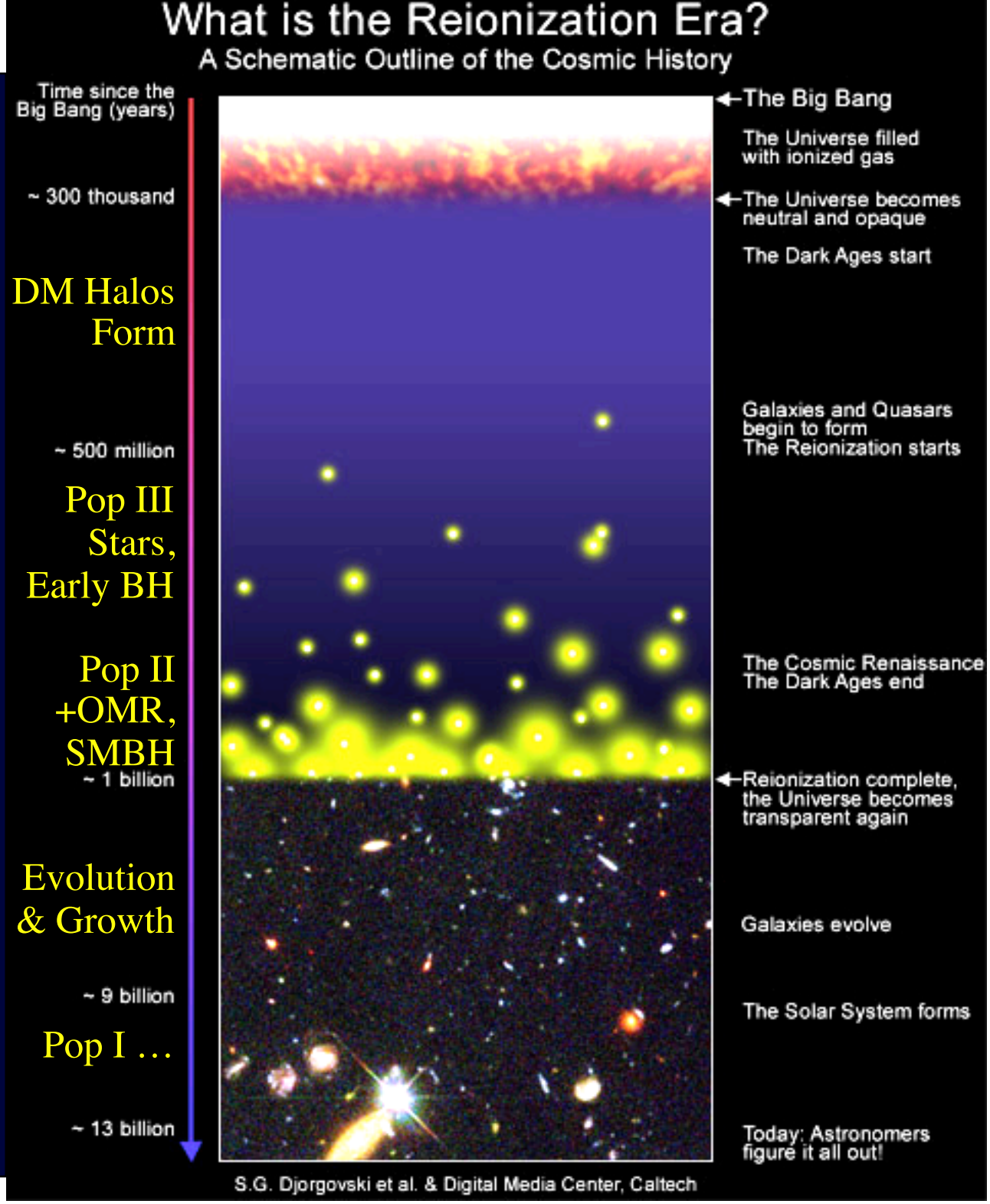

Reionization Era:
The Cosmic Renaissance

The Cosmic Reionization Era

(The Cosmic Renaissance)




Simulations of
the first stars
and galaxies
(Abel, Wise, et al.)

The Gunn-Peterson Effect

Even a slight amount of neutral hydrogen in the early IGM can completely absorb the flux blueward of Lyα

The Gunn-Peterson (1965) optical depth to Lyα photons is

$$\tau_{\rm GP} = \frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha H^{-1}(z) n_{\rm HI}, \quad (1)$$

where f_α is the oscillator strength of the Lyα transition, $\lambda_\alpha = 1216$ Å, $H(z)$ is the *Hubble* constant at redshift z, and $n_{\rm HI}$ is the density of neutral hydrogen in the IGM. At high redshifts,

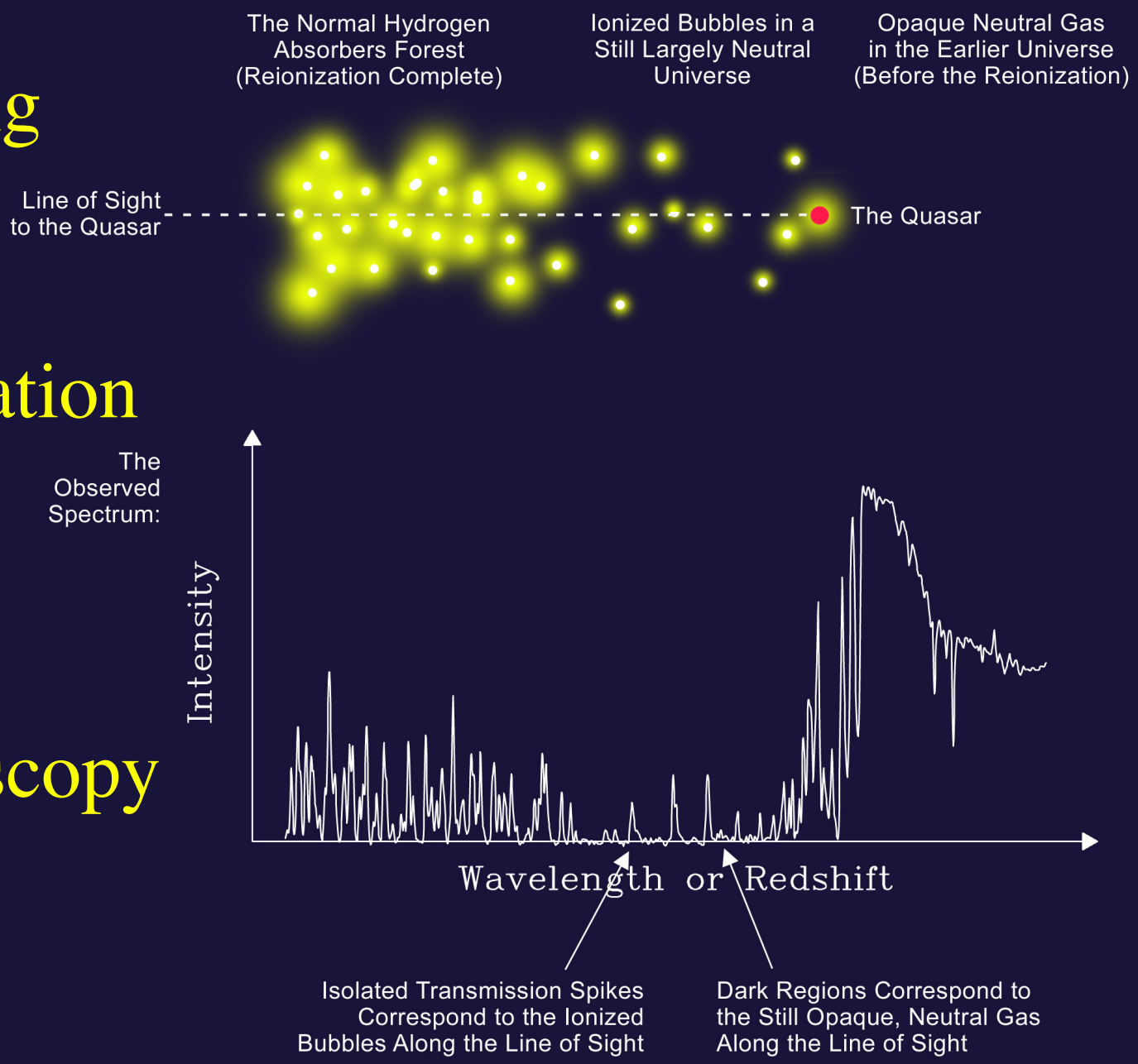
$$\tau_{\rm GP}(z) = 4.9 \times 10^5 \left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{\rm HI}}{n_{\rm H}}\right) \quad (2)$$

for a uniform IGM. Even a tiny neutral fraction, $x_{\rm HI} \sim 10^{-4}$, gives rise to complete GP absorption. This test is only sensitive at the end of the reionization when the IGM is already mostly ionized, and the absorption saturates for the higher neutral fraction in the earlier stage.

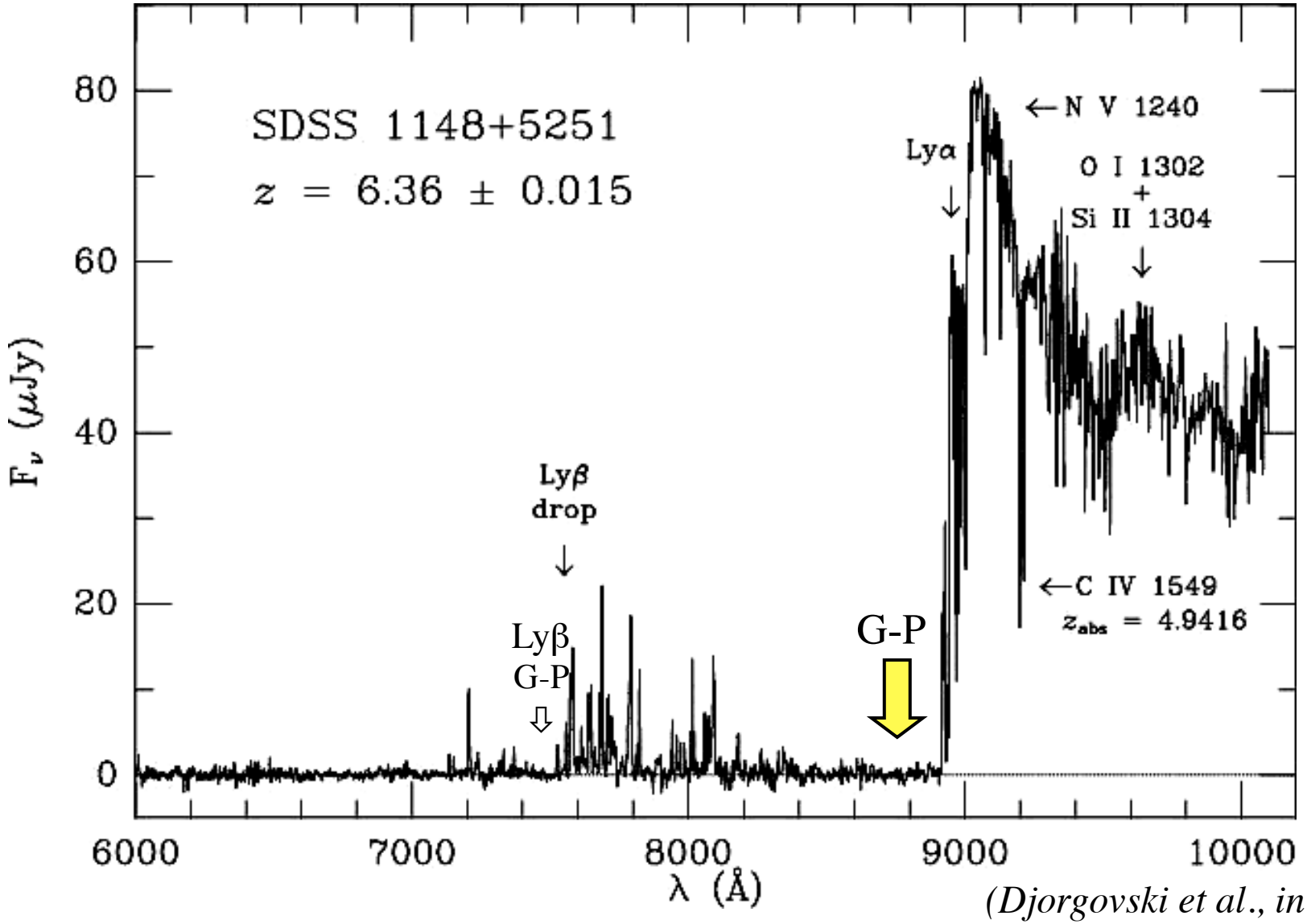
(from Fan et al. 2006, ARAA, 44, 415)

How the Discovery Was Made

Detecting The Cosmic Reionization From High-z Quasar Spectroscopy

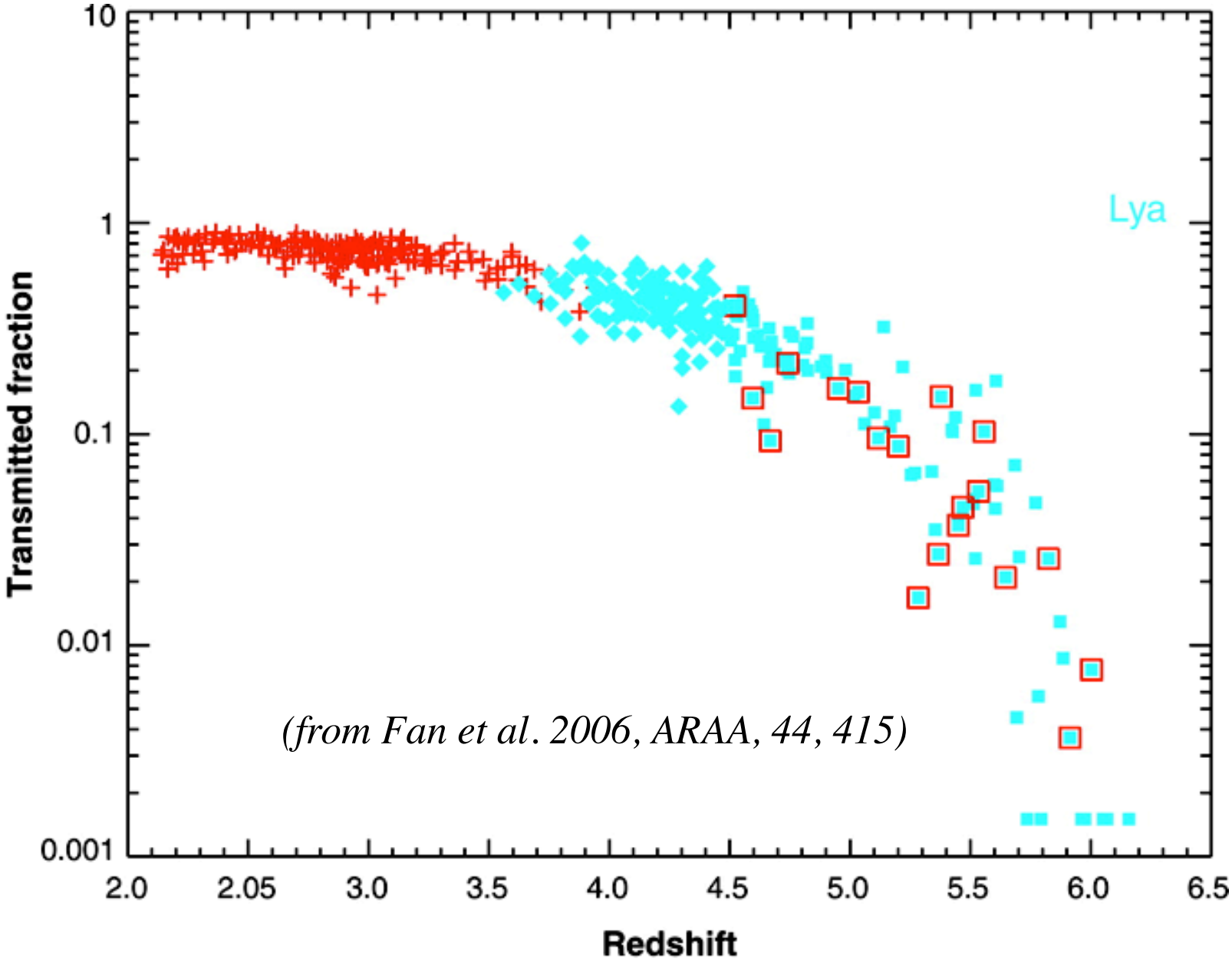


"Gunn-Peterson like" troughs are now observed along all available lines-of-sight at at $z \sim 6$



(Djorgovski et al., in prep.)

Transmitted Lyα Flux vs. Redshift

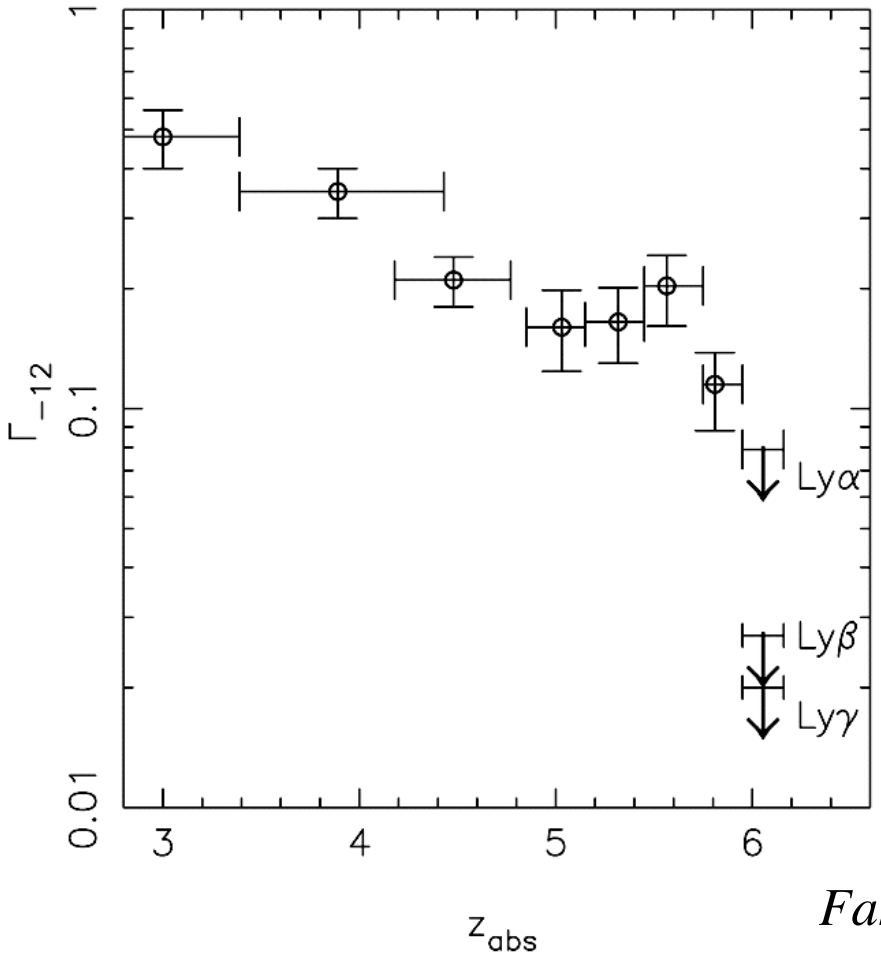


(from Fan et al. 2006, ARAA, 44, 415)

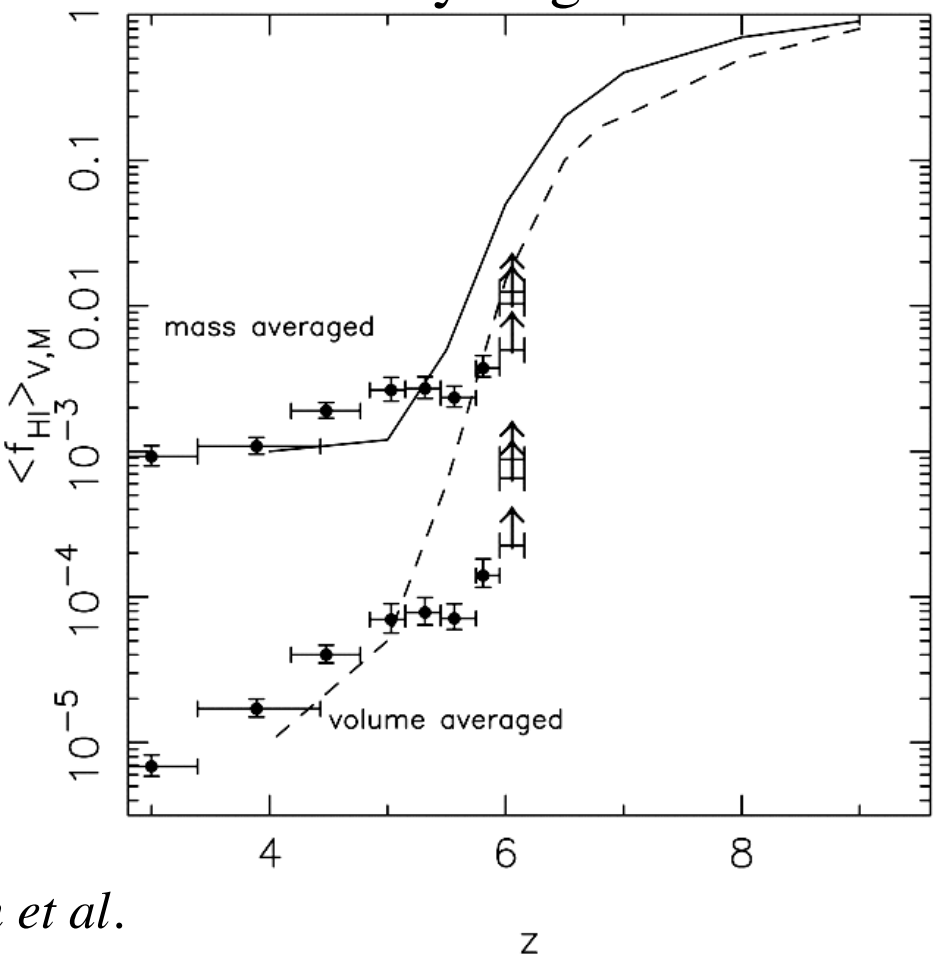
QSO Observations Suggest the End of the Reionization at z ~ 6

A sudden change in the UV opacity of the intergalactic medium

Photoionization Rate



Neutral Hydrogen Fraction

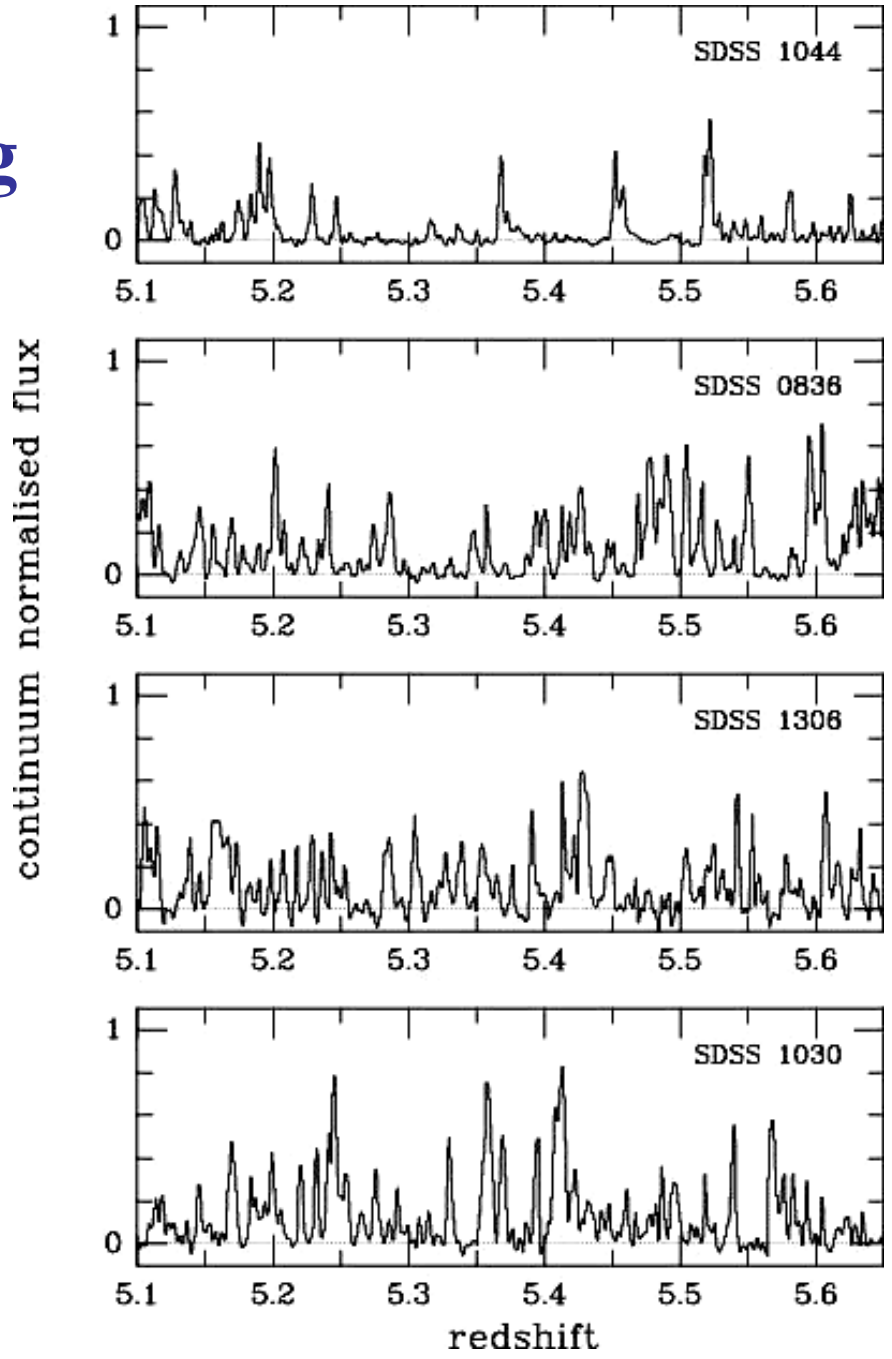


Fan et al.

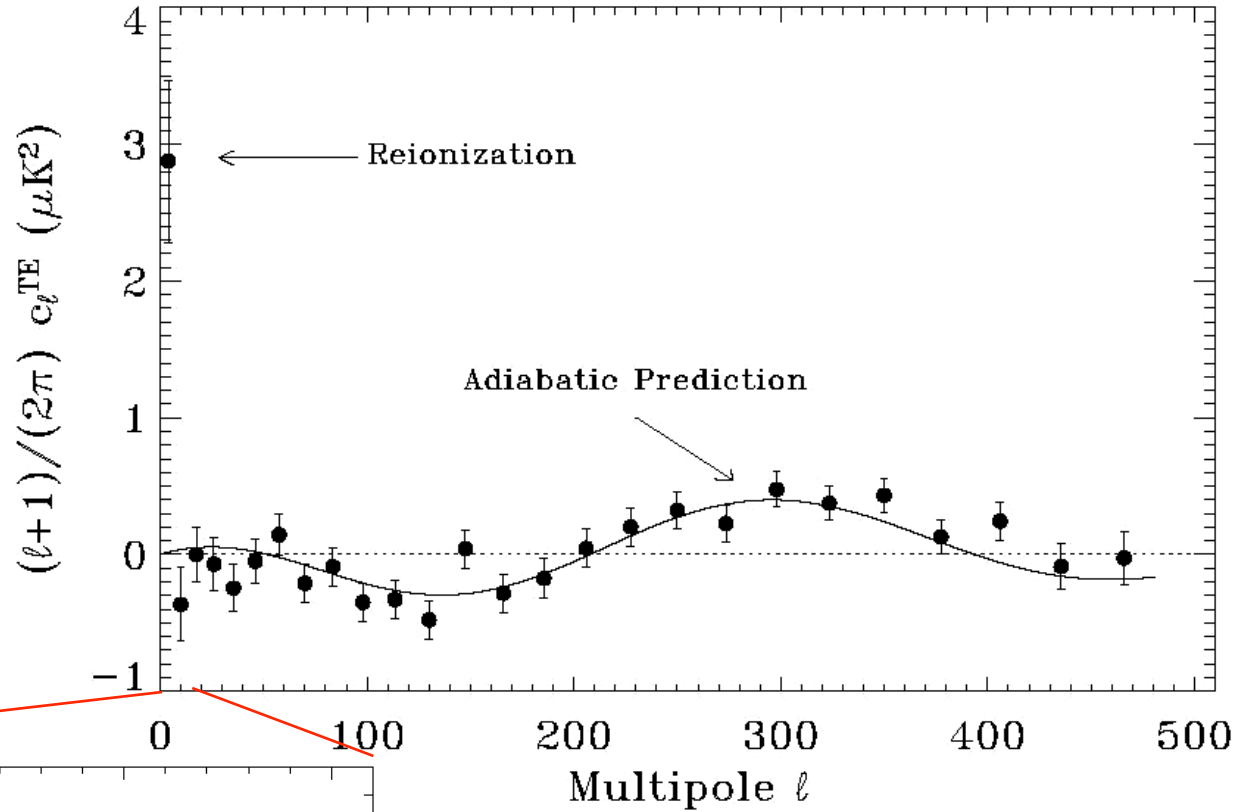
Substantial Diversity of IGM Absorption Seen Along Diffferent Lines of Sight

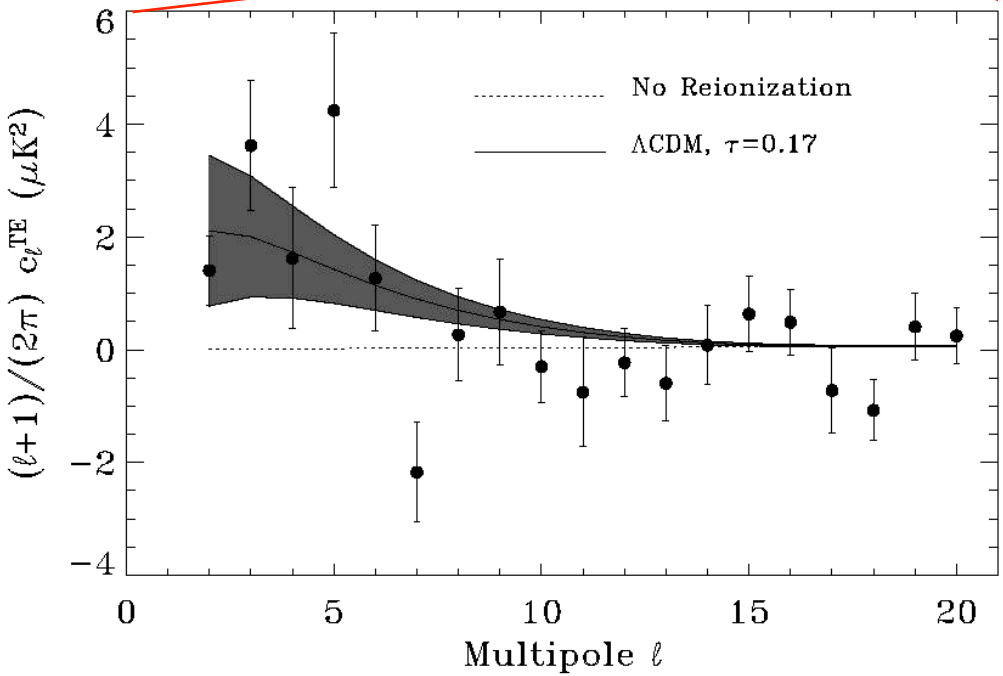
Shown here is the IGM transmission over the same redshift window, but along 4 different QSO lines of sight

A Considerable Cosmic Variance Exists in the transmission of the Lyα forest at $z > 5$



However, this cannot be the complete story:



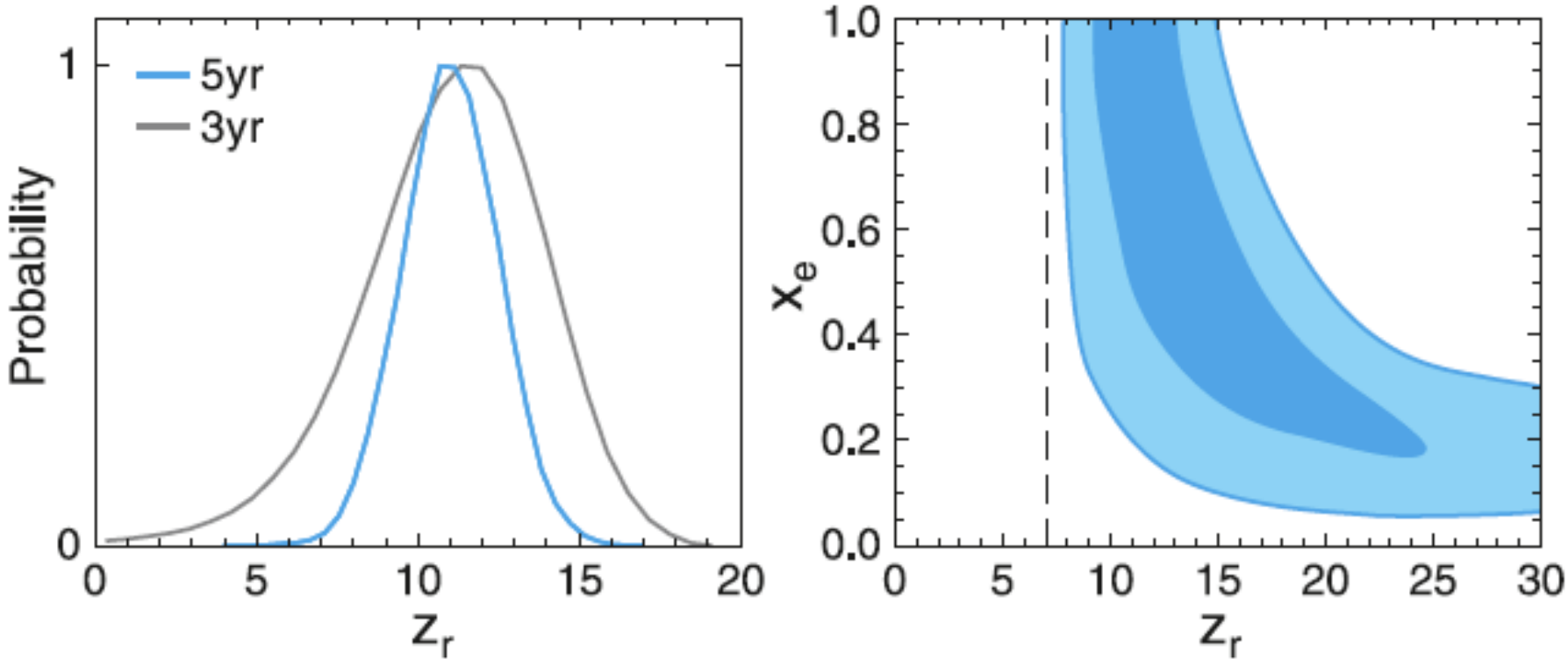


WMAP detection of the (initial) reionization at z ~ 10 - 20 …

(Kogut et al. 2003)

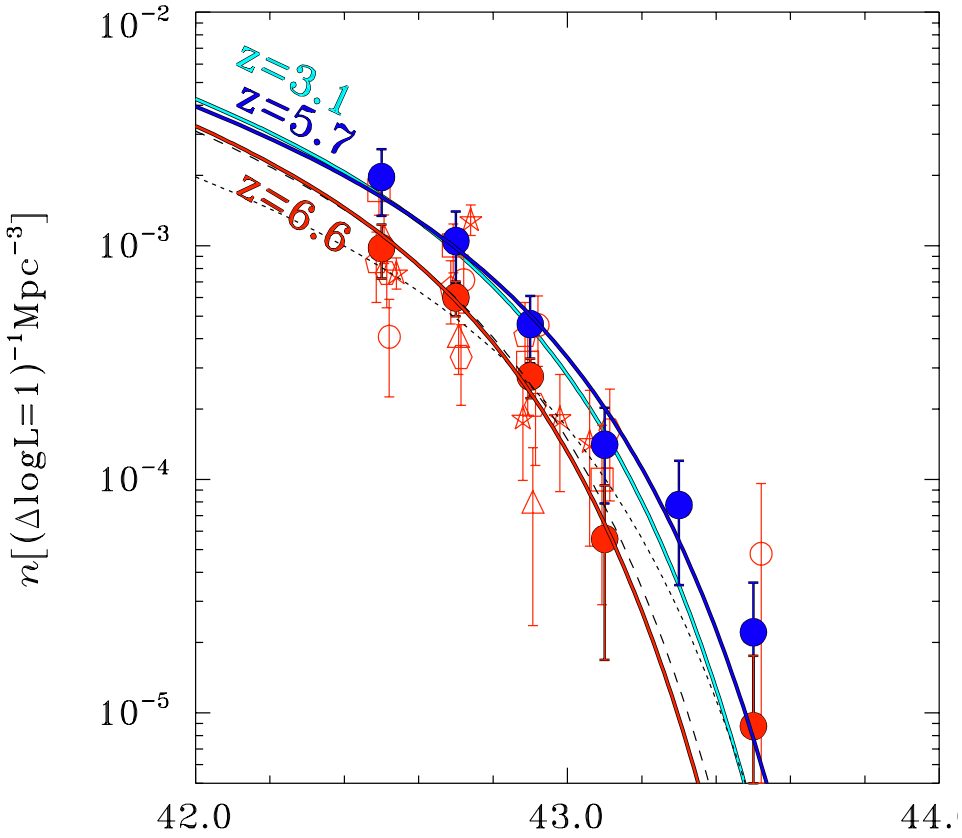
CMB Constraints on Reionization

WMAP+eCMB, Hinshaw et al (2012): $\tau = 0.084 \pm 0.013$
consistent with an instantaneous reionization at $z = 10.3 \pm 1.1$
But also consistent with an extended reionization from
$z \sim 20 - 25$ to $z \sim 6$ (more realistic)

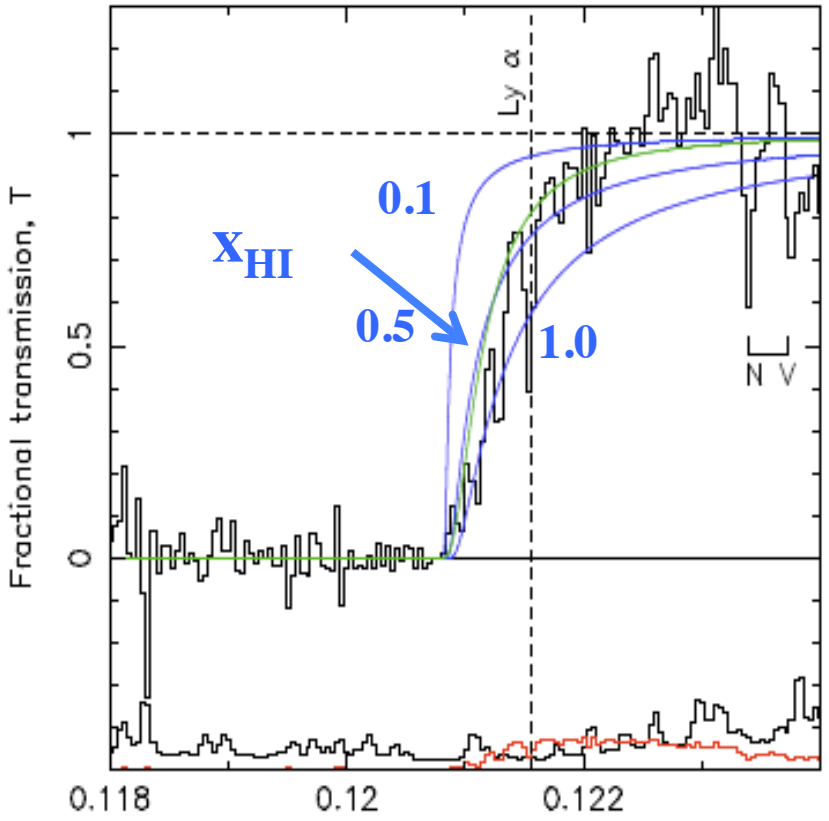


Further Evidence for Late Reionization

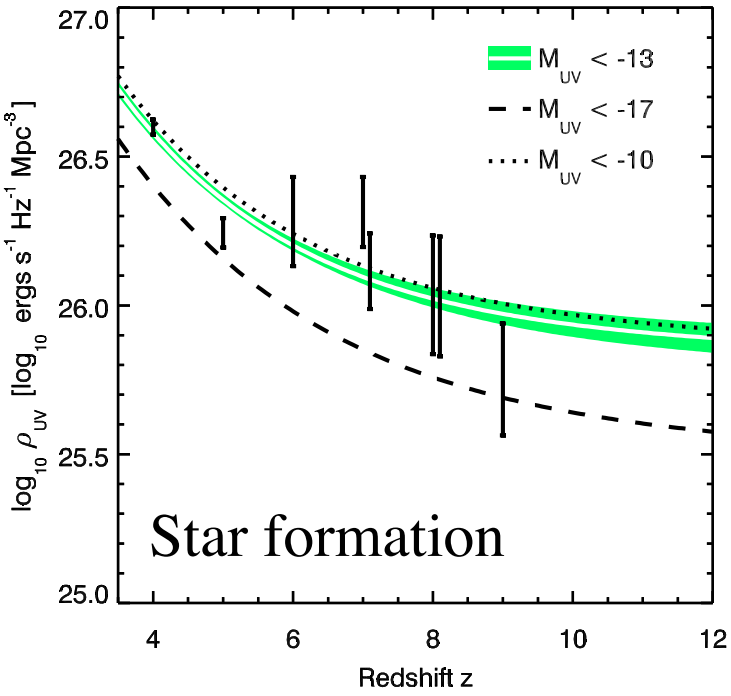
Rapid decline in abundance of Lyα emitters from $5.7 < z < 6.6$ (Ouchi et al 2010): $x_{HI} \sim 0.1$ at $z = 6.6$?

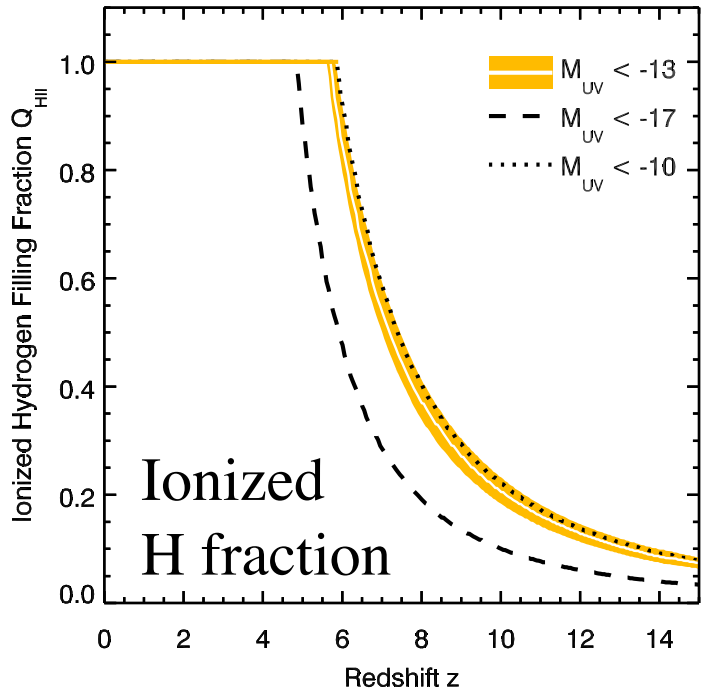


Damping wing of Lyα in z=7.085 QSO: $x_{HI} > 0.1$ at z~7? (Mortlock et al. 2011, Bolton et al. 2011)

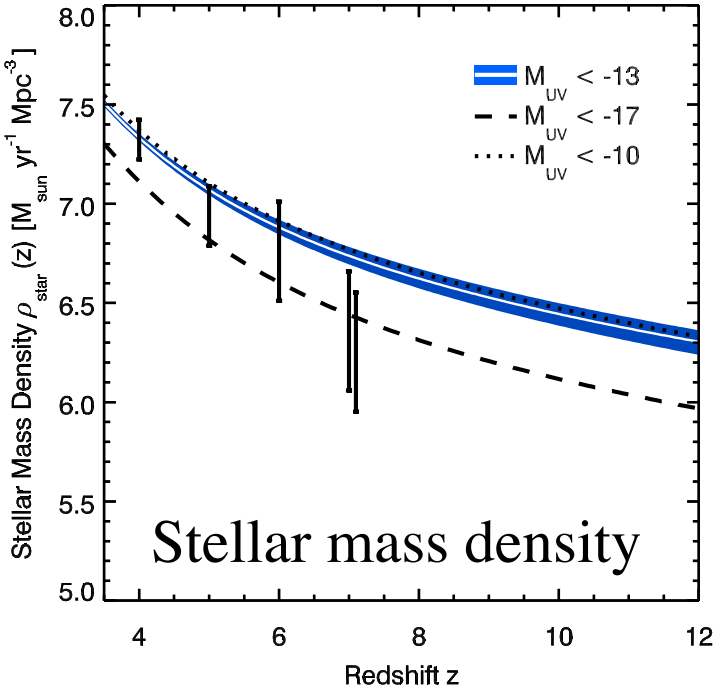


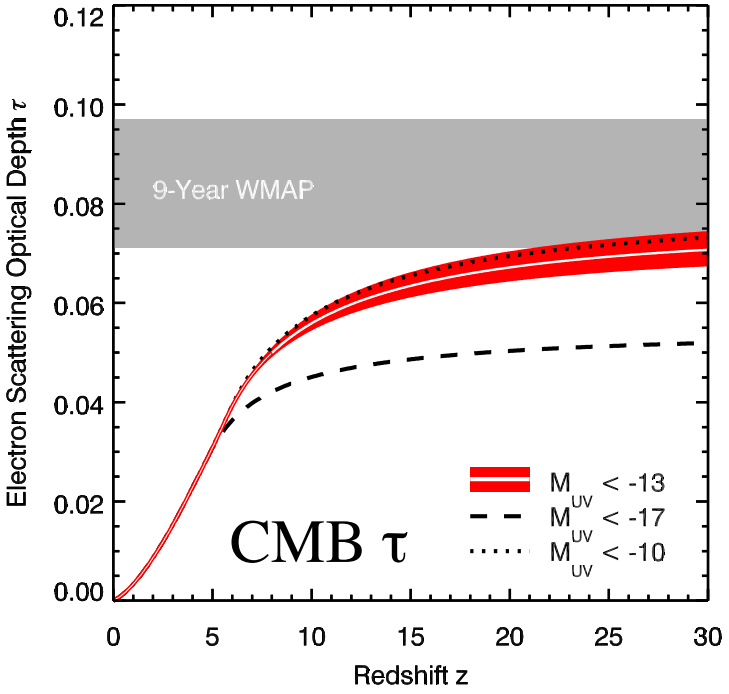
Putting It All Together





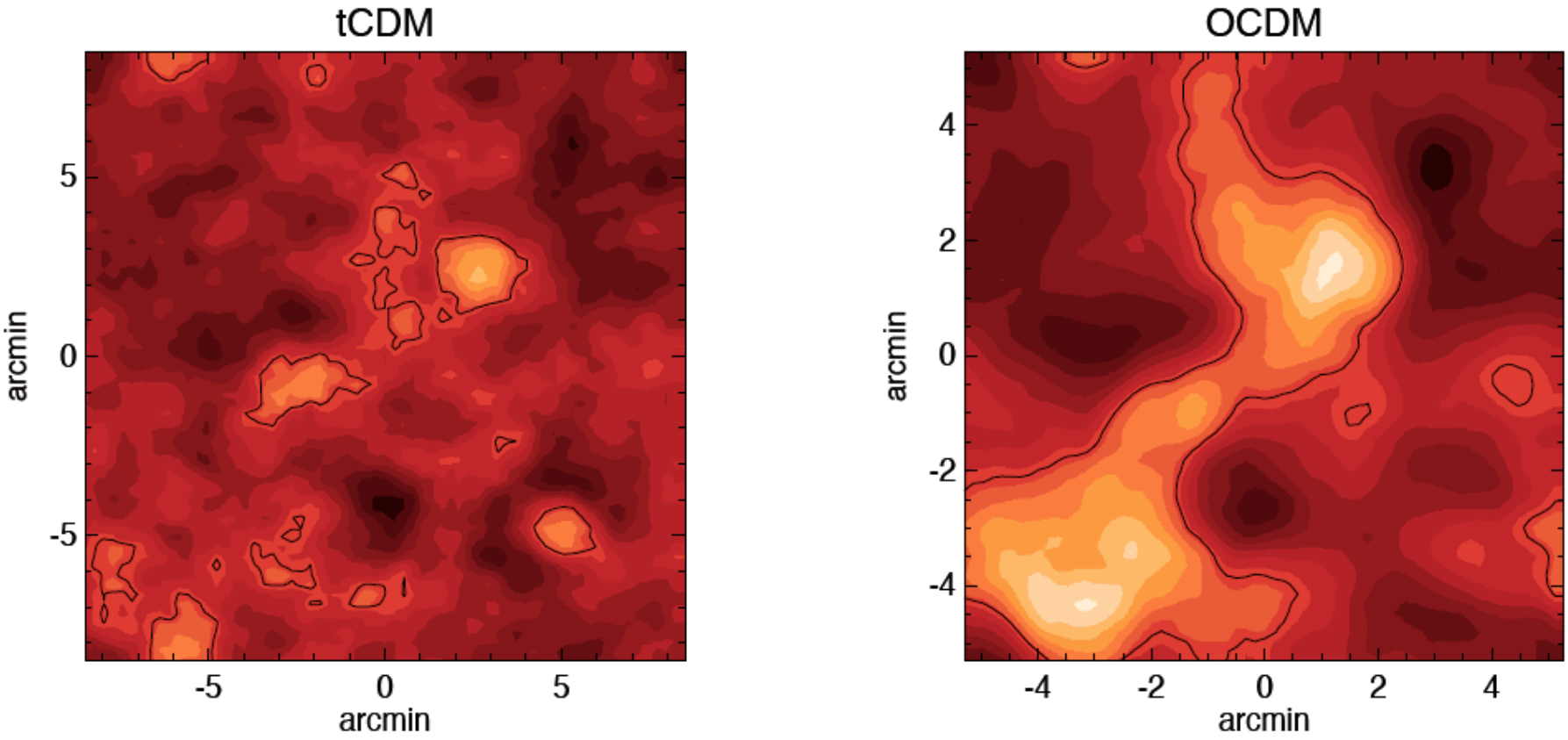
Based on the Hubble Ultra Deep Field analysis (Robertson et al. 2013)



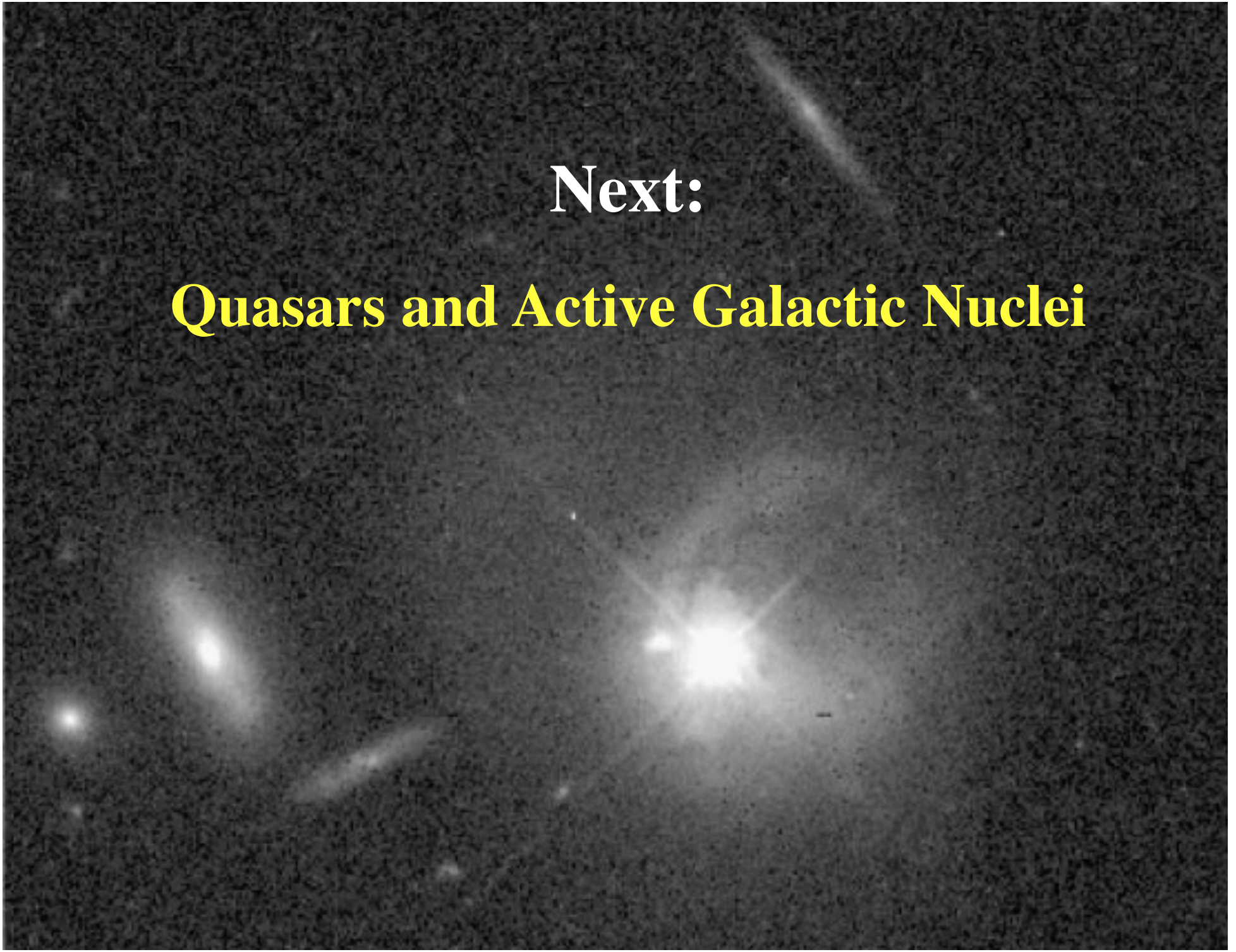


Looking Even Deeper: The 21cm Line

We can in principle image H I condensations in the still neutral, pre-reionization universe using the 21cm line. Several experiments are now being constructed or planned to do this, e.g., the Mileura Wide-Field Array in Australia, or the Square Kilometer Array (SKA)



(Simulations of z = 8.5 H I, from P. Madau)


Next:
Quasars and Active Galactic Nuclei