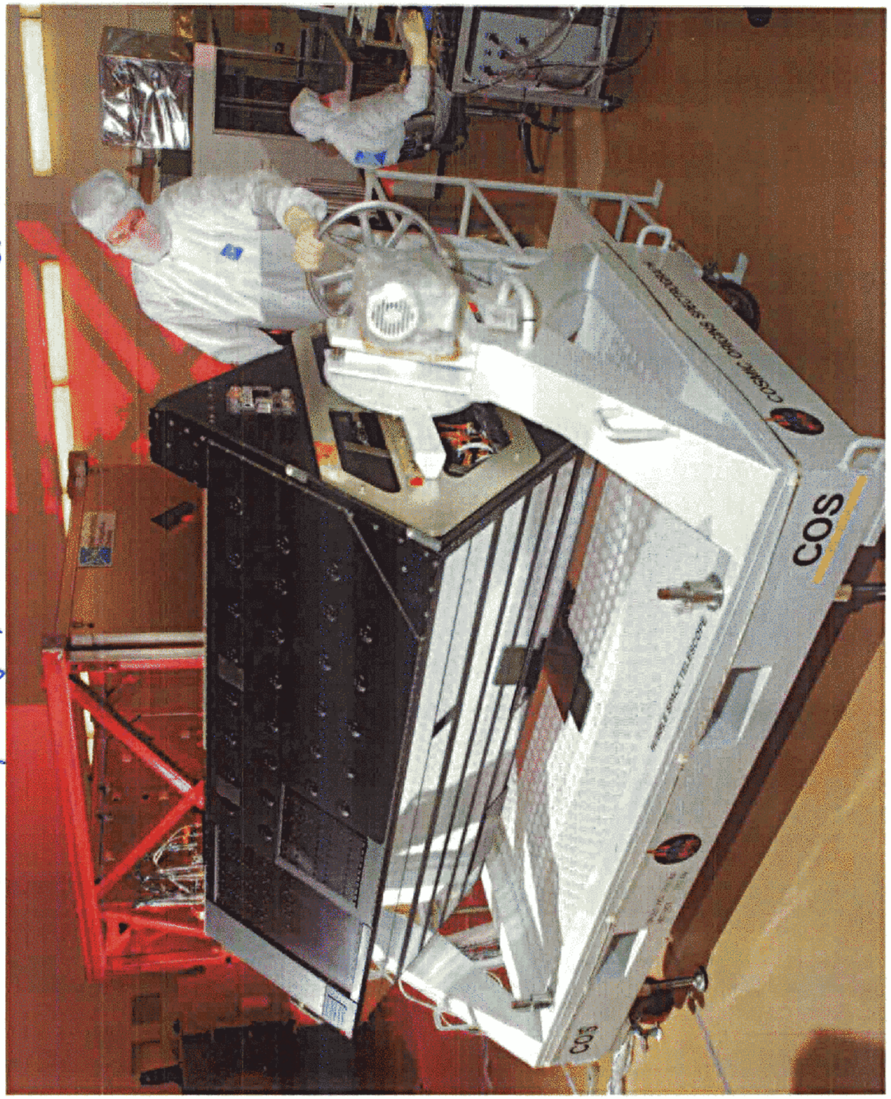

HST/STIS
λ(Å)
1730
1180Å
1200
1300
1400
1500
1600
1700
3×10⁻¹³
2×10⁻¹³
1×10⁻¹³
0
−1×10⁻¹³


FUSE
λ(Å)
1180Å
920Å
950
1000
1050
1100
1150
2.0×10⁻¹³
1.5×10⁻¹³
1.0×10⁻¹³
5.0×10⁻¹⁴
0
−5.0×10⁻¹⁴


Scott et al. (2004)
"Composite QSO"
Lyβ OVI
NeVIII+OIV
OIII
Ly series Lyγ
SIV HeII+
NII+
ArI
CIII NIII
Fλ ~ λ^-1.44
Fν ~ ν^-0.56
Relative Flux (Fλ)
0.5
1
1.5
2
2.5
700
800
900
1000
1100
Rest−frame Wavelength (Å)


HST Composite
ν^-1.8
ν^0.6
FUSE Composite
Relative Flux (Fλ)
4
2
1
0.8
0.6
600
700
800
900
1000
Rest−frame Wavelength (Å)

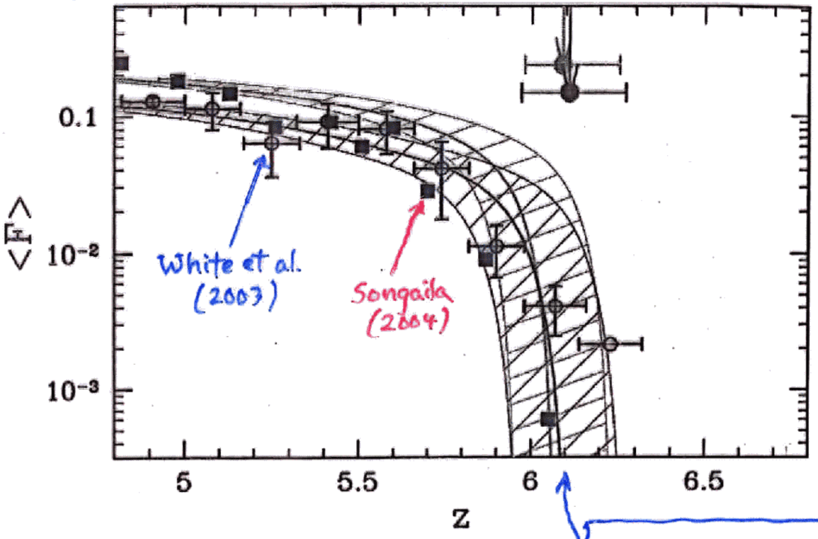
Future UV Spectrograph ? COSMIC ORIGINS SPECTROGRAPH



H^0

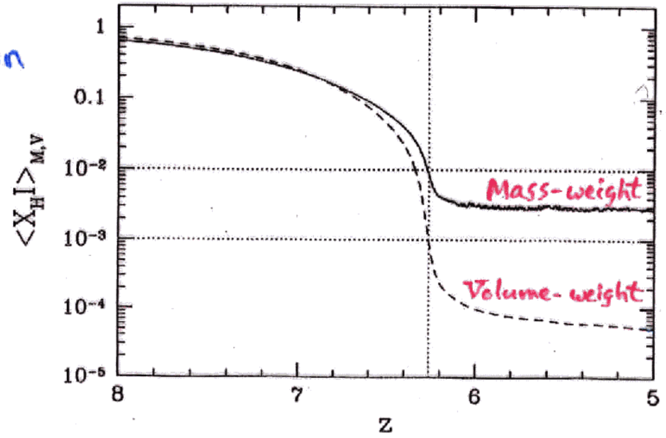
"Reionization"
Gnedin (2004)
ApJ, 610, 9

Transmission

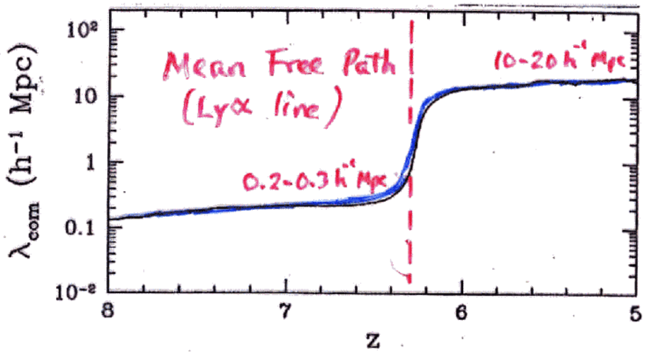


$Z_{reion} = 6.1 \pm 0.3$

Neutral Fraction



Gnedin (2004)

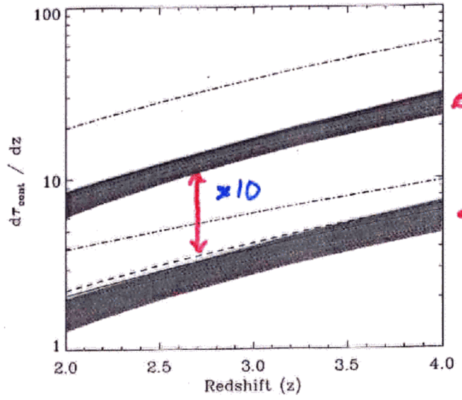


Mean Free Path (Lyα line)

10-20 h^{-1} Mpc

0.2-0.3 h^{-1} Mpc

Fardal, Giroux, & Shull (1998)



4 ryd

He II Opacity (Continuum)

[$d\tau/dz \sim 10 \Rightarrow \Delta z \sim 0.1$] 34 Mpc

1 ryd

H I Opacity (Continuum)

[$d\tau/dz \sim 2 \Rightarrow \Delta z \sim 0.5$] 180 Mpc

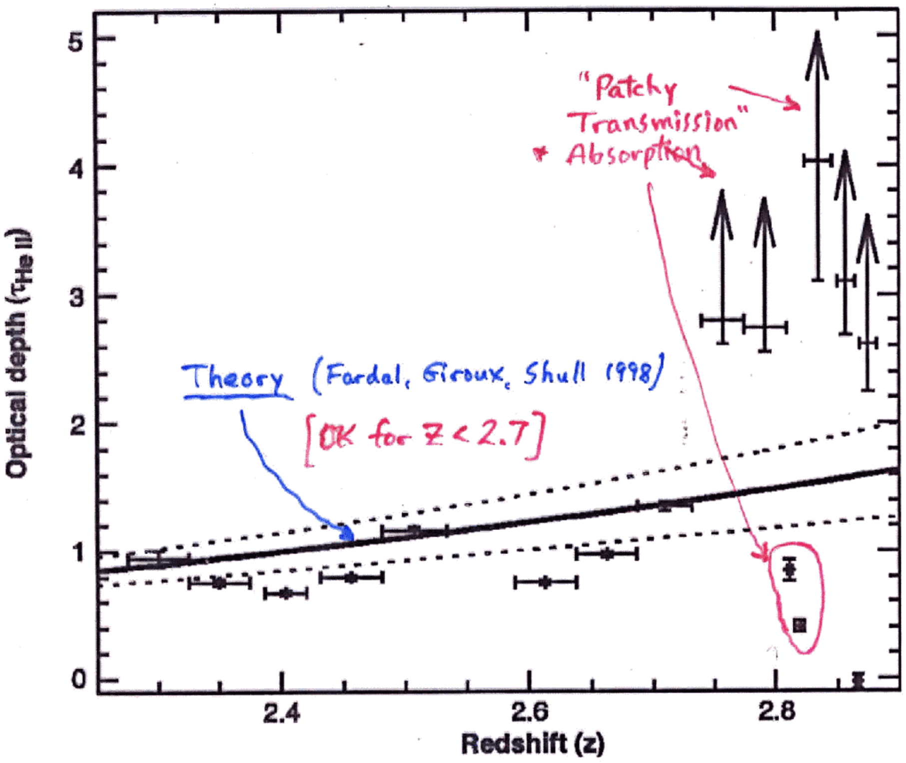
He II opacity >> H I opacity

He$^+$ optical depth

[HE 2347-4342]

Kriss et al. 2001
Science 293, 1112

$Z_{em} = 2.885$, $V = 16.1$ (Reimers et al. 1997)



"Patchy Transmission" + Absorption

Theory (Fardal, Giroux, Shull 1998)

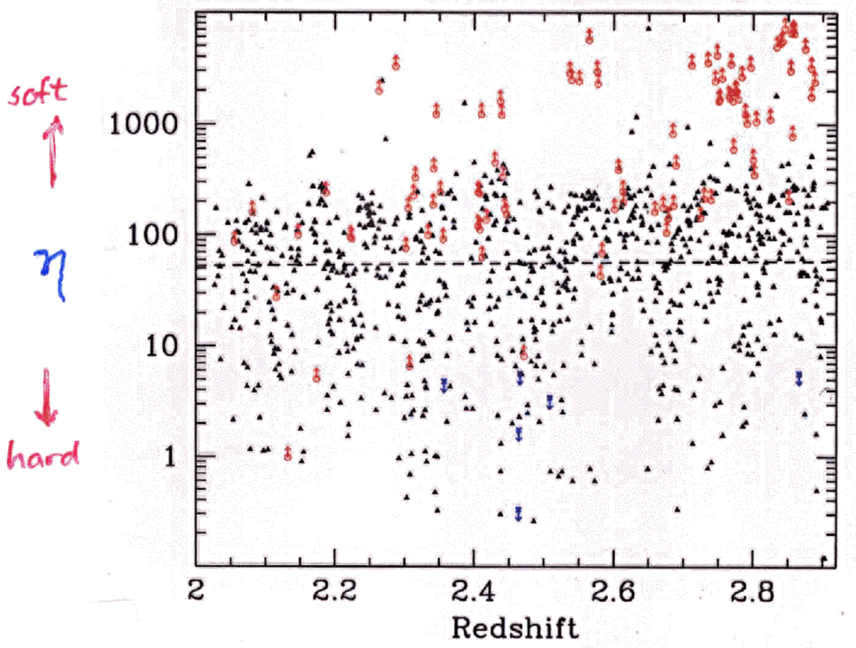
[OK for z < 2.7]

$$\eta = \frac{n_{\rm He\,III}}{n_{\rm H\,II}} \frac{\alpha^{(A)}_{\rm He\,II}}{\alpha^{(A)}_{\rm H\,I}} \frac{\Gamma_{\rm H\,I}}{\Gamma_{\rm He\,II}} \approx (1.70) \overset{4^{+\alpha_{\rm eff}}}{\boxed{\frac{J_{\rm H\,I}}{J_{\rm He\,II}}}} \frac{(3+\alpha_4)}{(3+\alpha_1)} T_{4.3}^{0.055}.$$

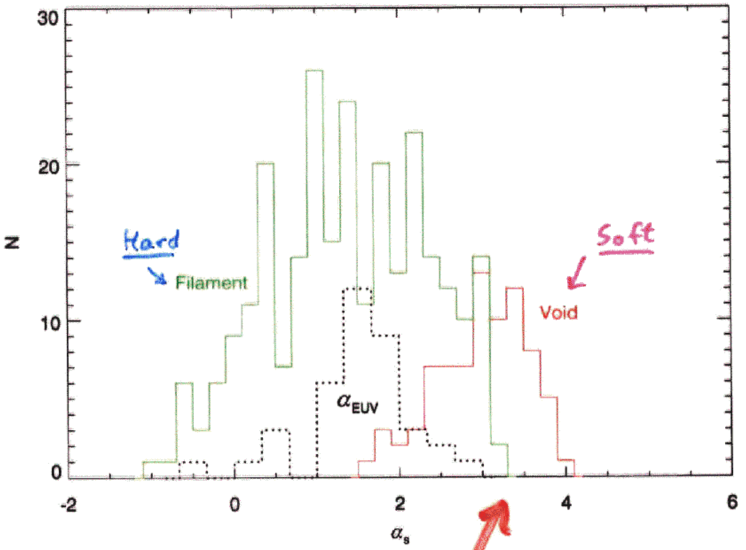
$$\boxed{\eta \equiv \frac{N({\rm He\,II})}{N({\rm H\,I})}}$$

Shull et al. (2004) ApJ

Zheng et al (2004) ApJ



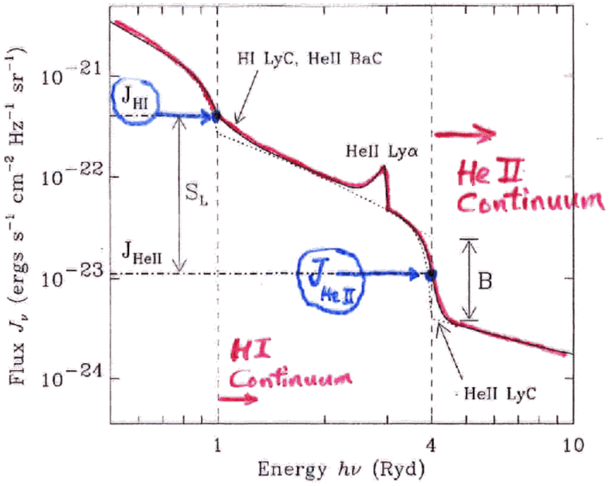
He II / H I toward HE 2347-4342 (FUSE + VLT)



Higher η (soft ioniz sources) in voids

- Not Pop III stars (η~10)
- Probably RT effect + AGN (clumpy IGM)

Metagalactic Ionizing Background



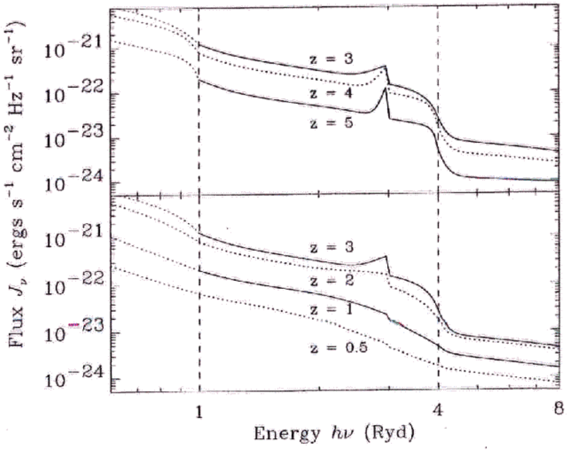


FIG. 7.—Evolution of the ionizing background with redshift, assuming quasar model Q2 with spectral index $\alpha_s = 2.1$ and absorption model A2. *Top*, $3 \le z \le 5$; *bottom*, $0.5 \le z \le 3$. See discussion in § 3.

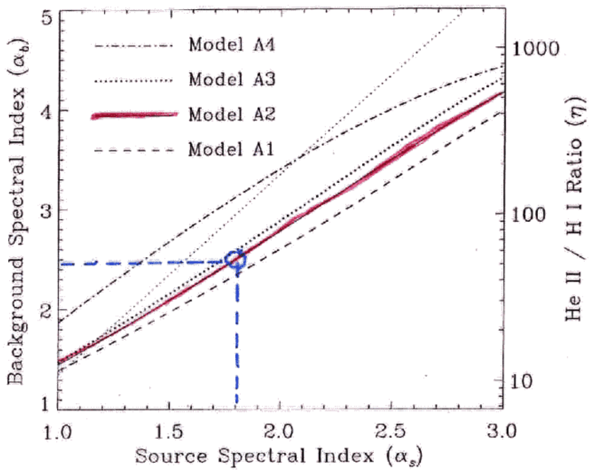


FIG. 10.—Dependence of the background spectral index α_b upon the intrinsic spectral index α_s of ionizing sources, for the four opacity models in the text, for quasar model Q1 and $z = 3$. The light dotted curve shows the analytic model, $\alpha_b = 2.0\alpha_s - 0.64$, of § 2.2. It is somewhat steeper than the numerical models, partly because it ignores the finite-density effects that affect models with soft spectra.

ApJ, 615, ~~in press~~ 135

A Composite Extreme Ultraviolet QSO Spectrum from *FUSE*

Jennifer E. Scott[1], Gerard A. Kriss[1,2], Michael Brotherton[3], Richard F. Green[4], John Hutchings[5], J. Michael Shull[6], & Wei Zheng[2]

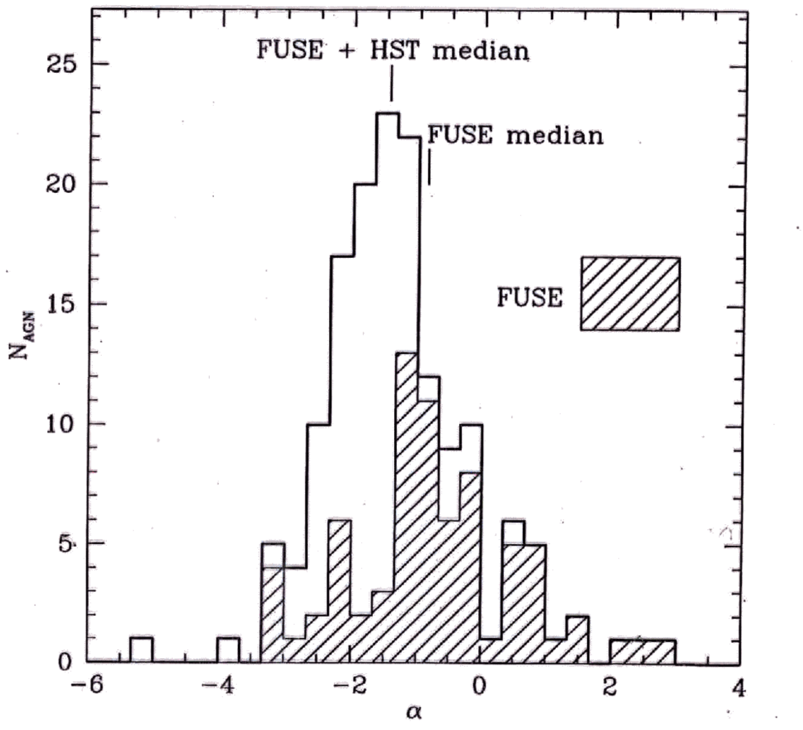
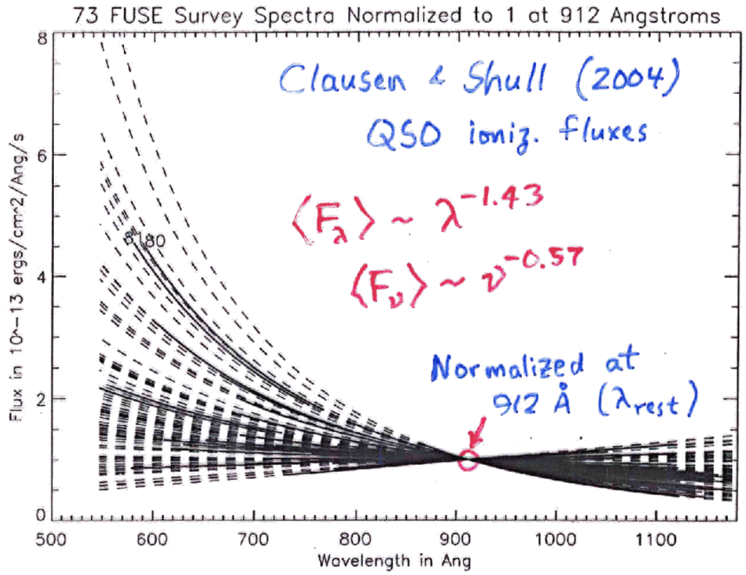


Fig. 12.— Histogram of EUV spectral slopes in *FUSE* sample and in the combined *FUSE* and *HST* sample.

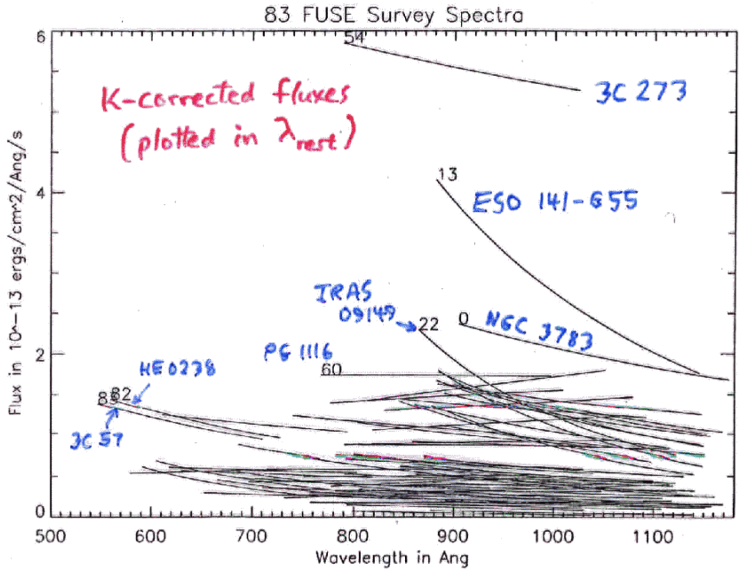


Clausen & Shull (2004)
QSO ioniz. fluxes

$\langle F_\lambda \rangle \sim \lambda^{-1.43}$

$\langle F_\nu \rangle \sim \nu^{-0.57}$

Normalized at 912 Å (λ_{rest})



K-corrected fluxes (plotted in λ_{rest})

3C 273

ESO 141-G55

IRAS 09149

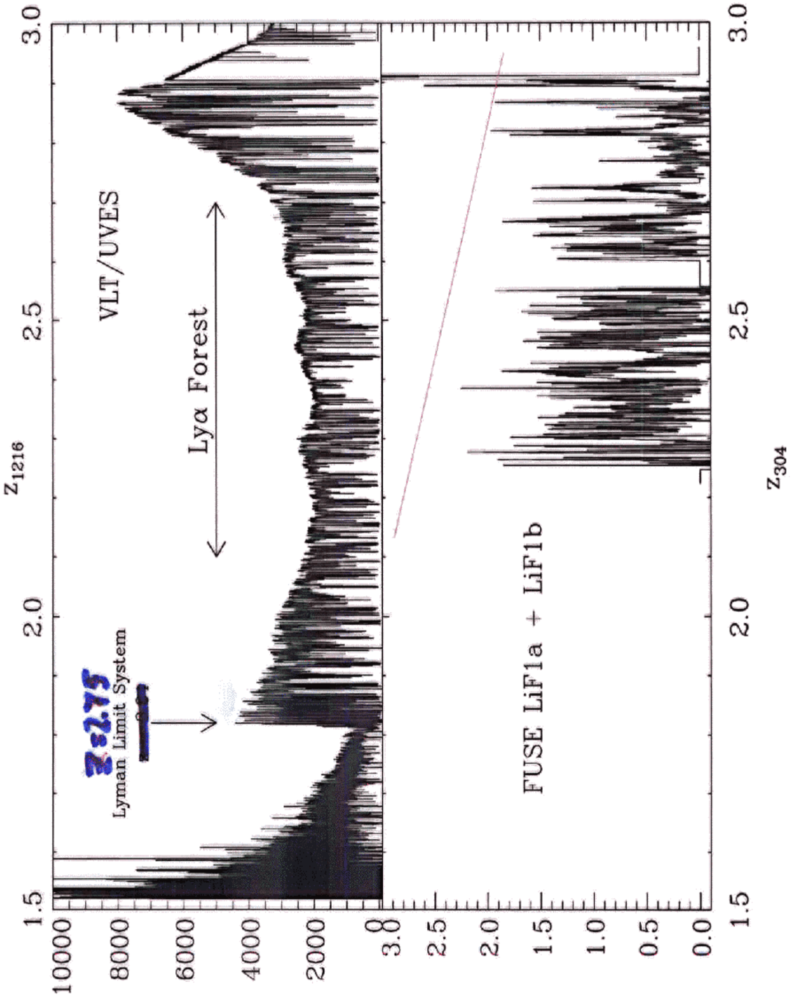
NGC 3783

PG 1116

HE 0238

3C 57

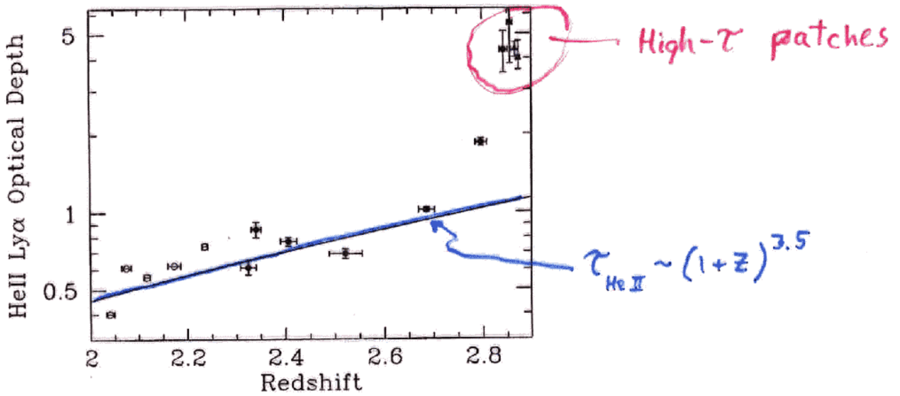
VLT/UVES data (Reimers) on HI Lyα



Shull, Tumlinson, et al. 2002

A STUDY OF THE REIONIZATION HISTORY OF INTERGALACTIC HELIUM WITH *FUSE* AND THE VERY LARGE TELESCOPE[1]

W. Zheng,[2] G. A. Kriss,[2,3] J.-M. Deharveng,[4] W. V. Dixon,[2] J. W. Kruk,[2] J. M. Shull,[5,6] M. L. Giroux,[7]
D. C. Morton,[8] G. M. Williger,[2] S. D. Friedman,[3] and H. W. Moos[2]



High-τ patches

$\tau_{He II} \sim (1+z)^{3.5}$

Fig. 10.—Redshift dependence of the He II Lyα opacity. Values below $z = 2.3$ are derived from a line spectrum reconstructed from the fitted parameters that omit Lyβ and higher order Lyman lines. Between $z = 2.3$ and 2.7 the values are direct measurements from the *FUSE* data, and at $z > 2.7$ they are derived from the observed He II Lyβ absorption region. The curve representing $\tau \propto (1 + z)^{3.5}$ is plotted for comparison.

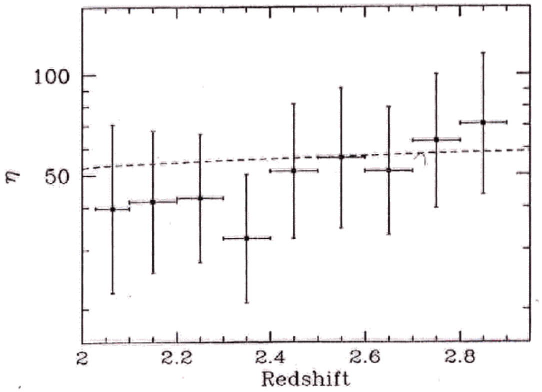
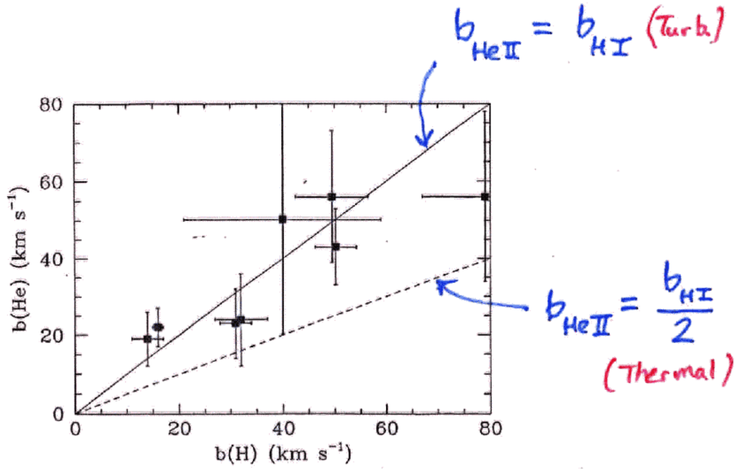


Fig. 8.—Column density ratio η vs. redshift. The average η-value is calculated from the components that are detected in both the *FUSE* and VLT spectra. The dashed curve represents the anticipated values if the ionizing sources are quasars with an EUV power law of $f_\nu \propto \nu^{-1.7}$, which are interpolated from results of Fardal et al. (1998).

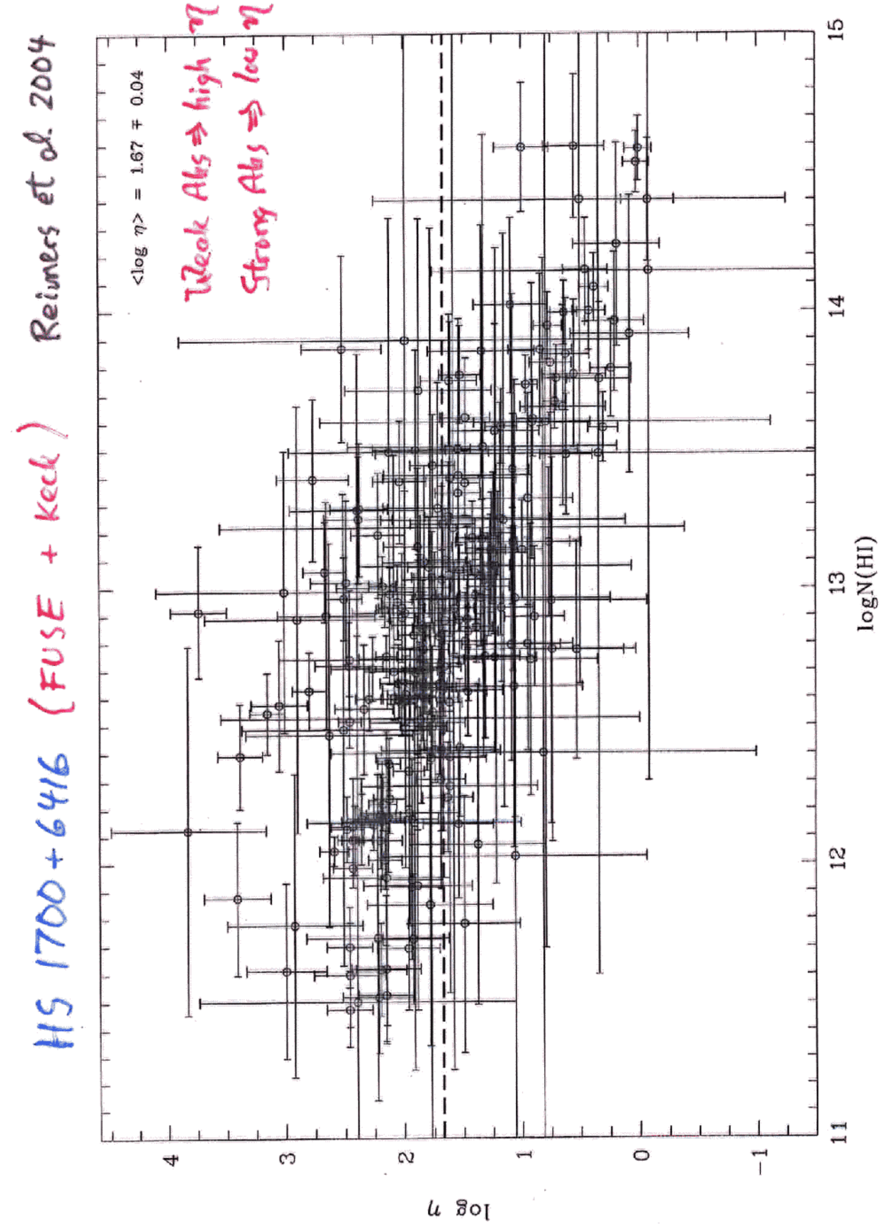


$b_{HeII} = b_{HI}$ (Turb.)

$b_{HeII} = \frac{b_{HI}}{2}$ (Thermal)

Fig. 6.—Doppler parameters for hydrogen and helium absorbers. The solid line stands for expected values with turbulence line-broadening, and the dashed line stands for thermal broadening.

best-fit: $b_{HeII} = (0.95 \pm 0.12)\, b_{HI}$



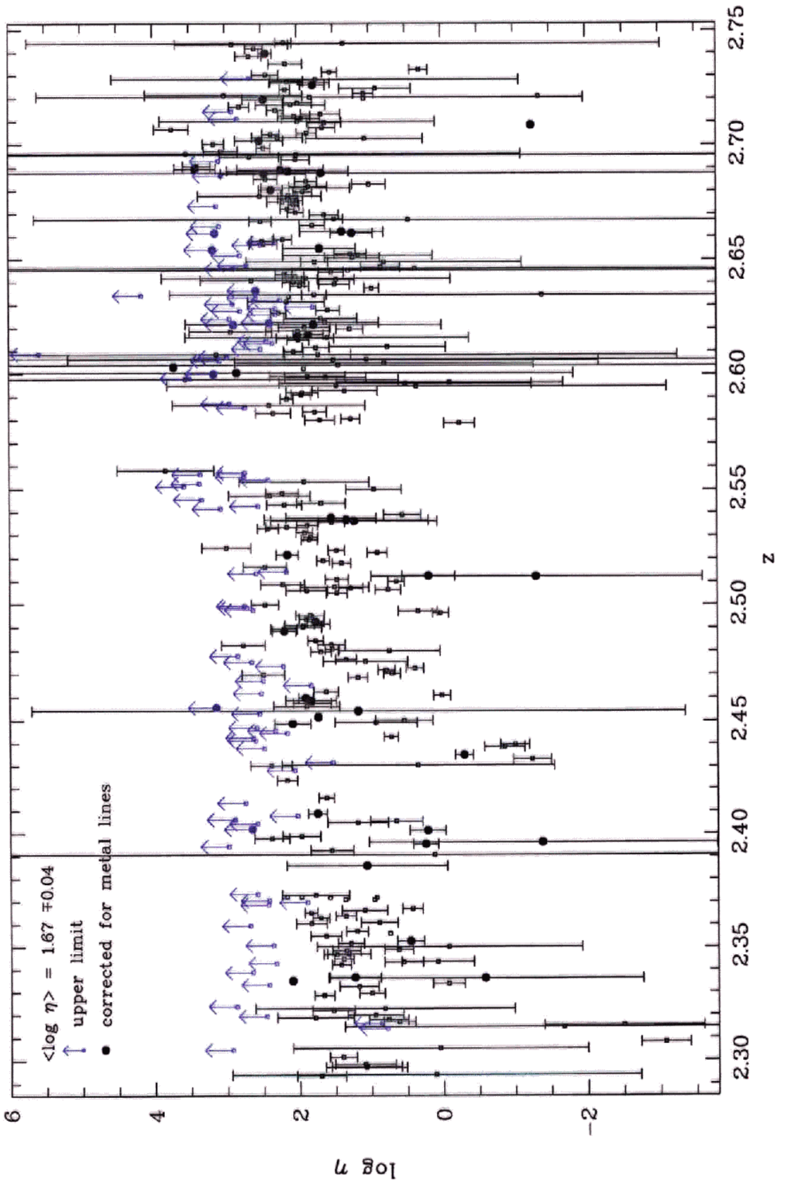
Reimers et al. 2004

HS 1700+6416 (FUSE + Keck)

Weak Abs ⇒ high η

Strong Abs ⇒ low η

$\langle \log \eta \rangle = 1.67 \pm 0.04 \quad (\bar{\eta} = 47)$



WMAP [Kogut et al ; Spergel et al 2003]

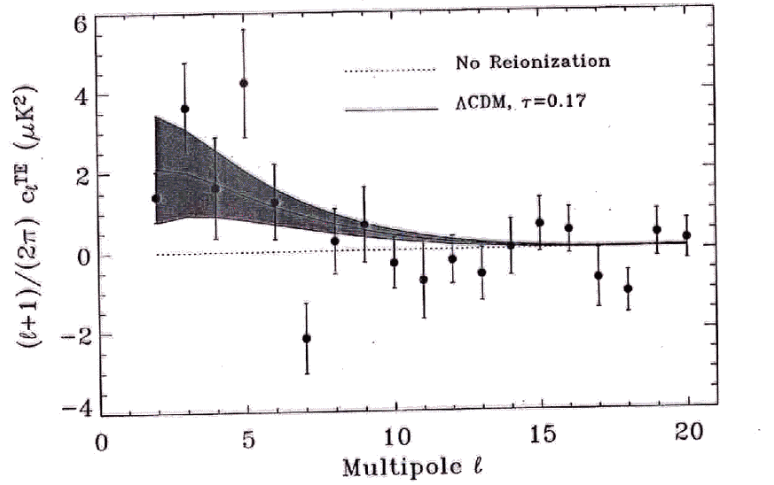
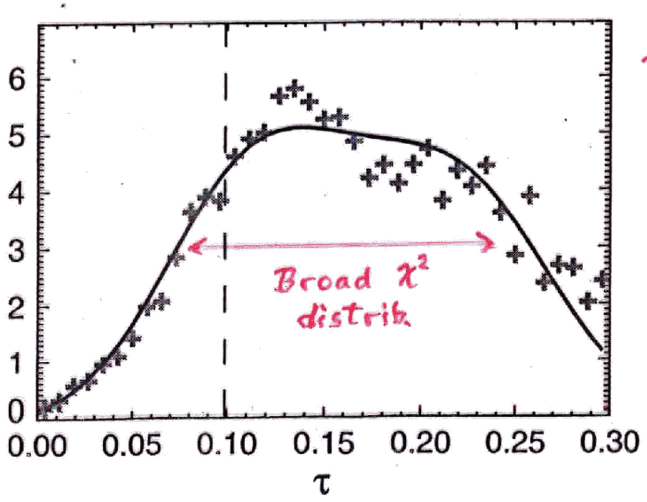


Fig. 8.— *WMAP* Polarization cross-power spectra c_l^{TE} (filled circles) compared to ΛCDM models with and without reionization. The rise in power for $l < 10$ is consistent with reionization optical depth $\tau = 0.17 \pm 0.04$. The error bars on *WMAP* data reflect measurement errors only; adjacent points are slightly anti-correlated. The grey band shows the 68% confidence interval from cosmic variance. The value at $l = 7$ is particularly sensitive to the foreground correction.



$\tau_e = 0.17$
± 0.04

WMAP+ Sloan:

$\tau_e = 0.12^{+0.09}_{-0.06}$

(Tegmark
et al 2004)

CMB Optical Depth

$$\tau_e = \int_0^{z_r} n_e \sigma_T \left(\frac{d\ell}{dz}\right) dz$$

$$\begin{aligned}\tau_e &= \left(\frac{c}{H_0}\right)\left(\frac{2\Omega_b}{3\Omega_m}\right)\left[\frac{\rho_{\rm cr}(1-Y)(1+y)\sigma_T}{m_H}\right]\left[\{\Omega_m(1+z_r)^3+\Omega_\Lambda\}^{1/2}-1\right] \\ &\approx (0.0376h)\left(\frac{\Omega_b}{\Omega_m}\right)\left[\{\Omega_m(1+z_r)^3+\Omega_\Lambda\}^{1/2}-1\right] .\end{aligned}$$

$$\tau_e \approx \left(\frac{c}{H_0}\right)\left(\frac{2\Omega_b}{3\Omega_m}\right)\left[\frac{\rho_{\rm cr}(1-Y)(1+y)\sigma_T}{m_H}\right]\Omega_m^{1/2}(1+z_r)^{3/2} \approx \boxed{(0.00229)(1+z_r)^{3/2}},$$

$$\Omega_b h^2 = 0.0224 \pm 0.0009$$

$$\Omega_m h^2 = 0.135^{+0.008}_{-0.009} \qquad (\Omega_m + \Omega_\Lambda = 1)$$

$$Y_{He} = 0.244 \qquad \text{(by mass)}$$

$$y_{He} = 0.0807 \qquad \text{(by number)}$$

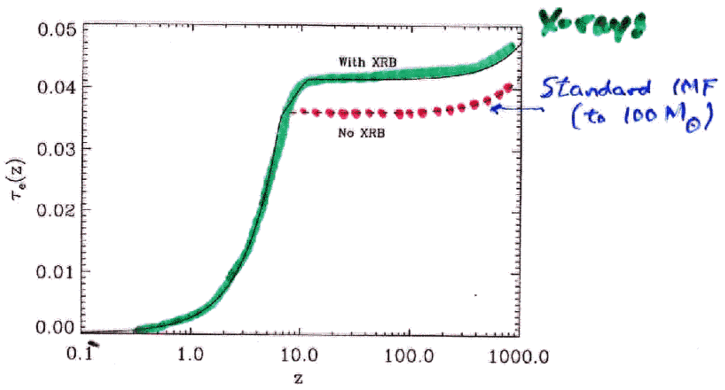
$$\boxed{(1+z_r) \approx (14.0)\left[\frac{\tau_e}{0.12}\right]^{2/3}}$$

Tegmark et al '04

WMAP + Sloan

EXTENDED/PARTIAL/DOUBLE REIONIZATION

1. X-rays from Massive and Mini-QSOs



$$\tau_e \approx 0.04 - 0.05 \quad \text{(Standard IMF)}$$

$$\approx 0.10 \quad \text{(High-Mass, Pop III stars)}$$

Venkatesan, Giroux & Shull 2001: X-rays can cause significant preheating – up to 10^4 K – and partial ionization – up to 20% – prior to full reionization.

Residual electrons (freeze out from decoupling)

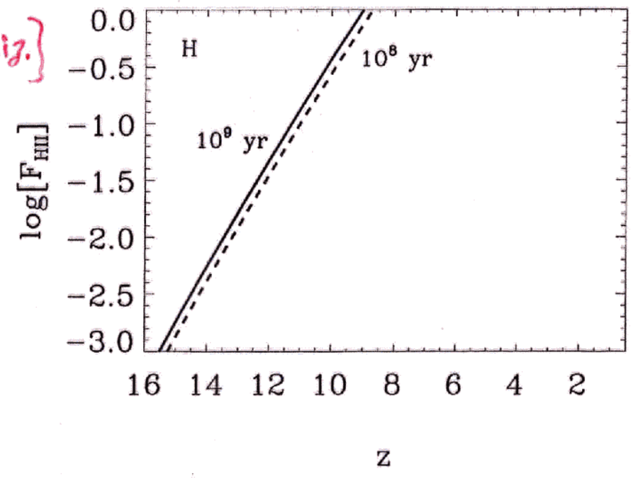
$$X_e \approx 10^{-3.3} \qquad \text{(Seager et al. 2000)}$$

$$\rightarrow \Delta\tau_e \approx (0.012)\left[\frac{1+z_r}{500}\right]^{3/2}$$

VENKATESAN, TUMLINSON, & SHULL

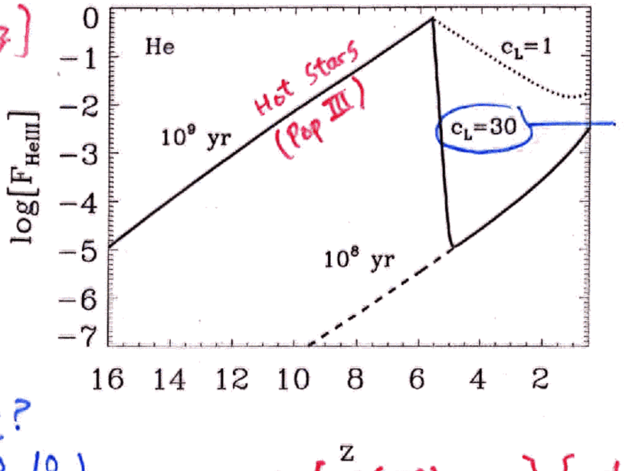
ApJ 584, 621 (2003)

[H reioniz.]



"Double Reionization"?

[He^+ reioniz]



clumping factor

$$\frac{\langle n_e^2\rangle^{1/2}}{\langle n_e\rangle}$$

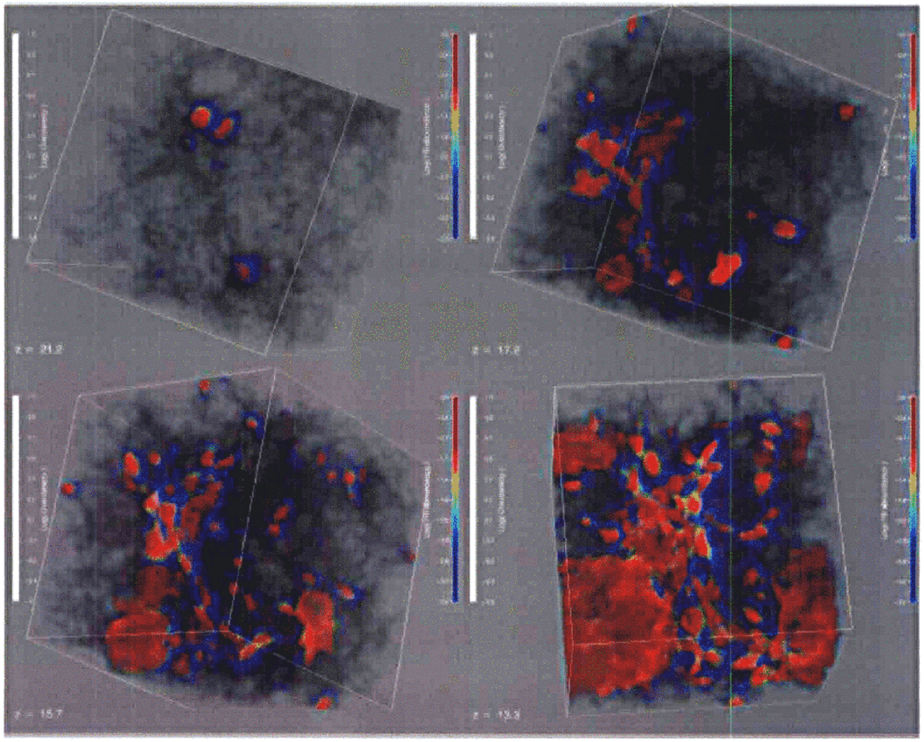
Metallicity?

$$Z_m \equiv \frac{(\rho_m/\rho_H)_{IGM}}{(\rho_m/\rho_H)_\odot} \approx (10^{-4})\left[\frac{\rho(SFR)}{0.1\ M_\odot\ yr^{-1}\ Mpc^{-3}}\right]\left[\frac{t}{10^8\ yr}\right]$$

Ionization Fronts (First Starbursts)

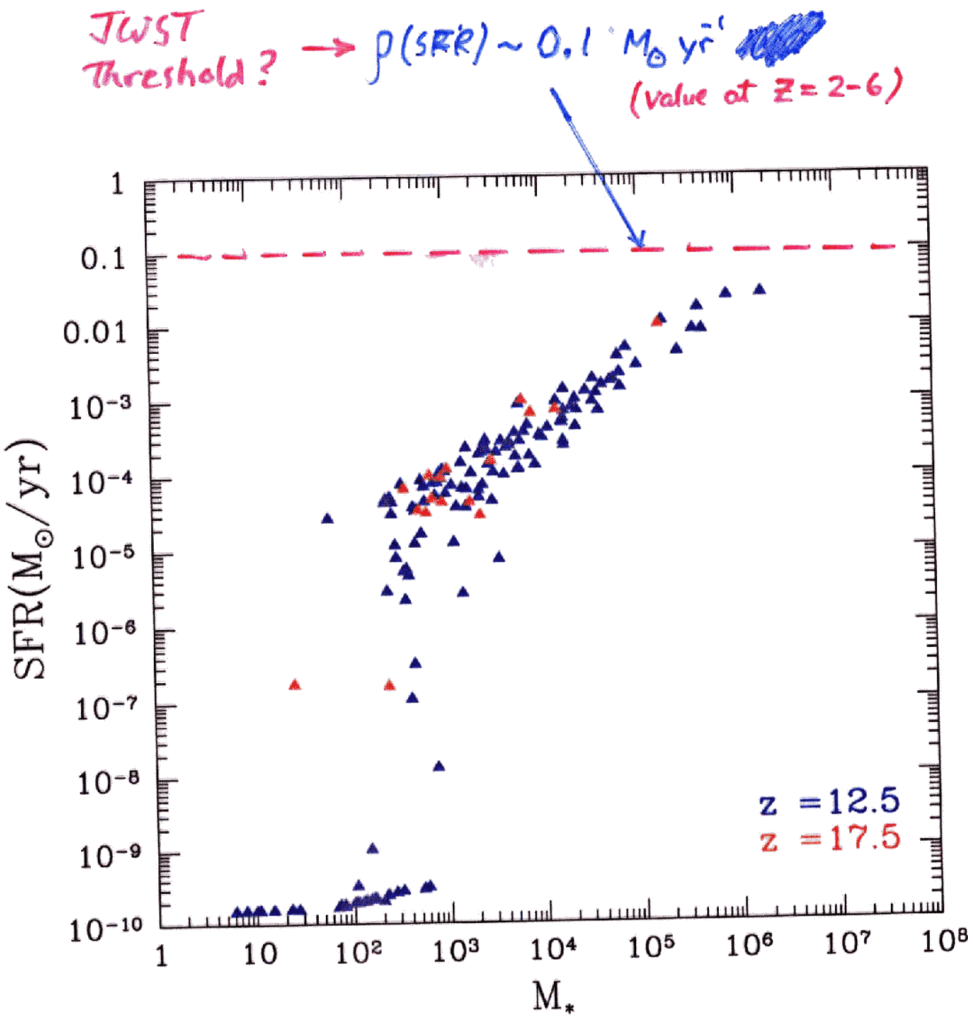
($z \approx$ 10-20)

Ricotti et al. (2002) ApJ, 575, 49



Z = 15.7

Z = 13.3



JWST Threshold? → $\rho(SFR) \sim 0.1 \; M_\odot \, yr^{-1}$

(value at $z = 2-6$)