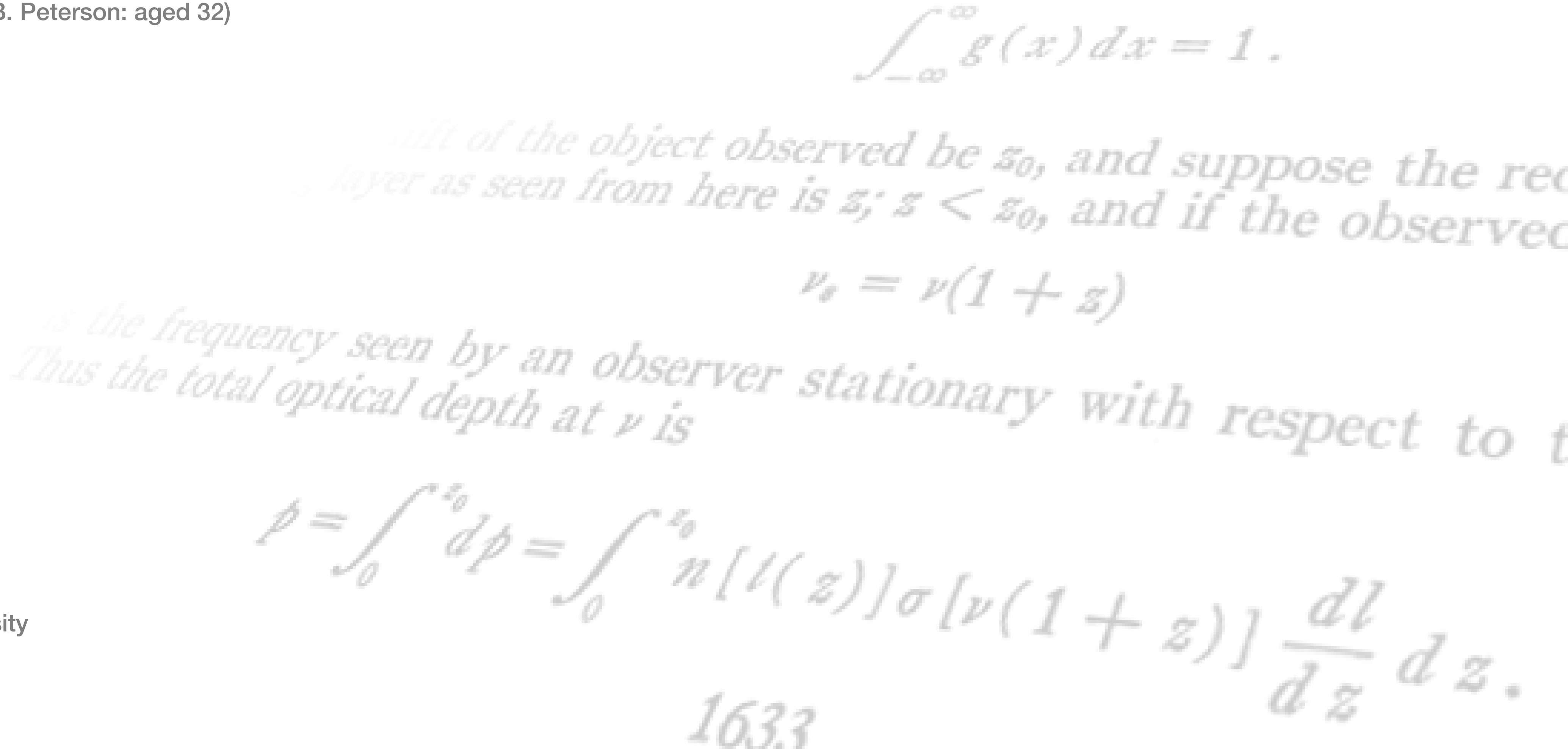
“On the Density of Neutral Hydrogen in Intergalactic Space”

James **Gunn** (Caltech) and Bruce **Peterson** (Caltech)

1965

(J. Gunn: aged 27; B. Peterson: aged 32)


$\int_{-\infty}^{\infty} g(x)\,dx = 1\,.$

...ift of the object observed be z_0, and suppose the re...
...layer as seen from here is z; $z < z_0$, and if the observe...

$\nu_e = \nu(1+z)$

...is the frequency seen by an observer stationary with respect to t...
Thus the total optical depth at ν is

$p = \int_0^{z_0} dp = \int_0^{z_0} n[l(z)]\sigma[\nu(1+z)]\frac{dl}{dz}dz\,.$

1633

Presenter

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“On the Density of Neutral Hydrogen in Intergalactic Space”

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Preview:

1. G-P Optical Depth: A uniform neutral hydrogen assumption

2. Interpretations on low-z (z=2.01) hydrogen composition (HI or HII)

Introduction - Quasars

- Active Galactic Nucleus (AGN)
- Super Massive BlackHole
- The gas falling towards the quasar releases electromagnetic radiation.
- In 1965, the most distant quasar 3C 9 was only at redshift z=2.01.

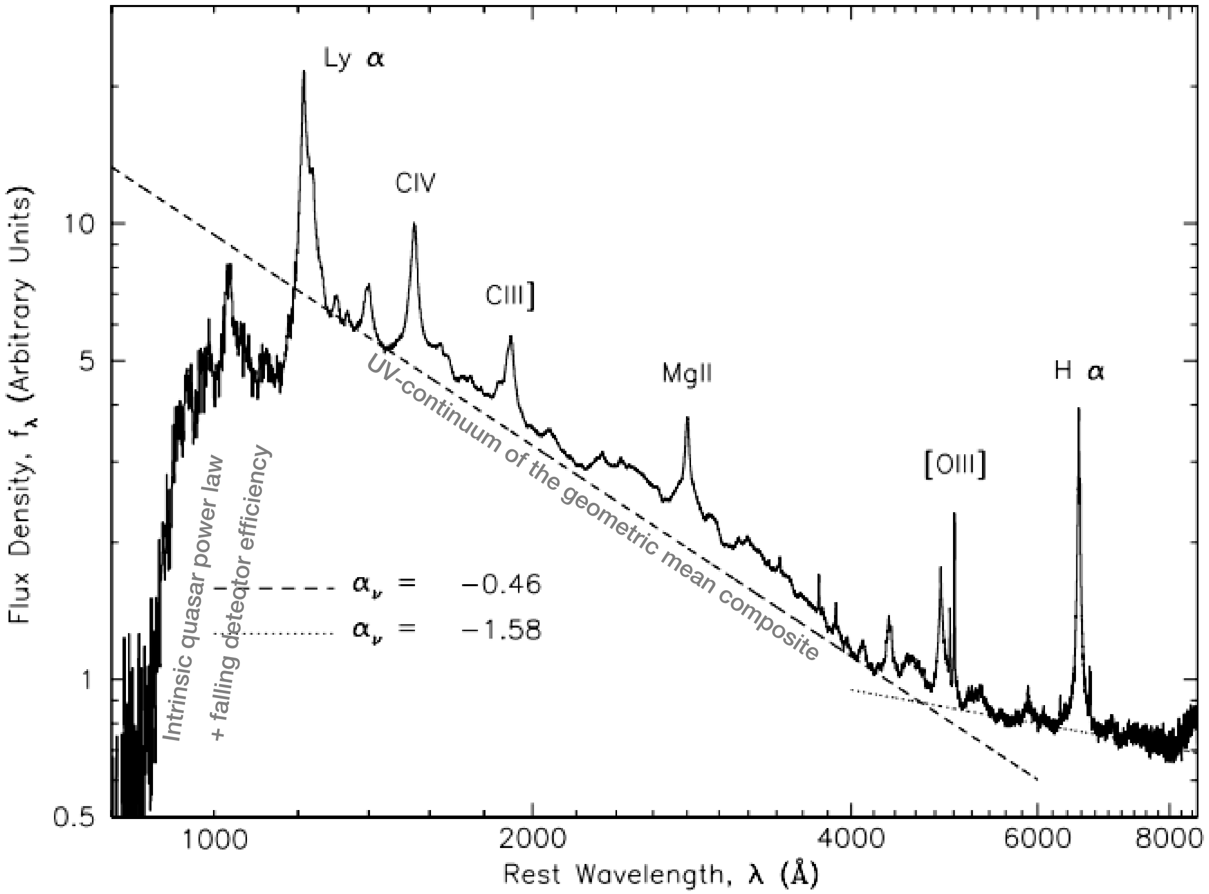
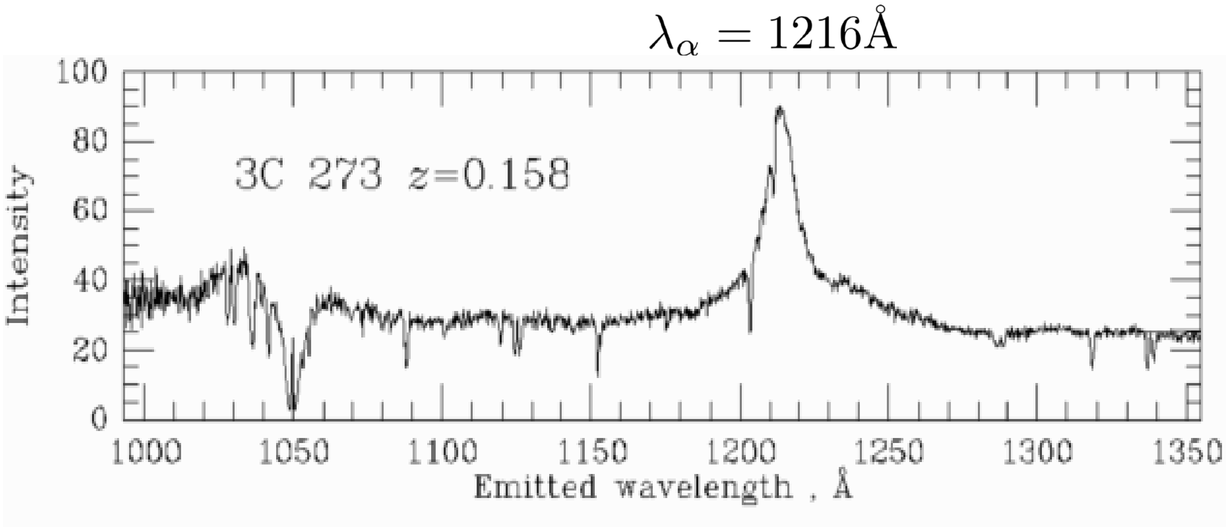


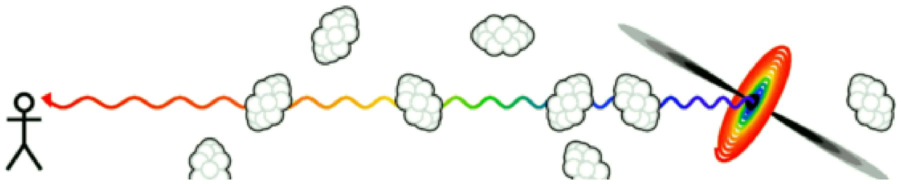
Fig. 3.— Composite quasar spectrum using median combining. Power-law fits to the estimated continuum flux are shown. The resolution of the input spectra is ≈ 1800, which gives a wavelength resolution of about 1Å in the rest frame.

Credits: Vanden Berk et al., 2001, AJ, 122, 549

Introduction – QSO's Spectrum

- Active Galactic Nucleus (AGN)
- Super Massive BlackHole
- The gas falling towards the quasar releases electromagnetic radiation.
- In 1965, the most distant quasar 3C 9 was only at redshift z=2.01.
- The HI (neutral hydrogen) regions along the light-of-sight can show absorption lines blueward $\lambda_\alpha = 1216\text{Å}$ in the spectrum.
- Notice the wings and depths of the absorption lines.





Credits: Bahcall et al., 1991, ApJL, 377, L5; E. Wright (UCLA)

Main Goals of Gunn&Peterson (1965)

1. Study a fate of photons emitted to the blue of $\mathrm{Ly}\alpha$.

2. Assume a uniform HI gas in IGM to calculate an optical depth as a function of redshift.

3. Compare the number density of HI gas derived from the observation of 3C 9 with other works.

4. Analyze an interpretation of HII (ionized hydrogen) at 3C 9 and support based on models and assumptions.

GP Optical Depth

Again, Gunn and Peterson (1965) assumed a uniformly distributed HI (neutral hydrogen) gas at the density of $n_{\rm HI}(z)$ in IGM at redshift z. Do not confuse this redshift of regions absorbing HI, z, with the quasar's redshift $z_{\rm em}$, e.g., $z < z_{\rm em} = 2.01$ for 3C 9. The optical depth is defined as

$$d\tau(z) = n_{\rm HI}(z)\,\sigma(\nu_s(z))\,dl(z), \tag{13}$$

where $\nu_s(z)$ is the frequency of the absorption scattering, with respect to the scattering plane at redshift z. This can be implied from the observed frequency ν by $\nu_s(z) = \nu(1+z)$. The $dl(z)$ and $\sigma(\nu(z))$ terms are read as the tiny length along the line-of-sight and cross-section of radiative excitation for Lyα transition respectively.

GP Optical Depth

Since we have integrated absorption coefficient (See Class Note 16), we can introduce an additional normalized and strongly peaked function $g(\nu - \nu_\alpha)$ at $\nu_\alpha = c/1216\text{Å}$ and rewrite the cross-section

$$\sigma(\nu) = \frac{\pi e^2 f_\alpha}{m_e c} g(\nu - \nu_\alpha), \tag{14}$$

in terms of the electron charge e, the electron mass m_e, the speed of light c, and $f_\alpha = 0.416$ is the oscillator strength of Lyα transition.

Using the scale relation and Hubble parameter at z, $H(z)$ simply rewrite $\mathrm{d}l(z)$ terms into

$$\mathrm{d}l(z) = \left(\frac{\mathrm{d}l}{\mathrm{d}z}\right) \mathrm{d}z = \frac{c\, H(z)^{-1}}{1+z} \mathrm{d}z. \tag{15}$$

GP Optical Depth

Now, taking $n_{\rm HI}(z) = n_{\rm HI}(1+z)^3$ and plugging above equations into the optical depth integrant, we get

$$\tau(z) = \int_0^z \mathrm{d}\tau(z) = \int_0^z \left[n_{\rm HI}(1+z)^3 \frac{\pi e^2 f_\alpha}{m_e c} g(\nu - \nu_\alpha) \frac{c\,H(z)^{-1}}{1+z} \right] \mathrm{d}z = n_{\rm HI} \frac{\pi e^2 f_\alpha}{m_e c} \lambda_\alpha H(z)^{-1}. \tag{16}$$

From a more intuitive perspective,

$$\tau(z) = 1.8 \times 10^5 h^{-1} \Omega_{\rm m}^{-1/2} \left(\frac{\Omega_{\rm b} h^2}{0.02} \right) \left(\frac{1+z}{7} \right)^{3/2} \left\langle \frac{n_{\rm HI}}{n_{\rm H}} \right\rangle . \tag{17}$$

Credits: Fan et al. 2006, AJ, 132, 117

GP Optical Depth

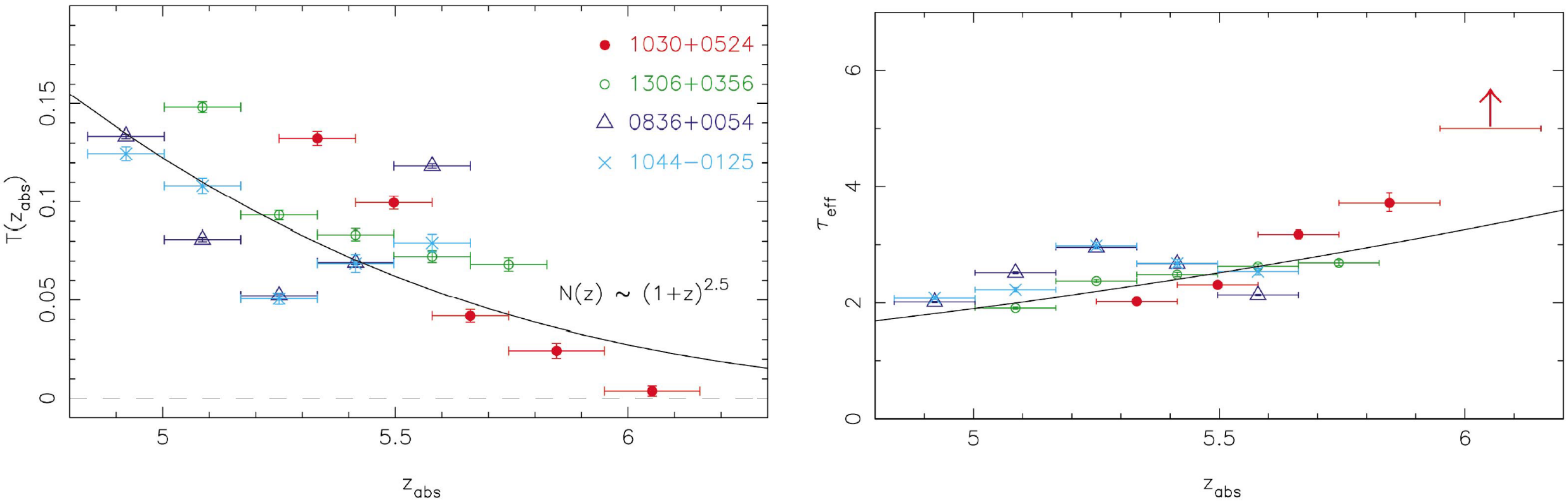


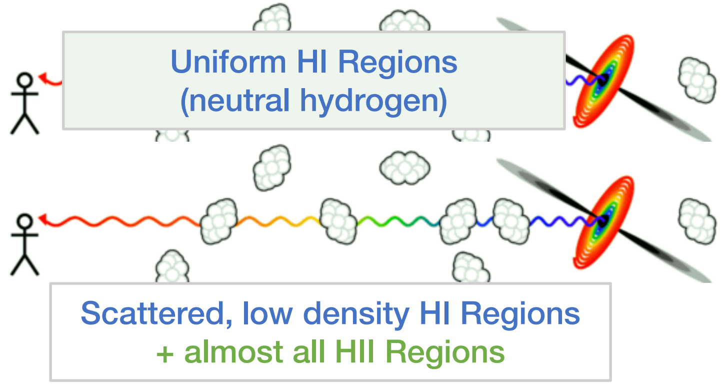
FIG. 2.—Evolution of transmitted flux ratio and effective Gunn-Peterson optical depth as functions of redshift. The solid line is the expected evolution if the number density of Lyα clouds increases as $N(z) \propto (1 + z)^{2.5}$. No flux is detected in the spectrum of SDSS 1030+0524 at $z_{\rm abs} \sim 6$, indicating $\tau_{\rm eff} > 5.0$. The nondetection of flux in the Lyβ trough gives a substantially stronger 1 σ upper limit of $\tau_{\rm eff} > 20$.

Credits: Becker et al., 2001, AJ, 122, 2850

HI Density from Quasar 3C 9

- The blueward flux of 3C 9 (z=2.01) component and the wing of the line are noticeably depressed about 40%.
- It corresponds to an optical depth of about $\tau(z=2.01)=\frac{1}{2}$.
- Field (1962) derived a $\rho_{\mathrm{HI}} \sim 10^{-29}\ \mathrm{g\ cm^{-3}}$ from the 21cm hydrogen observation.
- For the $q_0=0.5$, $\Omega_{\mathrm{m}}=1$ model,
  - The mass density of neutral hydrogen is $\rho_{\mathrm{HI}}=1\times10^{-34}\ \mathrm{g\ cm^{-3}}$. Much smaller than Field (1962).
  - The total density is $\rho_{\mathrm{total}}=5\times10^{-28}\ \mathrm{g\ cm^{-3}}$.
  - Thus, only about $\Omega_{\mathrm{HI}}(z=2.01):=\rho_{\mathrm{HI}}/\rho_{\mathrm{total}}=\boxed{2\times10^{-7}}$ of the total mass at that time could have been in the form of intergalactic neutral hydrogen.
- For the steady-state model ($\Omega_{\mathrm{m}}=1$, creation of matter),
  - $\rho_{\mathrm{HI}}=2\times10^{-35}\ \mathrm{g\ cm^{-3}}$.
  - Constant total density is $4\times10^{-29}\ \mathrm{g\ cm^{-3}}$.
  - the factor here is somewhat less about $\Omega_{\mathrm{HI}}(z=2.01)=\boxed{5\times10^{-7}}$.

HI Density from Quasar 3C 9 - Outcomes



Interpretation:

Either

- the cosmological ideas (in 1960s) are grossly incorrect,
- that space is very nearly empty.

Or,

- the matter (all hydrogen contents) exists in some other form.

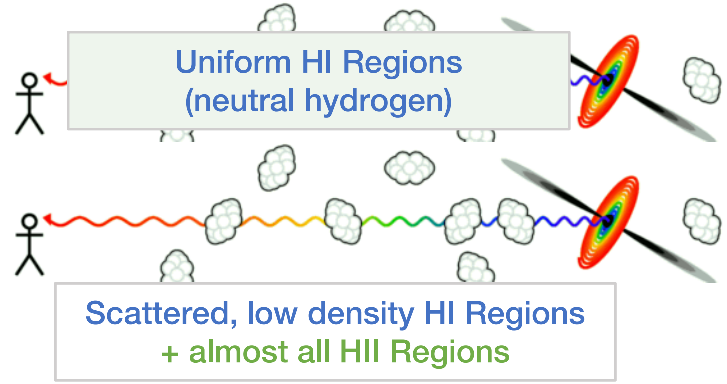
It is possible that this interpretation is still valid but requires essentially all hydrogen is ionized.

If the universe was uniformly neutral at z~2, then HI should strongly absorb the flux.

Hence, the hydrogen gas must be highly ionized so that the flux at wavelengths can go through.

This can be defended if we are allowed to make the intergalactic electron temperature is high enough.

More on Highly Ionized HII

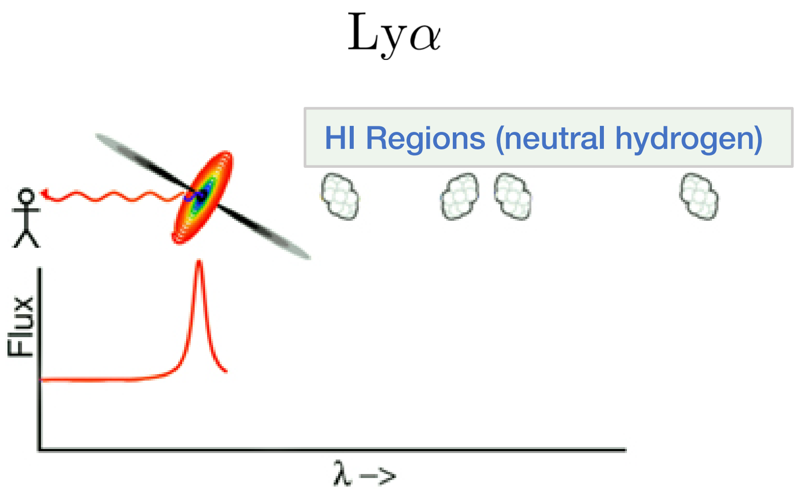


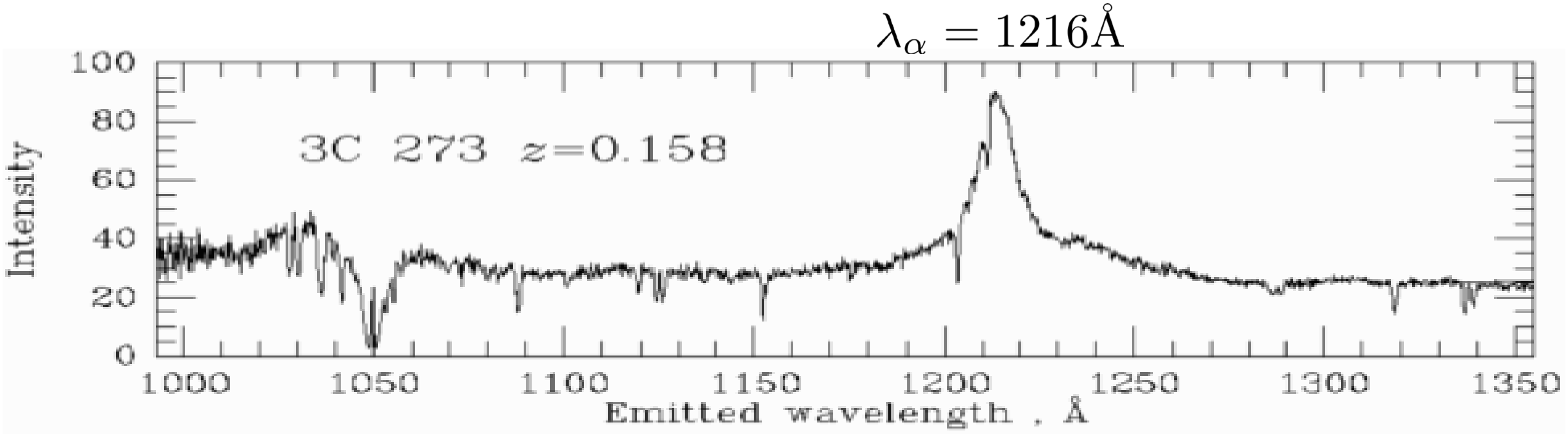
- Mechanism of reionization:
  - Recombination requires a mean time of reionization:

    500 years per hydrogen atom.
  - Collisional reionization: Inadequate (mean lifetime $\sim 10^4 \text{ years}$)
  - Radiative reionization: need a mean intensity $\sim 1.2 \times 10^{20} \text{ erg cm}^{-2} \text{ (c/s)}^{-1} \text{ sec}^{-1} \text{ ster}^{-1}$.
    - Normal galaxies, Radiogalaxies: too low, ~10% from quasars
    - Quasars
    - IGM itself: more promising if $T = 2 \times 10^5 \text{ K}$ at $z = 2$.
  - Ionization is more collisionally-dominant as T goes higher.

A Sidenote - $\mathrm{Ly}\alpha$ Forest

- At low z, HI (neutral hydrogen) is ionized into HII (ionized hydrogen).
- At low z, only small portion of spectrum is absorbed by light-of-sight scattered HI regions.





Credits: E. Wright (UCLA); Bahcall et al., 1991, ApJL, 377, L5

A Sidenote - Gunn-Peterson Trough

- Early Universe (high-z, “dark”):
  - Dense HI region
  - High optical depth
- Late Universe (low-z):
  - Reionization
  - HI region is less dense
  - Higher transparency

Redshift

~1100

HI Regions

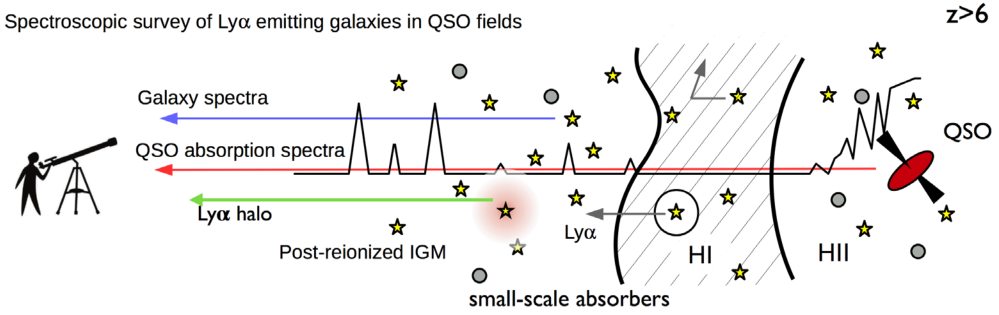
~12

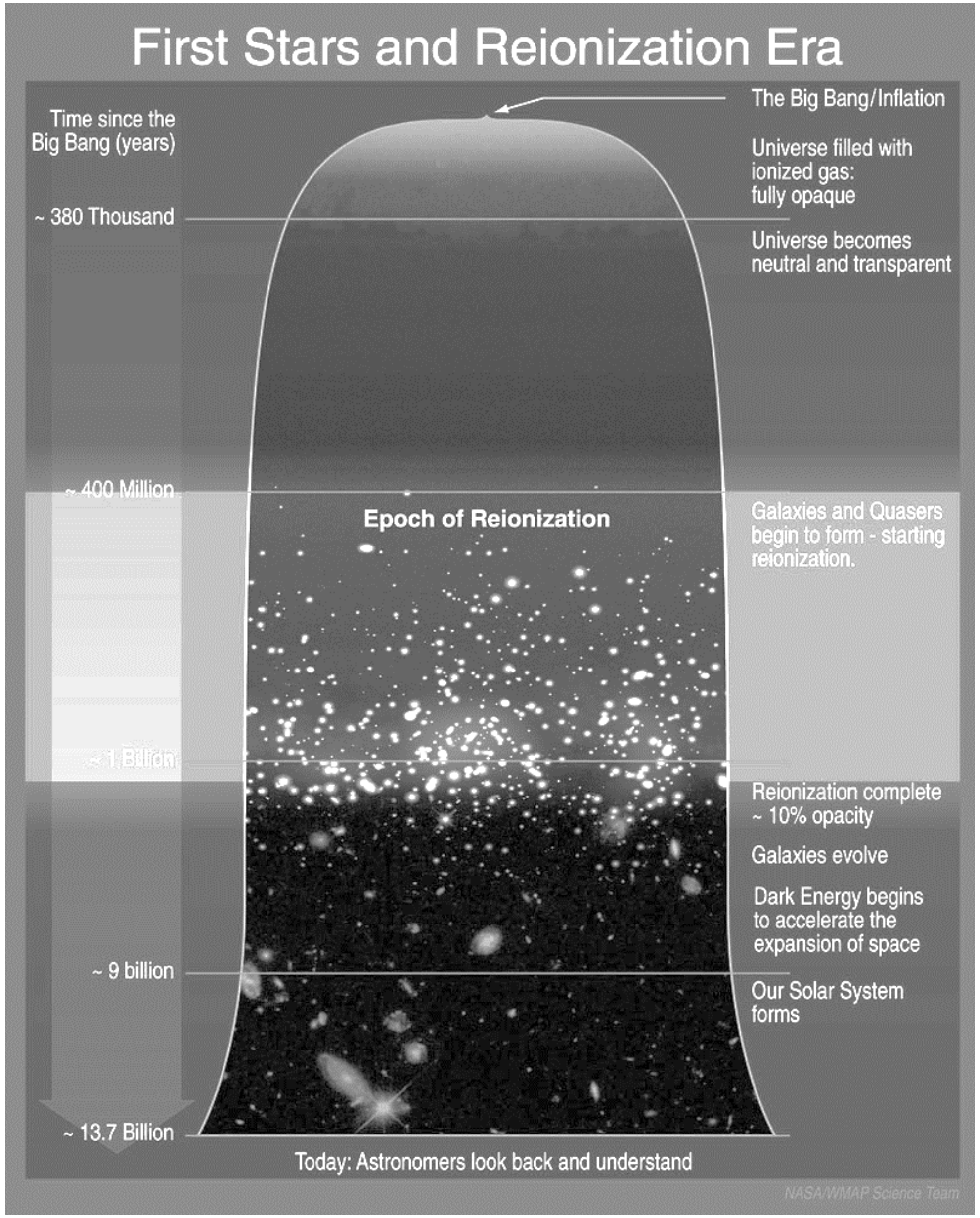
~6

HI Regions
HII Regions

1

0





Credits: Koki Kakiichi (UCL); NASA/WMAP

GP Optical Depth vs. HI Density at High-z

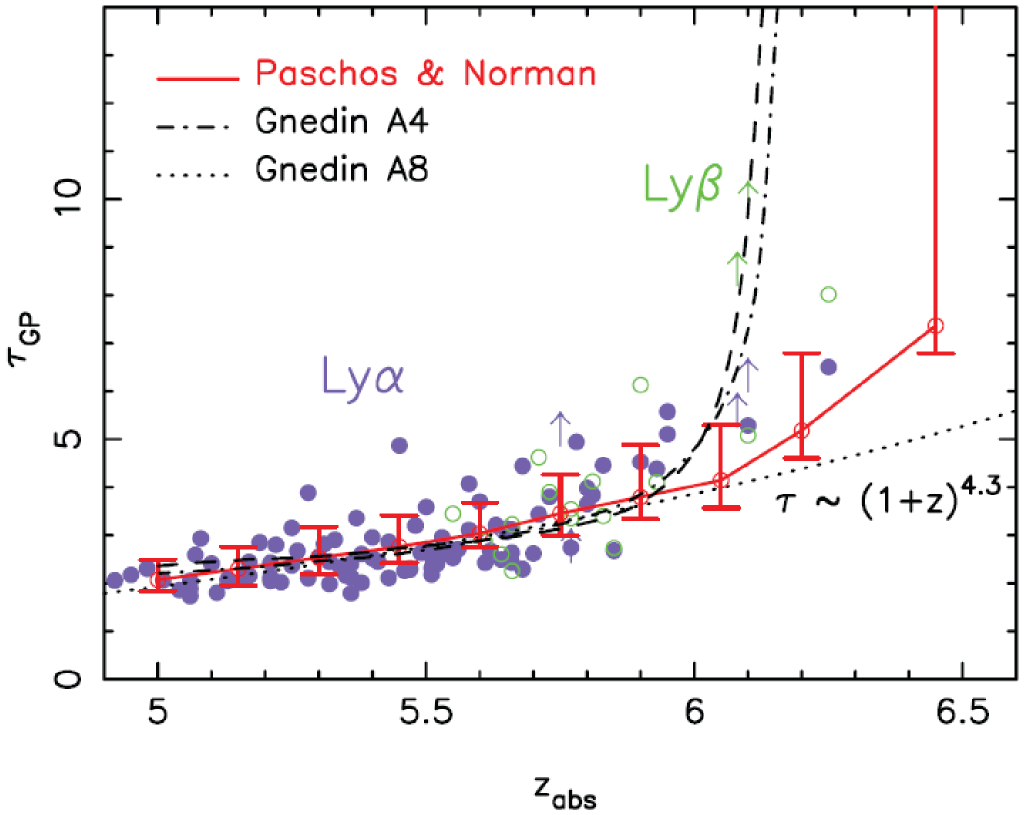
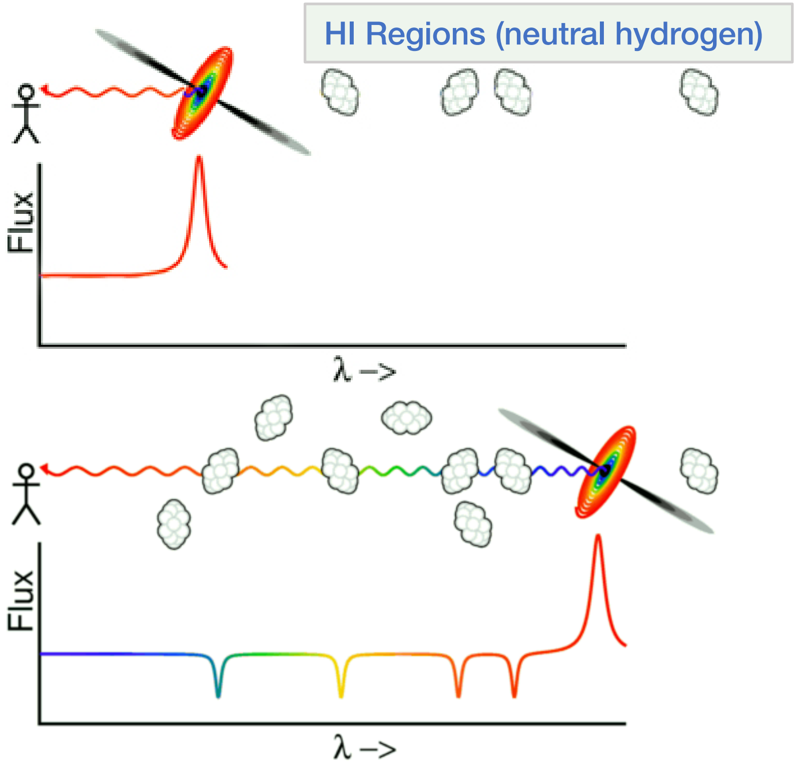


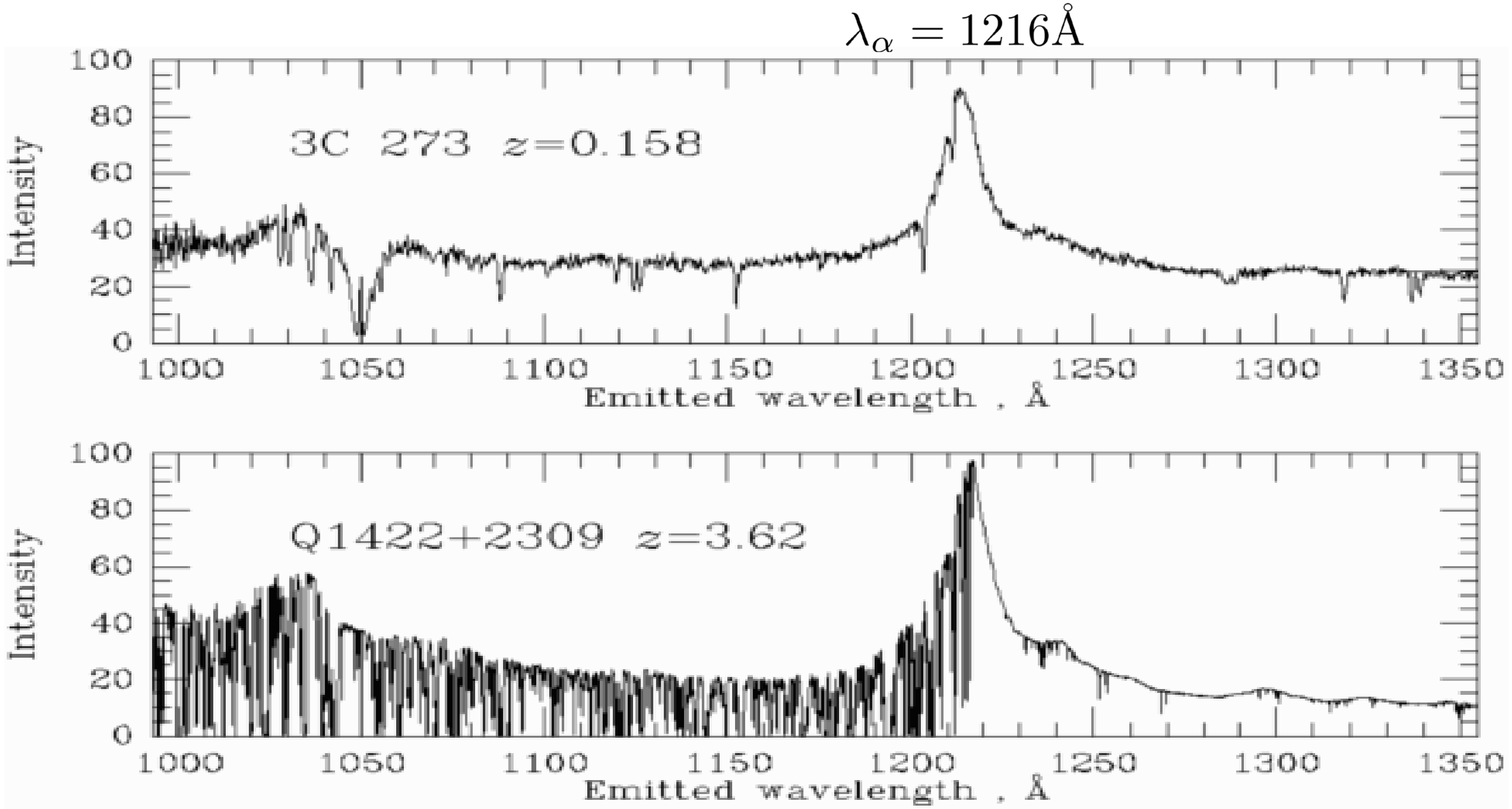
FIG. 9.— Comparison of the evolution of observed GP optical depth with simulations. Data points are the same as in Fig. 5. The dotted line is the power-law fit to the optical depth evolution at $z < 5.5$: $\tau_{GP} \propto (1+z)^{4.3}$. The solid line with error bars is the result from simulations of Paschos & Norman (2005), which have $z_{reion} \sim 7$. The dashed and dot-dashed lines are the 4 and 8 Mpc simulations of Gnedin (2004), respectively, which have $z_{reion} \sim 6.5$. The data points fall between the two simulations but are somewhat closer to those of Gnedin.

Credits: Fan et al. 2006, AJ, 132, 117

A Sidenote - $\mathrm{Ly}\alpha$ Forest

- At low z, HI (neutral hydrogen) is ionized into HII (ionized hydrogen).
- At low z, only small portion of spectrum is absorbed by light-of-sight scattered HI regions.
- As more HI regions appear along line-of-sight, or redshift increases, the radiation from quasars can be scattered: "$\mathrm{Ly}\alpha$ Forest".



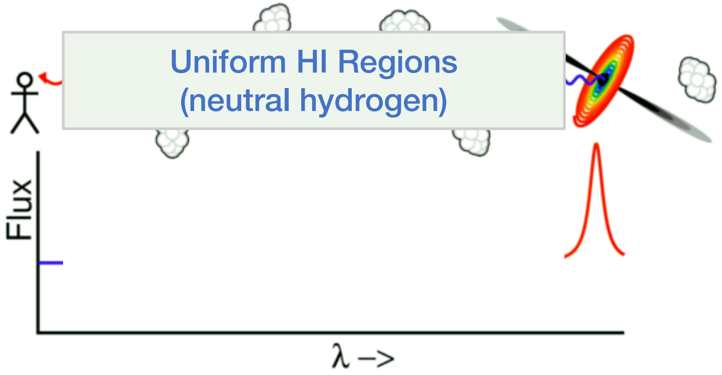


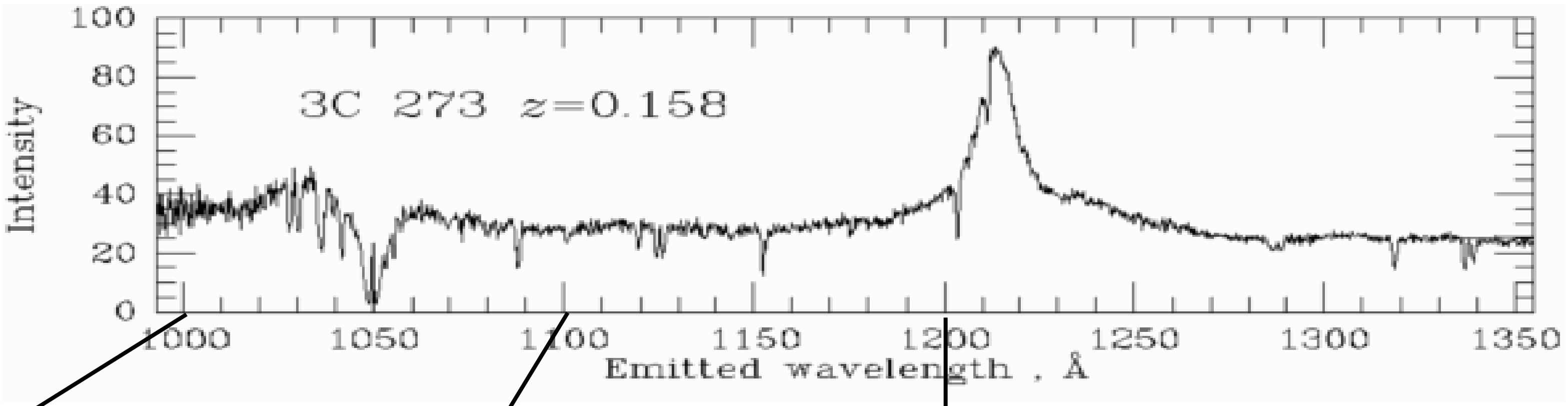
Credits: E. Wright (UCLA); Bahcall et al., 1991, ApJL, 377, L5

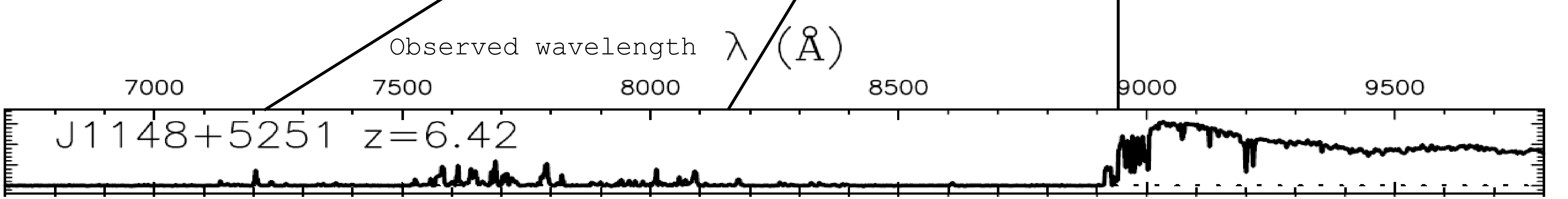
A Sidenote - Gunn-Peterson Trough

- Notice: “ $\mathrm{Ly}\alpha$ Forest” has discrete absorptions since it is not uniform along line-of-sight.
- Assume we have a uniform and optically-thick HI gas in IGM.

  Just on the left of $\lambda_\alpha = 1216\text{Å}$, the forest should turn into a continued absorption (close to zero) dip.







Credits: E. Wright (UCLA); Bahcall et al., 1991, ApJL, 377, L5; Fan et al. 2006, AJ, 132, 117

To myself: When encountering HI, the light passed thru HI will not be zero since it only absorbed some wavelengths’ flux

A Sidenote - Quasars' Spectra Around $z \sim 6$

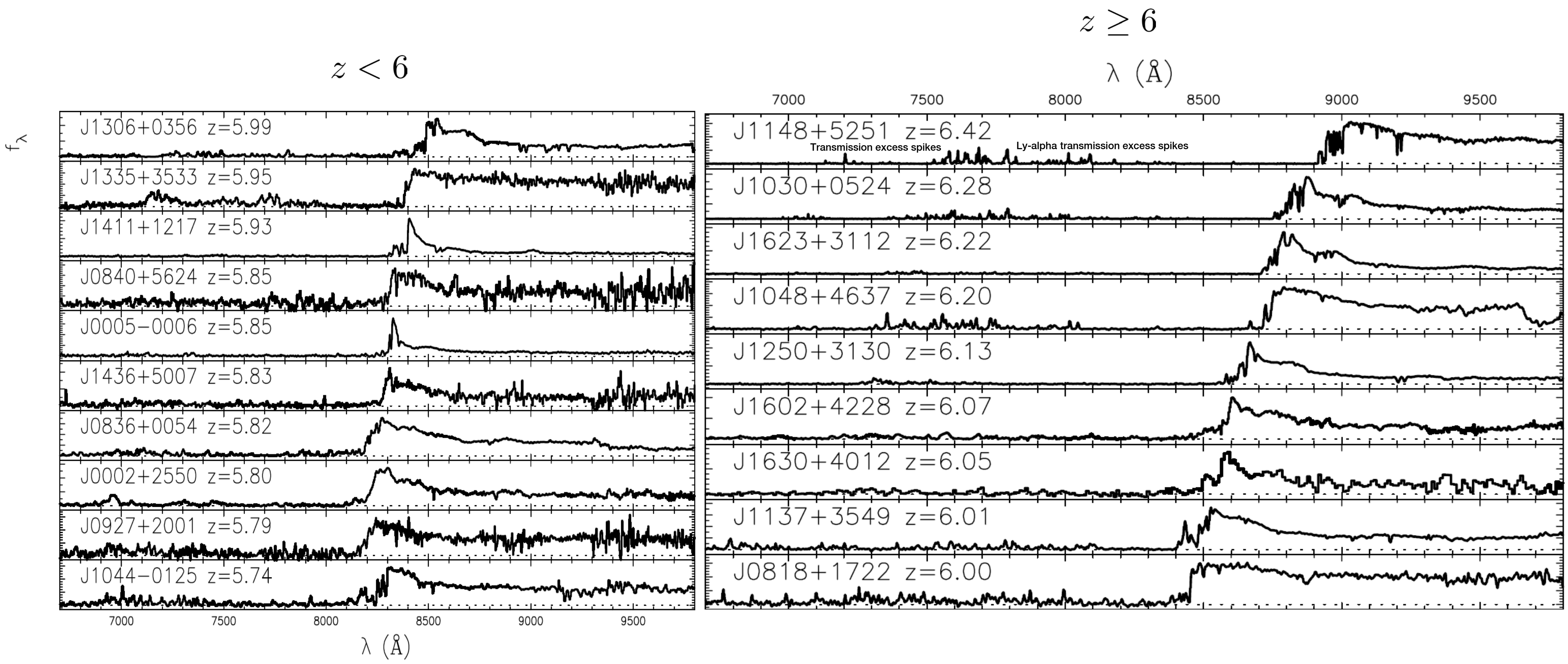


Fig. 1. — Spectra of our sample of 19 SDSS quasars at 5.74 < z < 6.42. Twelve of the spectra were taken with Keck ESI, while the others were observed with the MMT Red Channel and Kitt Peak 4 m MARS spectrographs. See Table 1 for detailed information. (Fan et al., 2006, AJ, 132, 117)

Takeaway

Gunn-Peterson limit provided the first evidence that the universe was reionized by the formation of the first stars and quasars.

Most of the 30 most distant quasars are known in 2000s, which have led to the constraints of the epoch of reionization, predicted 60 years ago by Gunn and Peterson.

References

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Appendix 1: UV Spectral Slope (Power Law)

The ultraviolet part of the emitted light contains information on various facets of the state of the galaxy. The UV continuum between roughly 1250 Å and 2600 Å is commonly parametrized as a power law of the

$$F_\lambda \sim \lambda^{-\alpha}.$$

This parametrization was first introduced by Calzetti et al. (1994) as a means of studying the effects of dust extinction in galaxies, and has later been shown to trace the dust extinction at higher redshifts, as well as being correlated with far-infrared dust emission (see e.g. Finkelstein et al. 2012, Meurer et al. 1999, Reddy et al. 2012).