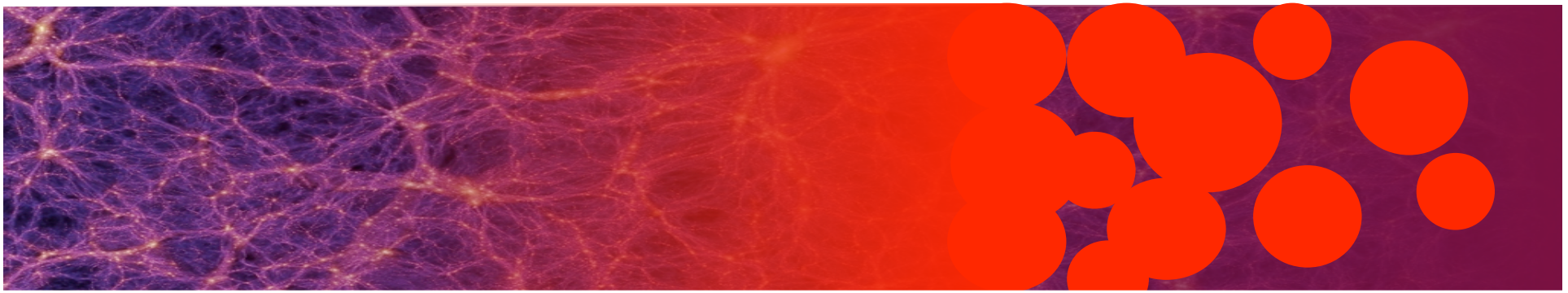
APPARENT SHRINKING CRITERION:

Tentative measurements for xHI @ z~6



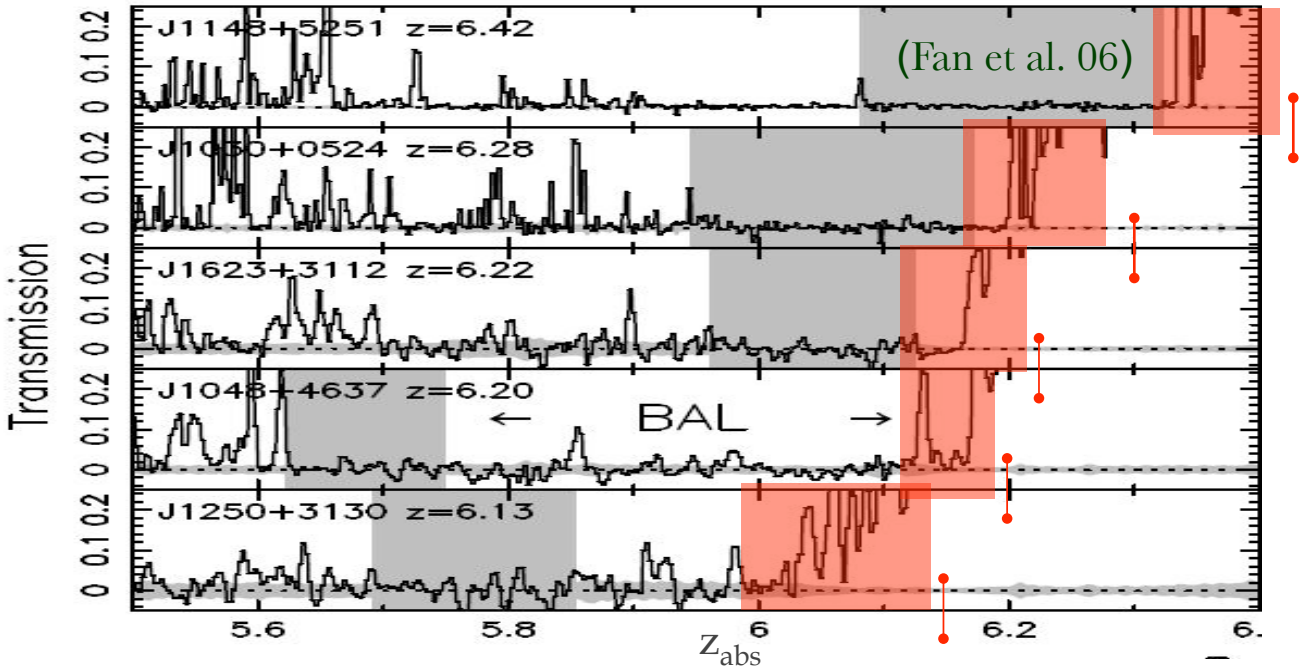
Antonella Maselli

Collaborators: *Andrea Ferrara*
Simona Gallerani

HRI, Allahabad, February 16th 2010

Windows of Transmission in the Opaque Universe

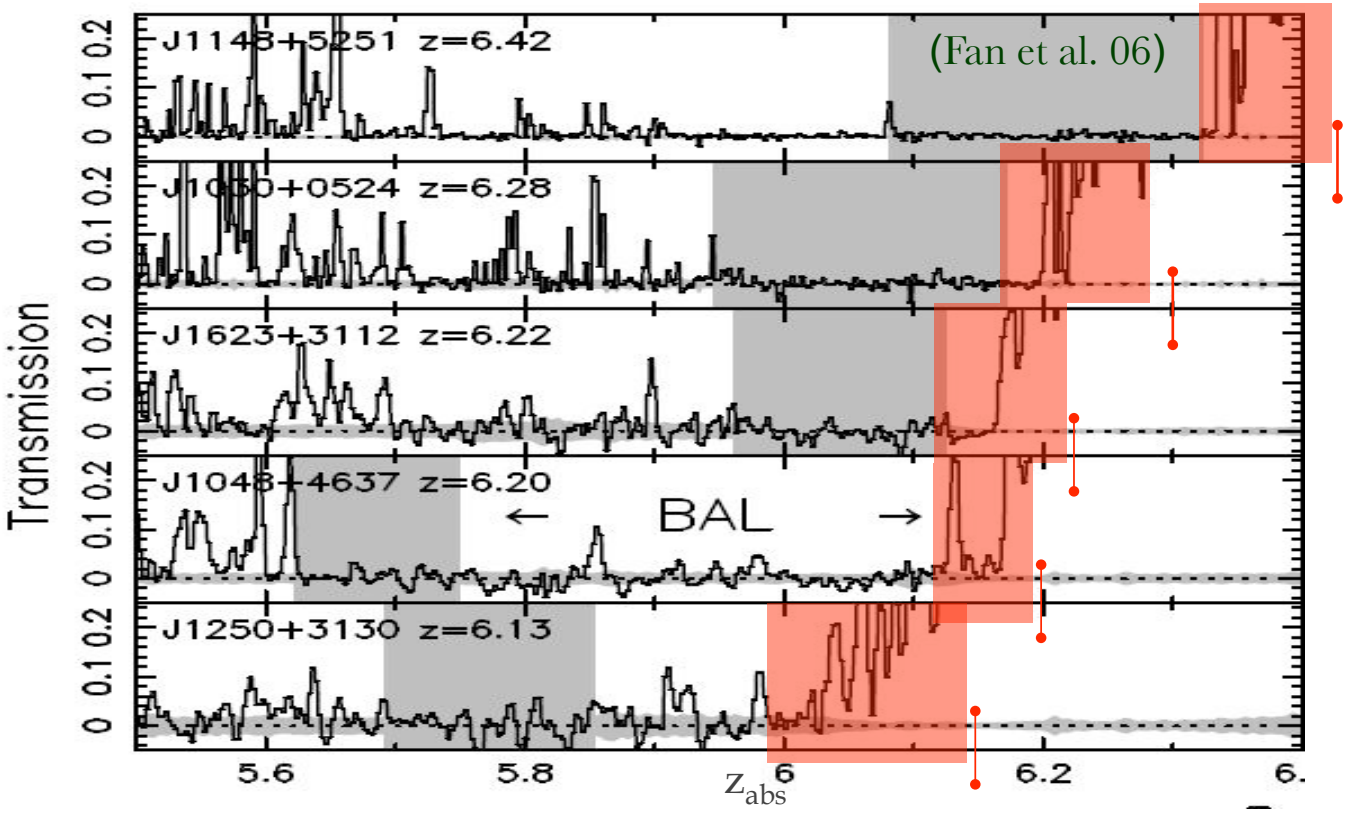
All the detected QSOs @ z > 5.7 show transmitted flux in a window bracket between the QSO and the blue side of the GP trough



No Transmitted Flux @ z> 5.7, i.e. Gunn Peterson Trough → $x_{HI} > 10^{-3..8}$

Transmitted Flux approaching the quasar redshift → $x_{HI} < 10^{-3.8}$

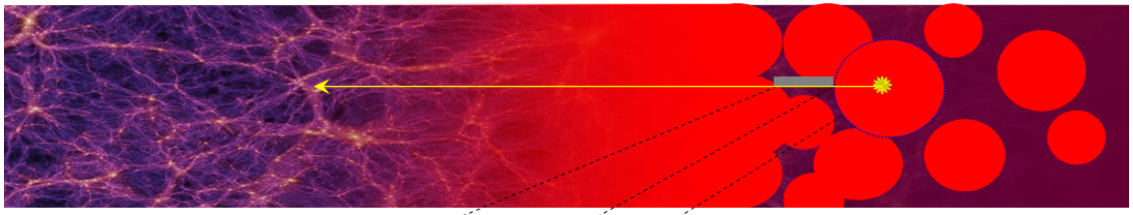
Windows of Transmission in the Opaque Universe

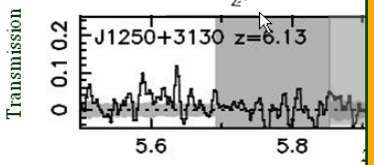


The spectral EXTENT and PROFILE can provide important insights on the physical state of the IGM at z~>6

Two Regimes -- One Emerging Spectra

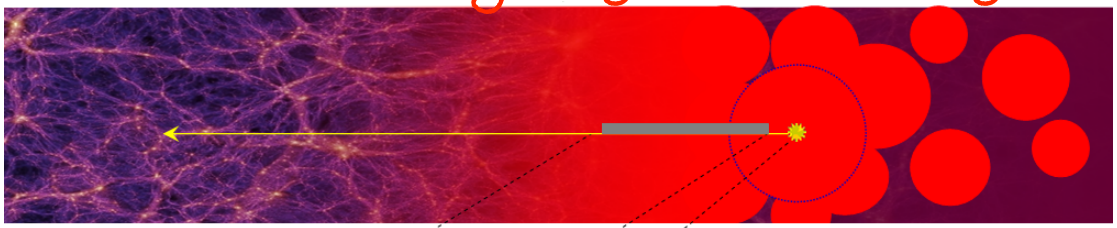
H_{II} Region (HR) Regime

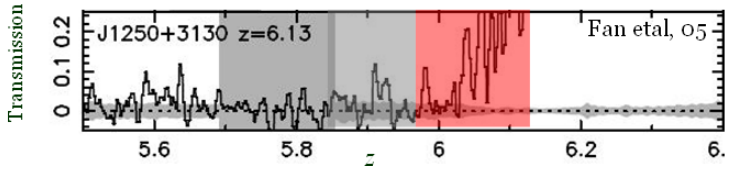




The same observed spectra have different implications for reionization according to the regime which applies

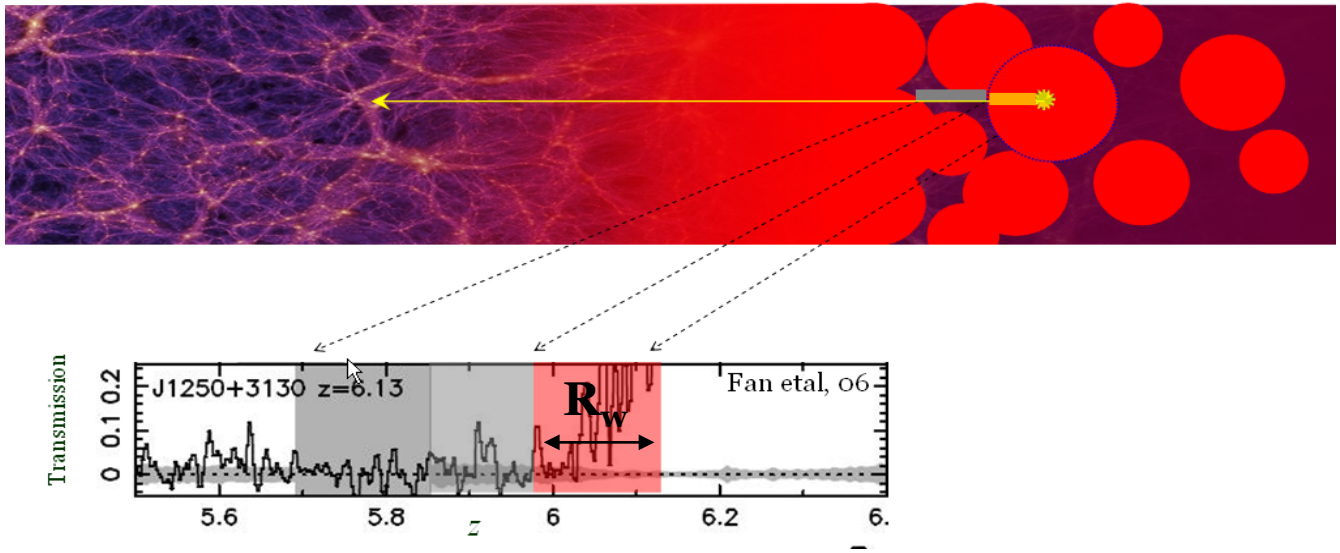
Proximity Region (PR) Regime





The H_{II} Region (HR) Regime

The window of transmitted flux is the spectral counterpart of the quasar H_{II} region

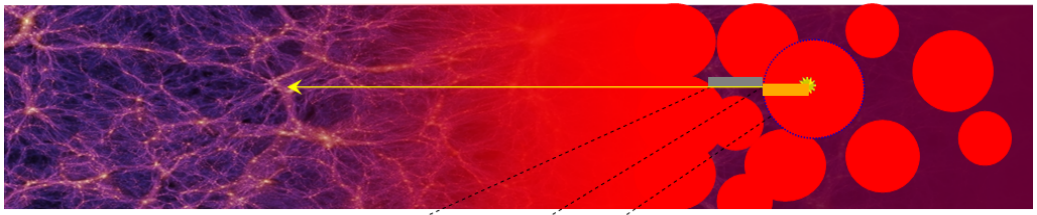


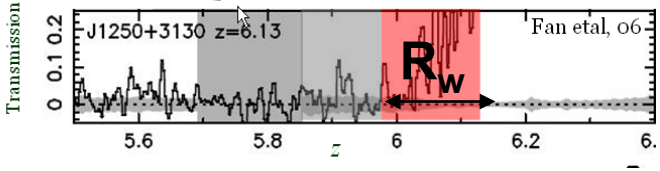
The window extent is set by the H_{II} region radius

$$R_W = R_{HII}$$

Constraints on Reionization in the HR Regimes

H_{II} Region (HR) Regime





The IGM ionization state can be constrained:

$$R_w = R_{HII}\ (x_{HI}, N_\gamma, t_Q)$$

$$x_{HI} \propto R_{HII}^{-3}$$

$$R_{\rm HII} \approx 3.3 \left(\frac{\dot{N}_\gamma}{10^{57}{\rm s}^{-1}} \frac{t_Q}{10^7{\rm yr}}\right)^{1/3} \left(\frac{1+z}{7}\right)^{-1} x_{\rm HI}^{-1/3} {\rm Mpc}$$

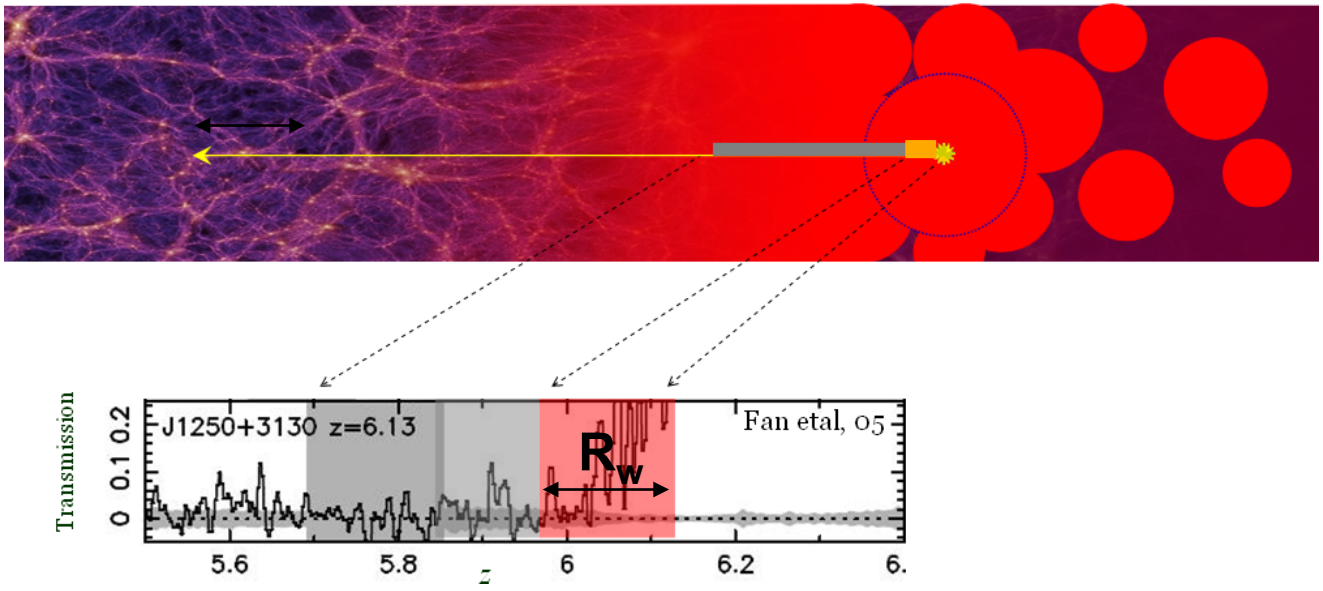
SDSS spectra imply a still highly neutral Universe at $z \sim 6$

$$x_{HI} > 0.1$$

Wyithe & Loeb 04
Wyithe, Loeb & Carilli 04
Yu & Lu 04
Fan etal. 06;

The Proximity Region (PR) Regimes

The window of transmitted flux is a signature of the quasar presence, i.e. proximity effect

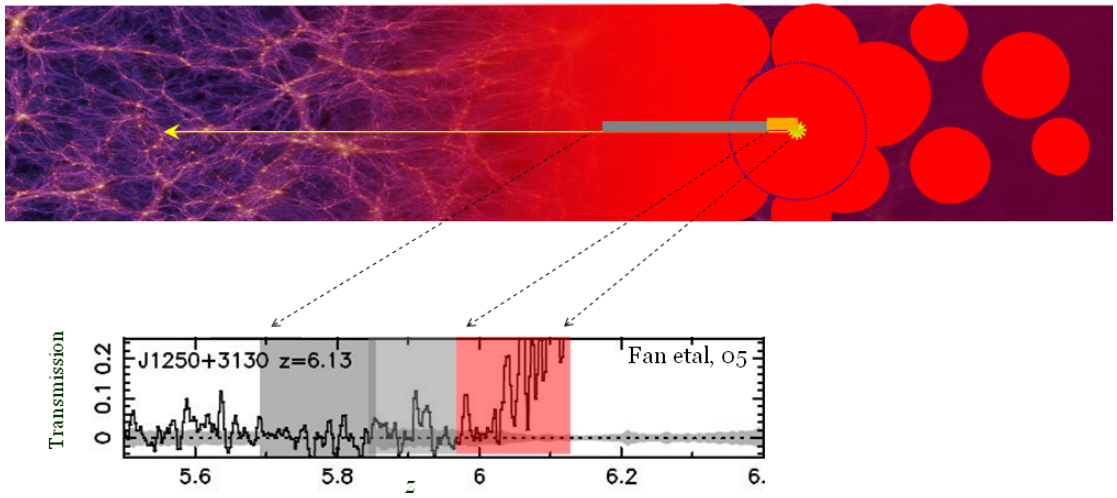


R_w is set by the onset of the GP through within the H_{II} region $R_w < R_{HII}$

"Apparent Shrinking Effect" (AM et al. 07)

The Apparent Shrinking Effect

.... why R_w does not grow with R_{HII}



AM et al. 07, MNRAS, 376L, 34

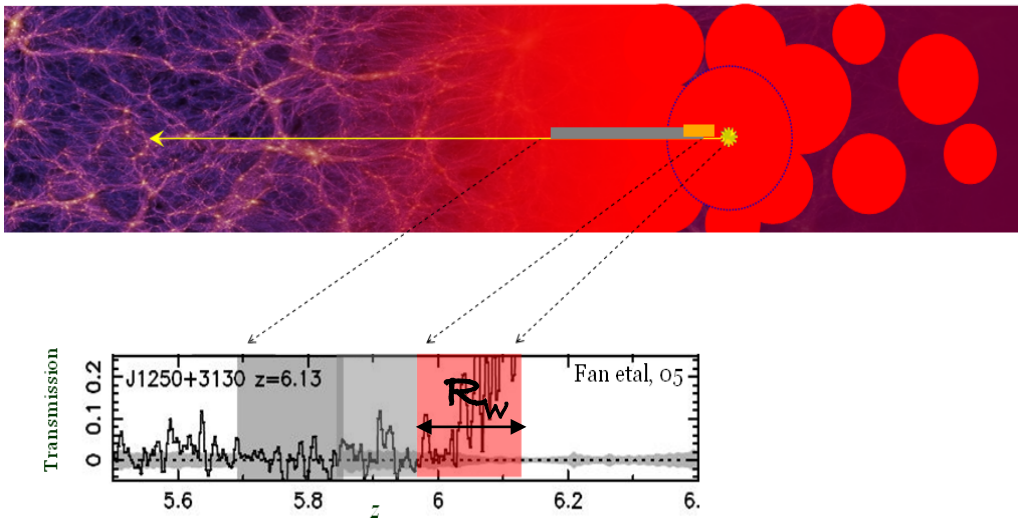
"Apparent Shrinking" occurs when the GP trough penetrates within the quasar H_{II} region

$\Gamma_Q \propto r^{-2}$ → At large distances Γ_Q becomes too small to produce enough extra ionization and to keep the IGM transparent →

$T \geq 2.3$ (i.e. GP trough) inside the H_{II} region

Constraints on Reionization in the PR Regimes

Proximity Region (PR) Regime



$R_w < R_{HII}$

R_w is independent on R_{HII}

R_w put NO CONSTRAINTS on x_{HI}.

SDSS observations consistent with highly ionized IGM at z~6

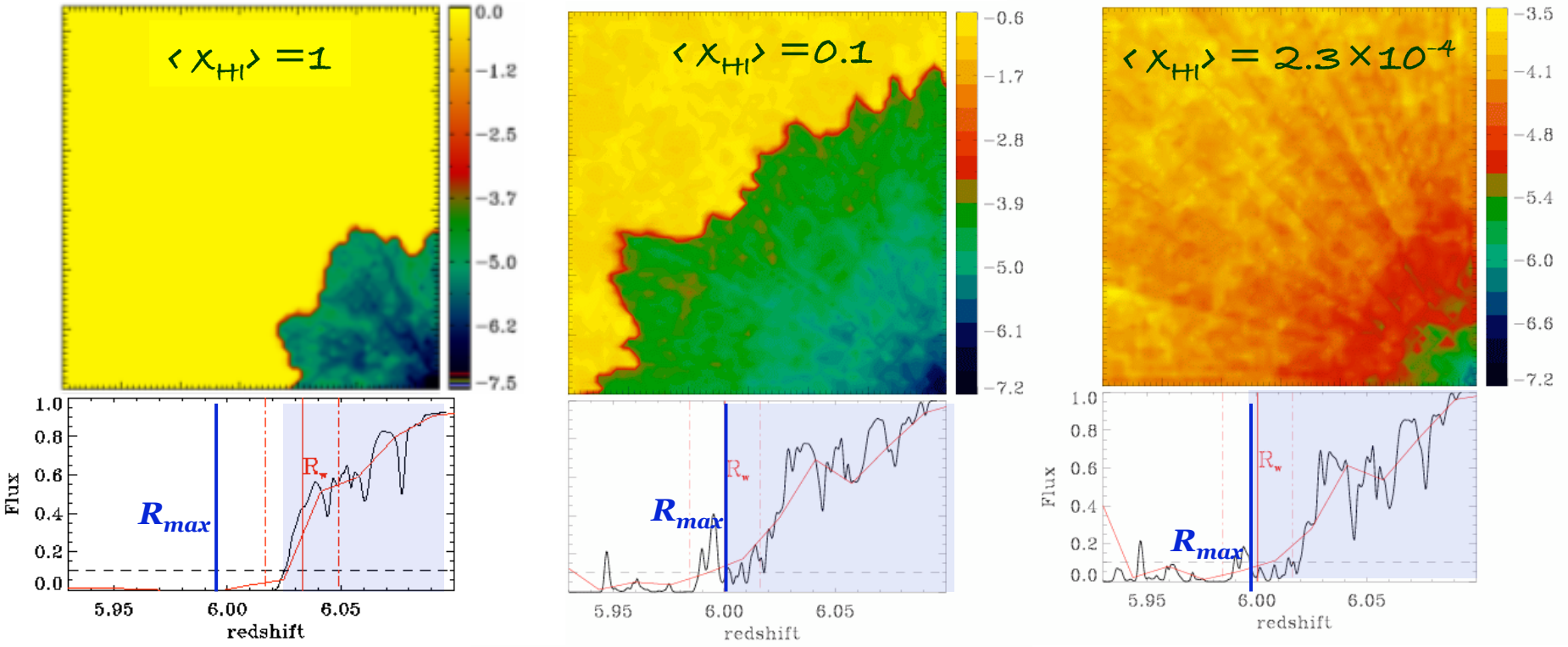
Bolton & Haehnelt 07

AM et al.07

Wyithe et al. 08

The Apparent Shrinking Effect

SPH + 3D Radiative Transfer (Gadget2 + CRASH)



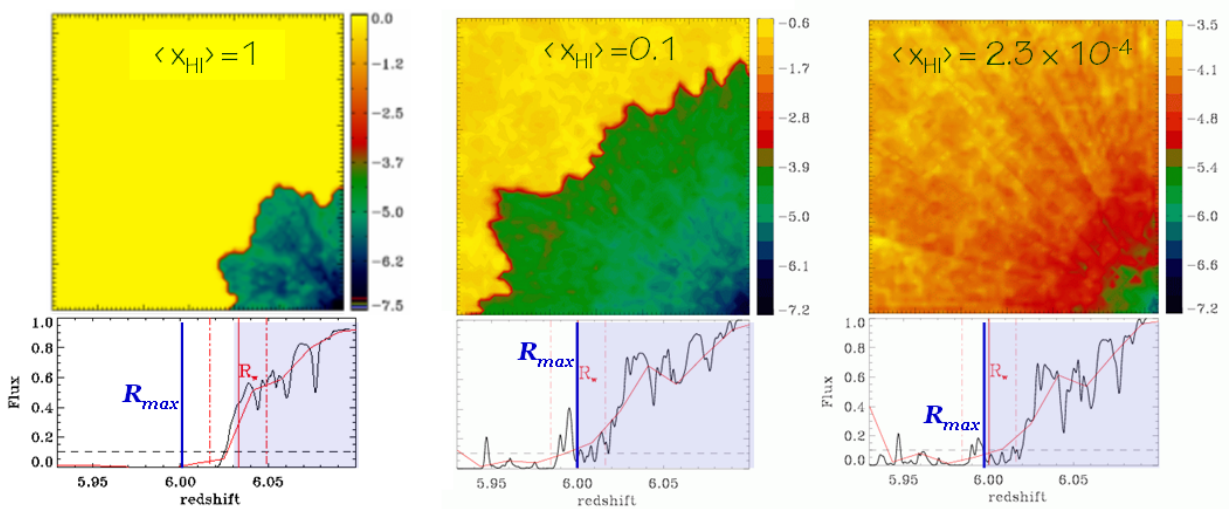
R_w saturates at a fixed distance from the QSO, independent from x_{HI} → R_{max}

$N_\gamma = 2 \times 10^{57} s^{-1}$, $t_Q = 10^7$ yr, $z_Q = 6.1$

The "Apparent Shrinking" Criterion (ASC)

The Apparent Shrinking Criterion allows to discriminate between the HR regime and the PR regime for each given observed QSO

- R_{HII} : H_{II} region size
- R_W : extent of the transmission window
- R_{max} : maximum distance from the QSO with transmitted flux detected



R_{max}: an Analytic Estimate

R_{max} : maximum distance from the QSO with transmitted flux detected
(distance from the quasar at which $\tau > 2.3$, i.e. $F < 0.1$)

$$F(R_{max}) = 0.1 \longrightarrow R_{max}$$

$$F = \int P(\Delta) e^{-\tau(\Delta)} d\Delta$$

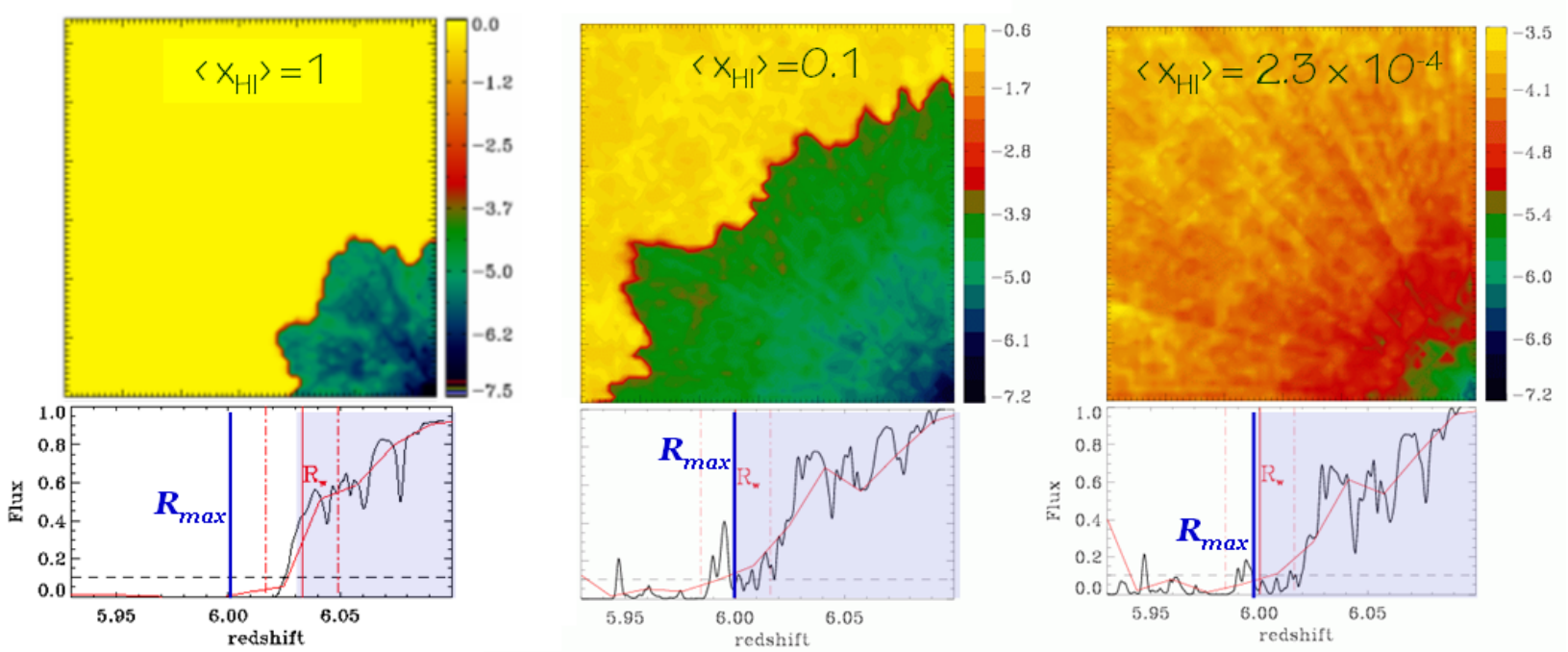
$$\tau = 4.25 \times 10^5 h^{-1} x_{\rm HI} \Delta \left(\frac{\Omega_m}{0.26}\right)^{-0.5} \left(\frac{\Omega_b h^2}{0.0241}\right) \left(\frac{1+z}{7}\right)^{3/2}$$

x_{HI} @ $\Gamma_{tot} = \Gamma_Q$ (quasar) + Γ_B (UV Backgrond)

R_{max} depends on: Γ_Q, Γ_B, IGM Temp

The "Apparent Shrinking" Criterion

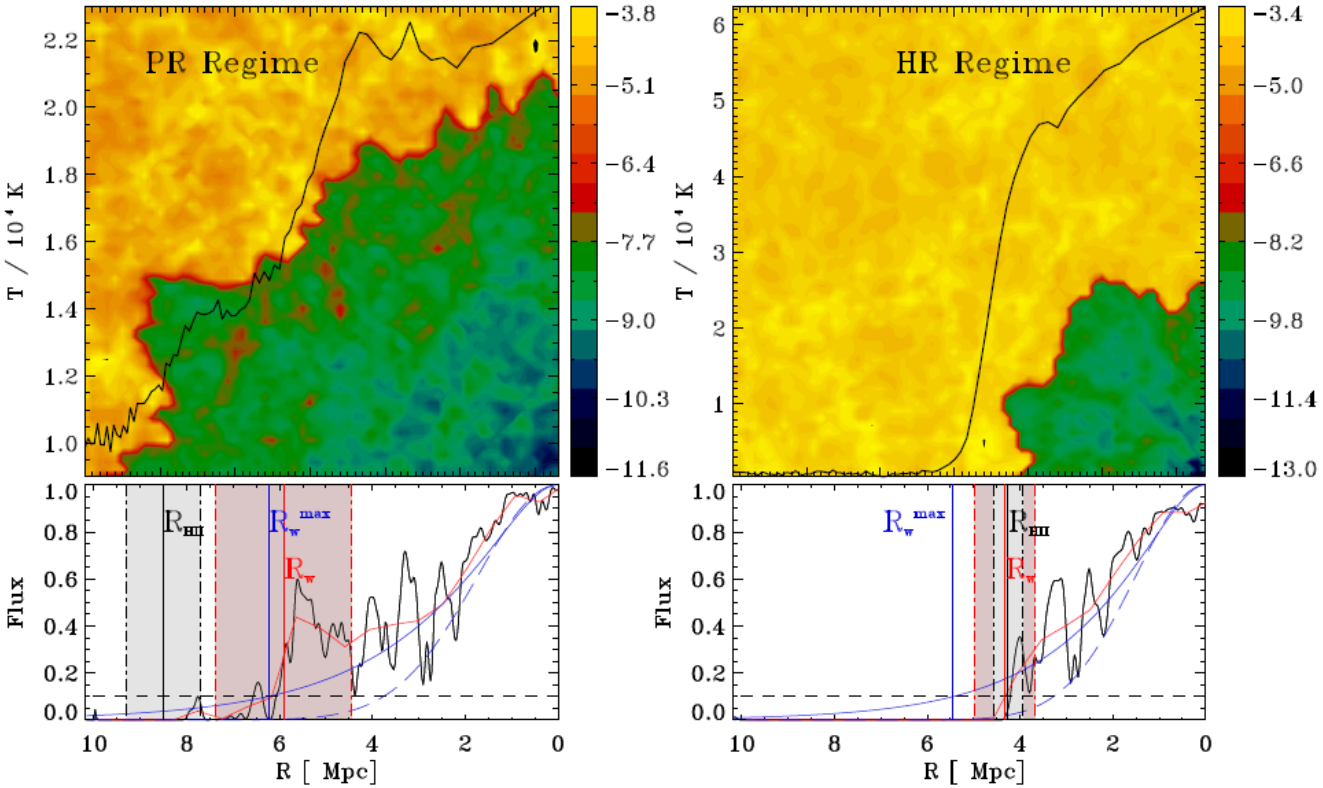
- $R_W < R_{max}$: HR Regime → $R_W = R_{HII}$ & x_{HI} can be constrained.
- $R_W = R_{max}$: PR Regime → $\Gamma_{tot} = \Gamma_B + \Gamma_Q$
- $R_W > R_{max}$: PR Regime → $\Gamma_{tot} > \Gamma_B + \Gamma_Q$



The "Apparent Shrinking" Criterion

- $R_w < R_{max}$: HR Regime → $R_w = R_{HII}$ & x_{HI} can be constrained.
- $R_w = R_{max}$: PR Regime → $\Gamma_{tot} = \Gamma_B + \Gamma_Q$
- $R_w > R_{max}$: PR Regime → $\Gamma_{tot} > \Gamma_B + \Gamma_Q$

$N_{\gamma,57} = 2$
$t_{Q,7} = 1$
$\langle x_{HI} \rangle = 0.1$



$N_{\gamma,57} = 2$
$t_{Q,7} = 1$
$\langle x_{HI} \rangle = 1$

AM, Ferrara & Gallerani, 09, MNRAS, 395, 1925

R_{max} Estimate for Observed Quasars

R_{max} depends on Γ_Q, Γ_B, IGM Temp

- $\Gamma_Q(R, M) = (N_\gamma\, \sigma) / (4\pi R^2)$

  constant luminosity, $N_\gamma = N_\gamma(M_{1450}, S_\nu)$, $R_{HII} \rightarrow \infty$

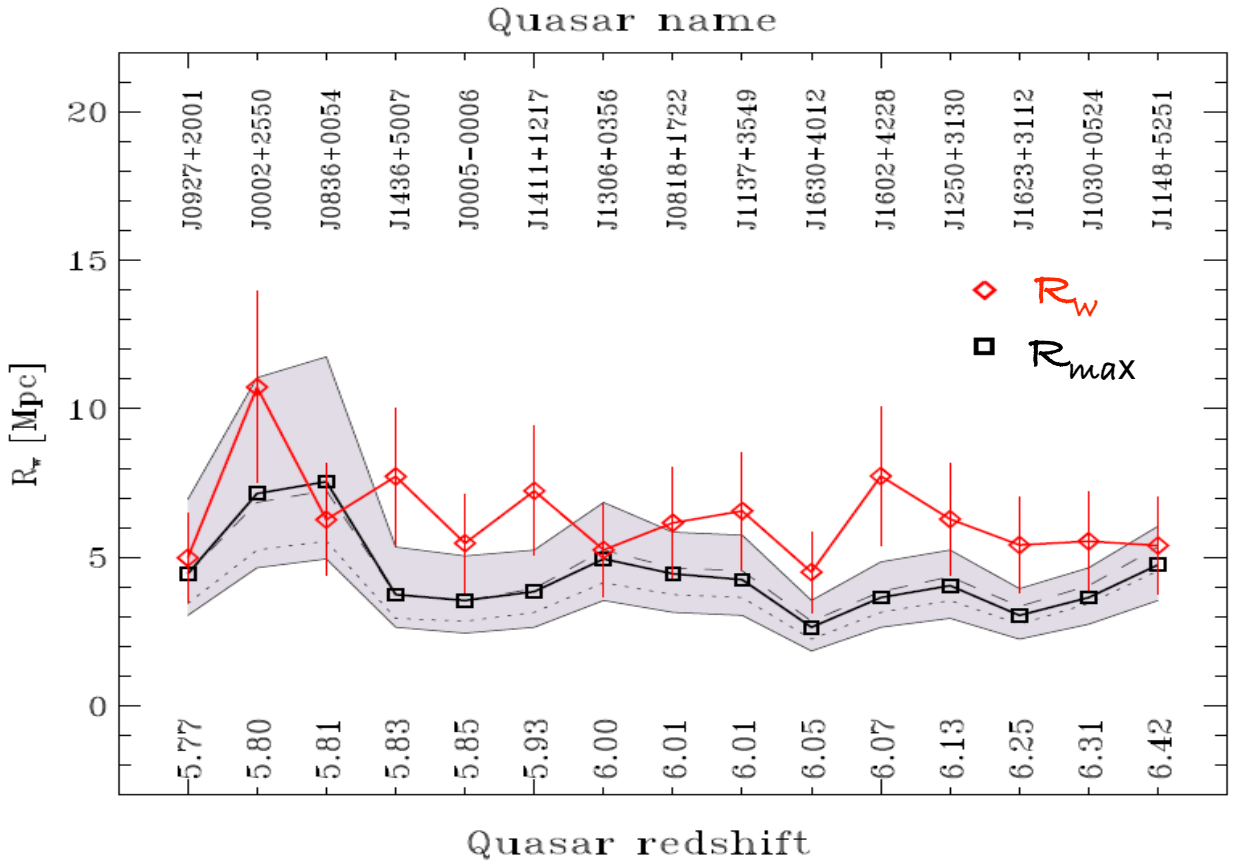
- T and Γ_B from Early Reionization Model (Gallerani et al. 07)

  $T = (1.5 \pm 0.5) \times 10^4$ K

  Γ_B consistent with Lya forest data (Bolton et al. 05, 07)

The ASC applied to observed Spectra

AM, Ferrara & Gallerani, 09, MNRAS, 395, 1925



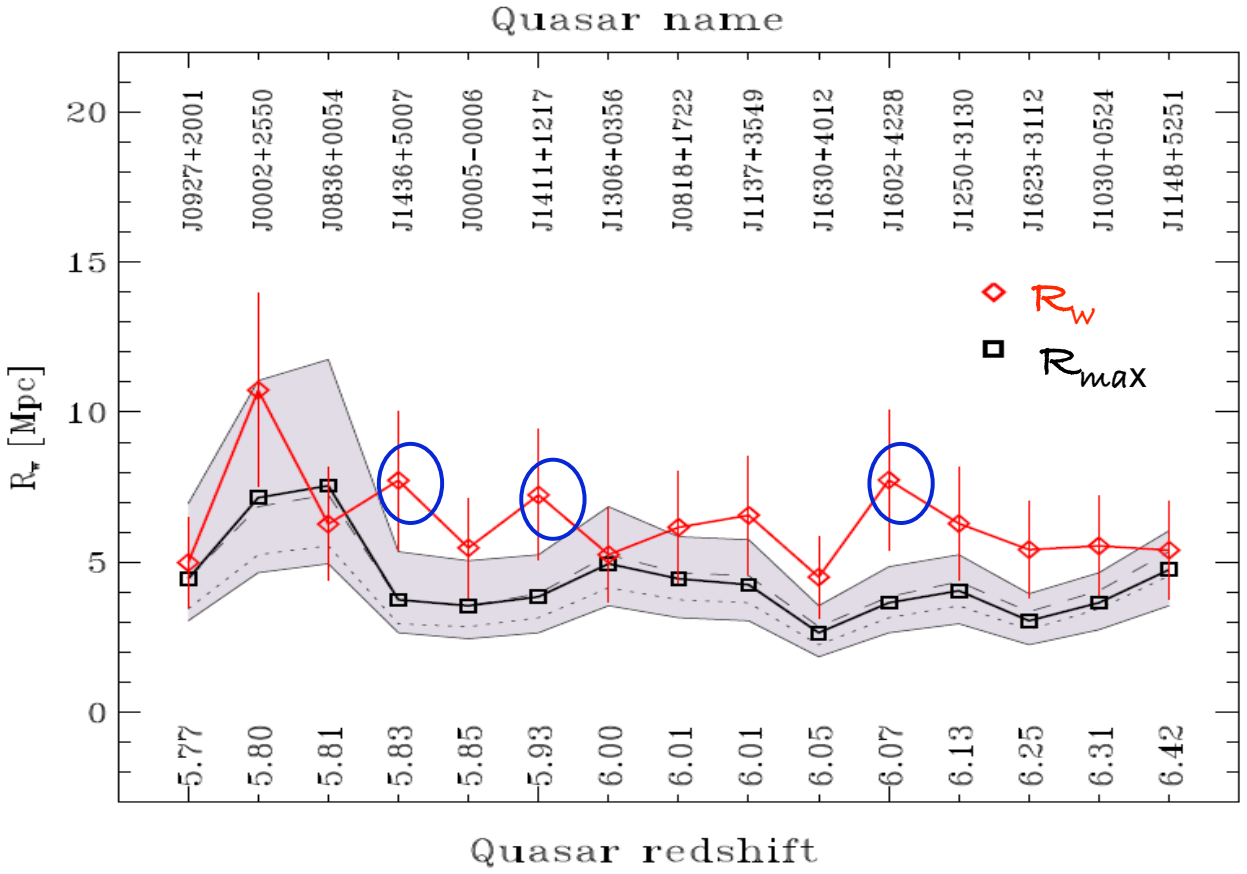
R_W : Fan et al. 06

R_{max} : Analytic estimate

1. The PR regime applies in all cases:
   current data do not allow to constraint $x_{HI.}$
2. Data consistent with a highly ionized IGM at $z \approx 6.4$

The ASC applied to observed Spectra

AM, Ferrara & Gallerani, 09, MNRAS, 395, 1925



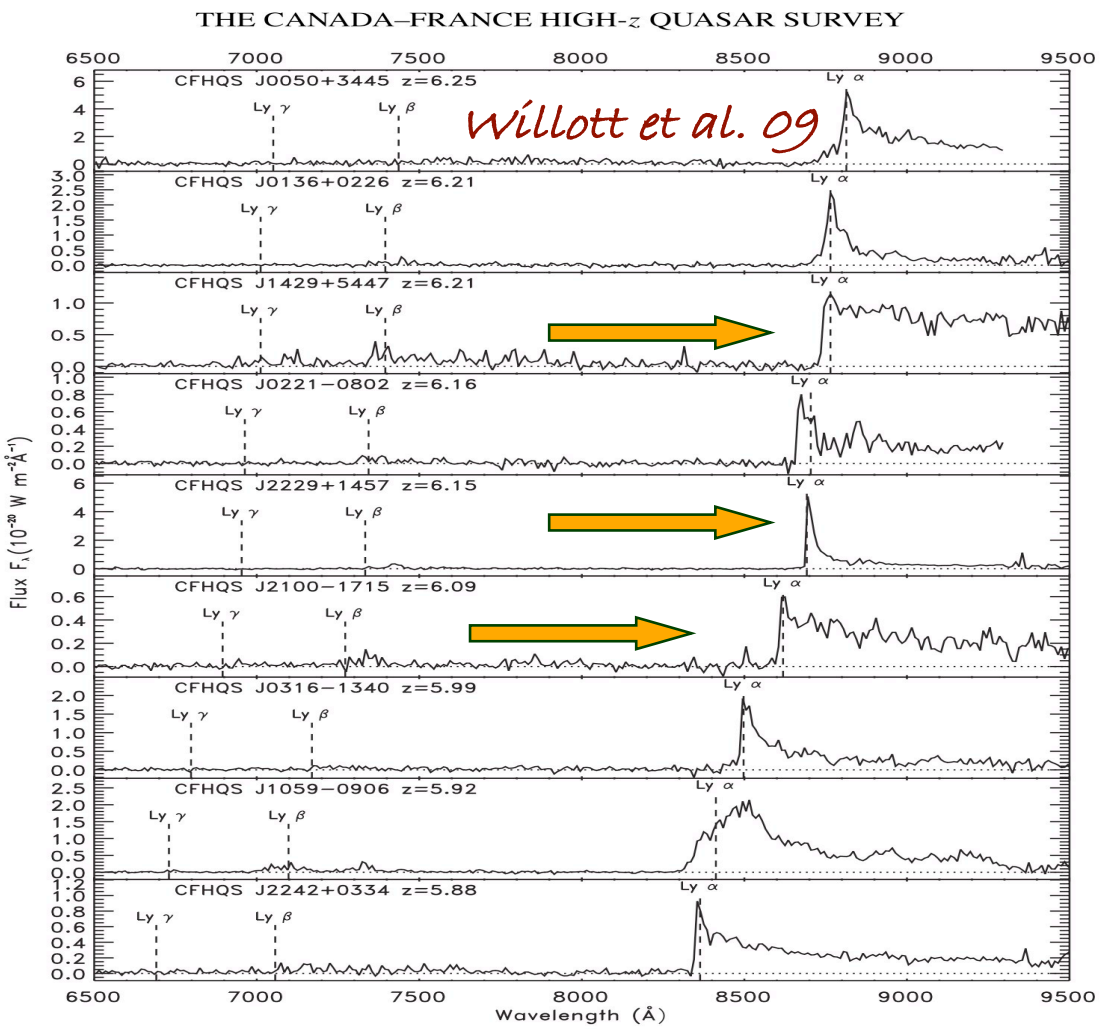
R_W : Fan et al. 06

R_{max} : Analytic estimate

$$R_W > R_{max} \rightarrow \Gamma_{tot} > \Gamma_B + \Gamma_Q$$

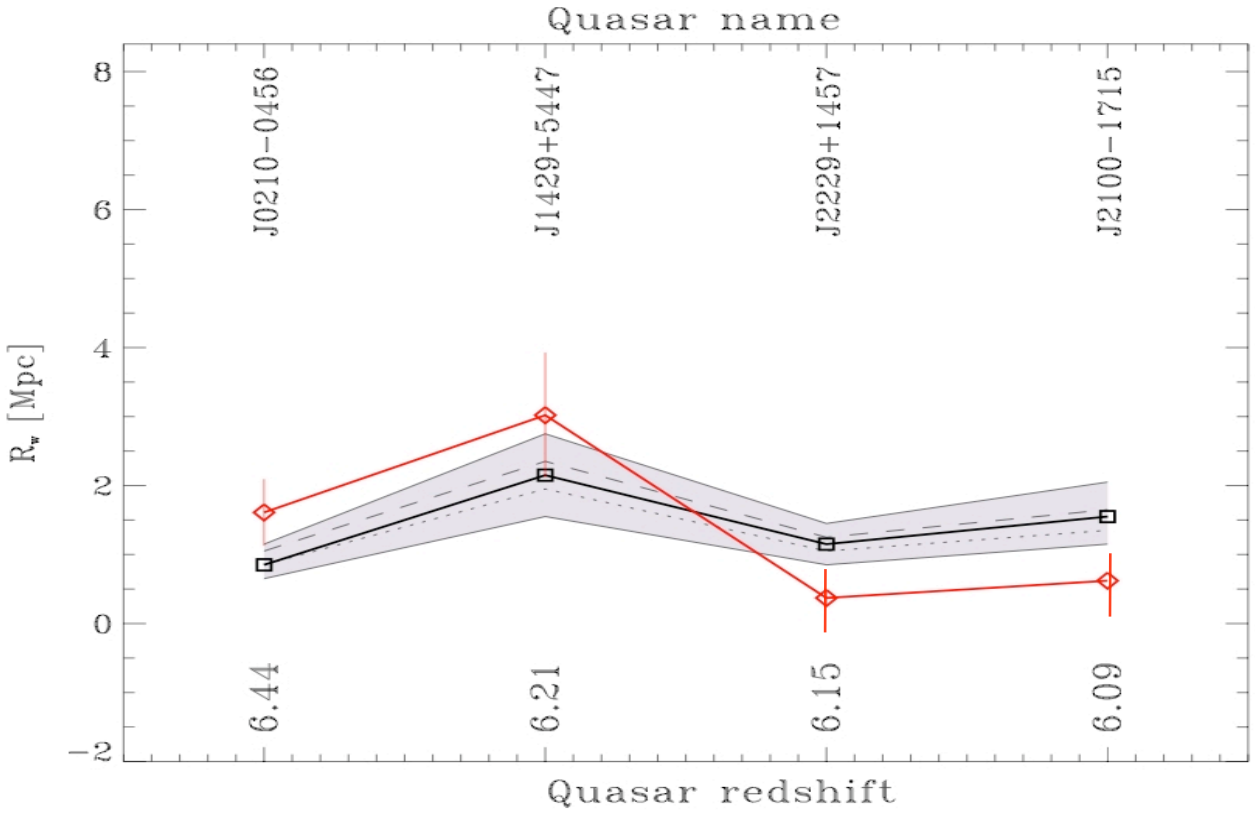
- Enhanced galaxy number density around the quasar (?)
- Evolving quasar luminosity (?)

Looking for QSOs in the HII Region Regime



- Small extent of the transmission windows
- Low luminosity QSOs

Looking for QSOs in the HII Region Regime

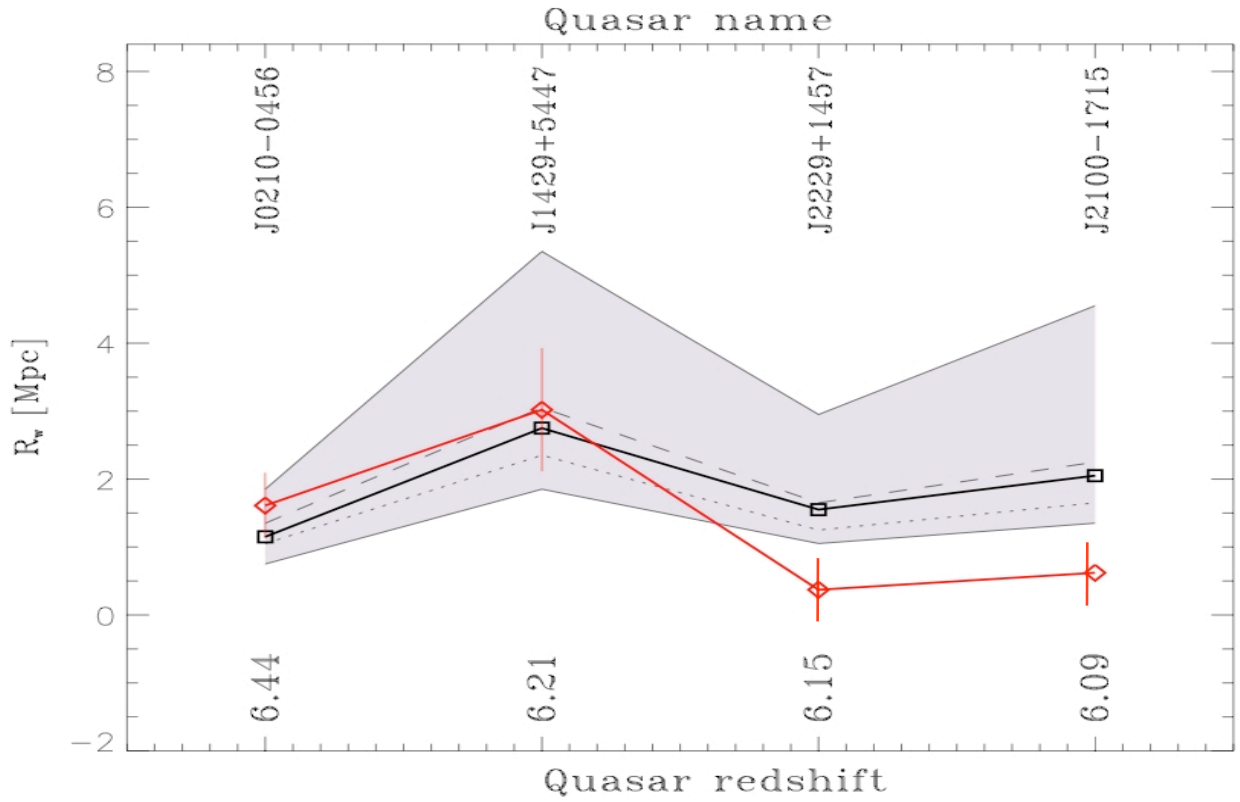


R_w : Willott et al. 10

R_{max}: Analytic estimate

- $T = (1.5 \pm 0.5) \times 10^4$ K
- Γ_B from Early Reionization Model (Gallerani et al. 07)

Looking for QSOs in the HII Region Regime



R_w : Willott et al. 10

R_{max}: Analytic estimate

- $T = (2.3 \pm 0.93) \times 10^4$ K (Bolton et al. 2010)
- Γ_B from Early Reionization Model (Gallerani et al. 07)

Tentative xHI local measurements

J2100 @ z=6.09 and J2229 @ z=6.15

$$R_{HII} \approx 3.3 \times \left(\frac{\dot{N}_\gamma}{10^{57} s^{-1}} \frac{t_Q}{10^7 yr} \Delta^{-1} \right)^{1/3} \left(\frac{1+z}{7} \right)^{-1} x_{HI}{}^{-1/3} Mpc$$

$$\rightarrow \quad x_{HI} \approx \left(\frac{\dot{N}_\gamma}{10^{57} s^{-1}} \frac{t_Q}{10^7 yr} \Delta^{-1} \right) \left(\frac{3.3 Mpc}{R_{HII}} \right)^3 \left(\frac{1+z}{7} \right)^{-3}$$

Tentative xHI local measurements

$$x_{HI} \approx \left(\frac{\dot{N}_\gamma}{10^{57} s^{-1}} \frac{t_Q}{10^7 yr} \Delta^{-1} \right) \left(\frac{3.3 Mpc}{R_{HII}} \right)^3 \left(\frac{1+z}{7} \right)^{-3}$$

J2100 @ z=6.09

$R_{HII} = 0.62$ Mpc

$N_\gamma = 2 \times 10^{56}\ s^{-1}$

$$x_{HI} \approx 0.28 \times \left(\frac{t_Q}{10^6 yr} \right) \left(\frac{\Delta}{10} \right)^{-1}$$

J2229 @ z=6.15

$R_{HII} = 0.37$ Mpc

$N_\gamma = 1.2 \times 10^{56}\ s^{-1}$

$$x_{HI} \approx 0.85 \times \left(\frac{t_Q}{10^6 yr} \right) \left(\frac{\Delta}{10} \right)^{-1}$$

Summary

- **The Apparent Shrinking Criterion (ASC) :**
  Semi-analytic method which discriminates between H_{II} Region (HR) and Proximity Region (PR) Regime for observed high redshift quasar.

- SDSS quasars (Fan 06) are in the PR regime and are consistent with a highly ionized Universe up to $z \sim 6.4$.

- Three SDSS objects show evidence for a locally enhanced photoionization rate, produced either by
  - intervening galaxy clustering (?)
  - quasar luminosity evolution (?)

- Two CFHQS (Willott 09), J2100 and J2229 are in the HR regime.
  - Tentative x_{HI} measurements show the presence of highly neutral gas ($x_{HI} > 0.28$; $x_{HI} > 0.85$) within 1Mpc from the source.
  - Constraints are week due to the lack of knowledge on t_Q and local Δ