Windows on the Opaque Intergalactic Medium in the Spectra of high-z Quasars

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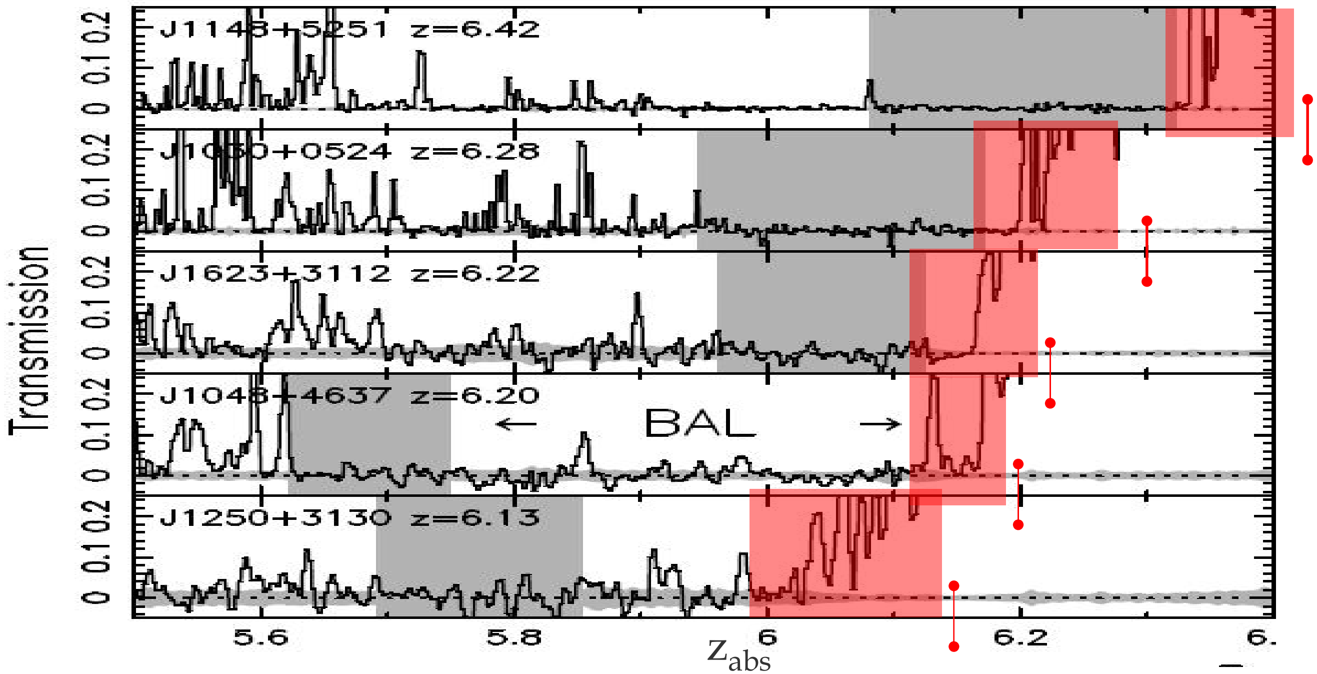
Windows of Transmission in the Opaque Universe

High-z QSO Spectra show:

- the onset of the GP through @ z > 5.7
- transmitted flux close by the QSO

(Fan et al. 06)



No Transmitted Flux @ z> 5.7, i.e. Gunn Peterson Trough ⇒ $\{ \tau_{IGM} > 2.5,\ x_{HI} > 10^{-3.8}$

Transmitted Flux approaching the quasar redshift ⇒ $\{ \tau_{IGM} < 2.5,\ x_{HI} < 10^{-3.8}$

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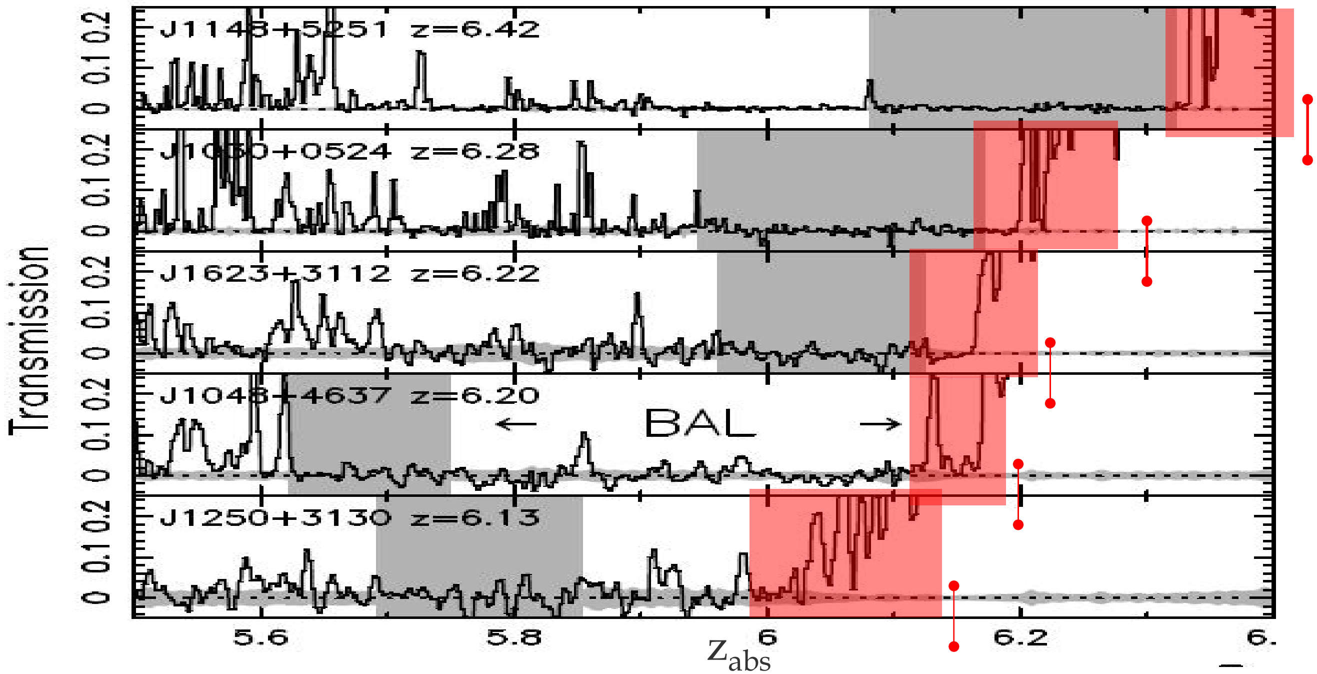
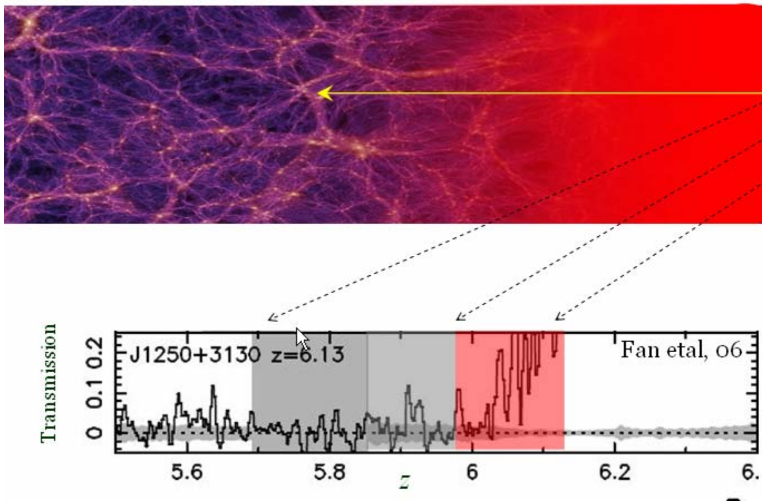


These spectral features offer the unique possibility to look through stretches of the IGM in the Opaque Universe and can provides important insights on the physical state of the IGM at z>6

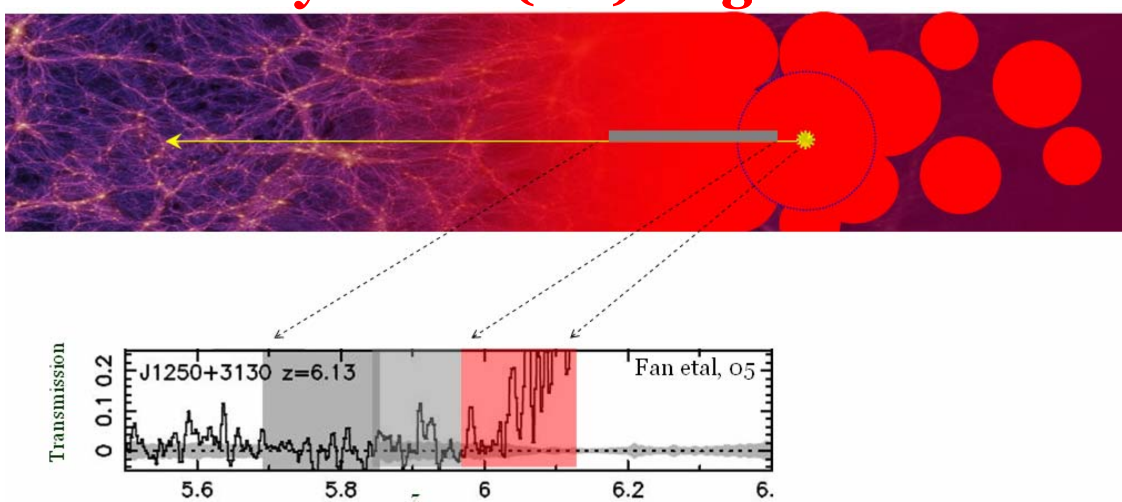
Two Physical Regimes with Similar Emerging Spectra

H_{II} Region (HR) Regime



Observed spectra have Different Implications for each of the two Regimes

Proximity Effect (PE) Regime



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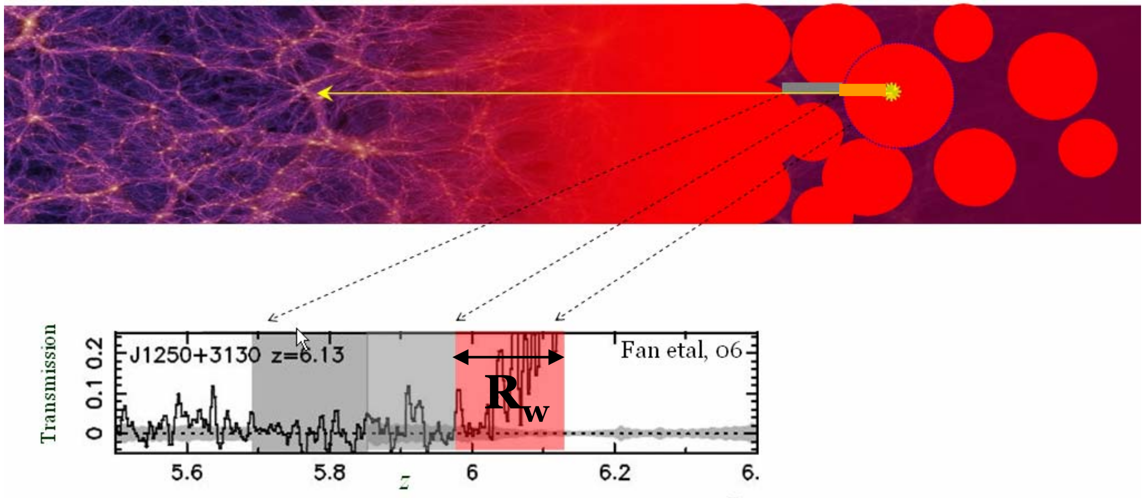


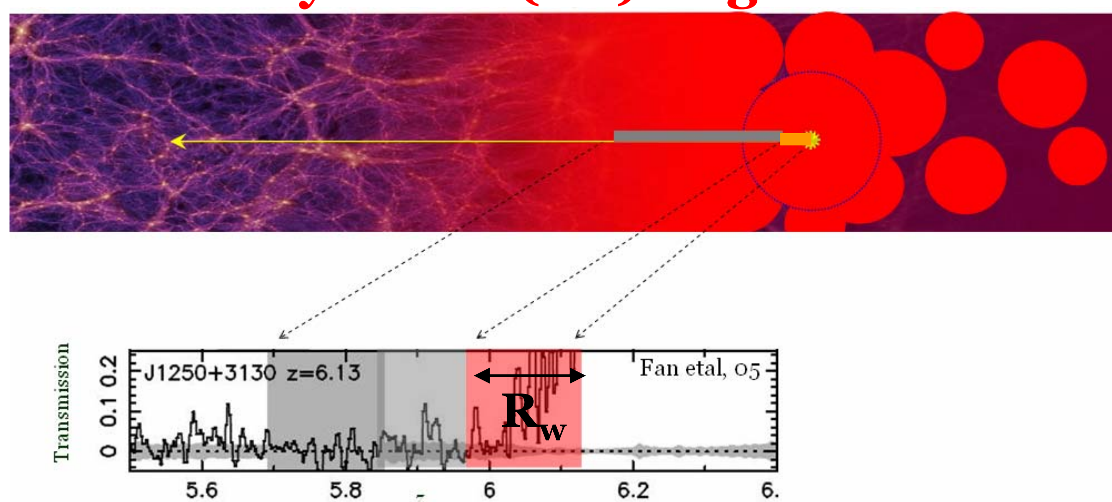
The window of transmitted flux is the spectral counterpart of the quasar H_{II} region

Its extent is set by H_{II} region radius
$R_w = R_{HII}\,(x_{HI}, N_\gamma, t_Q)$

Proximity Effect (PE) Regime

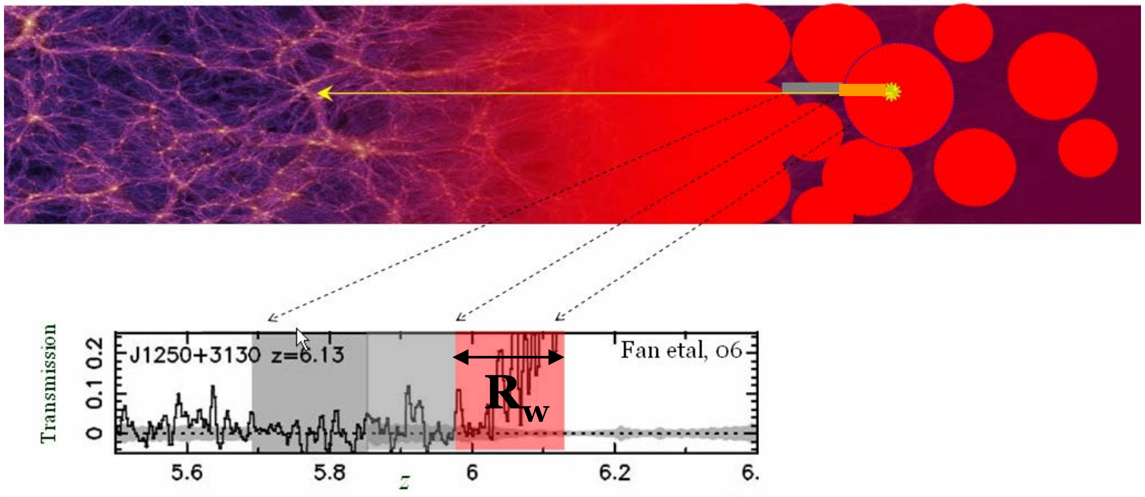
The window of transmitted flux is a signature of the quasar PE

Its extent is set by the onset of the GP through within the H_{II} region
$R_w < R_{HII}$
"Apparent Shrinking"



The HR Regimes Constraints on Reionization

H_{II} Region (HR) Regime



The IGM ionization state can be constrained:

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

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

$$R_{\rm HII} = \left(\frac{3\dot{N}_\gamma t_Q}{4\pi x_{\rm HI}}\right)^{1/3}$$

Assuming that the HR Regime applies, current observations imply a still neutral Universe at $z \sim 6$

$\mathbf{x_{HI} > 0.1}$

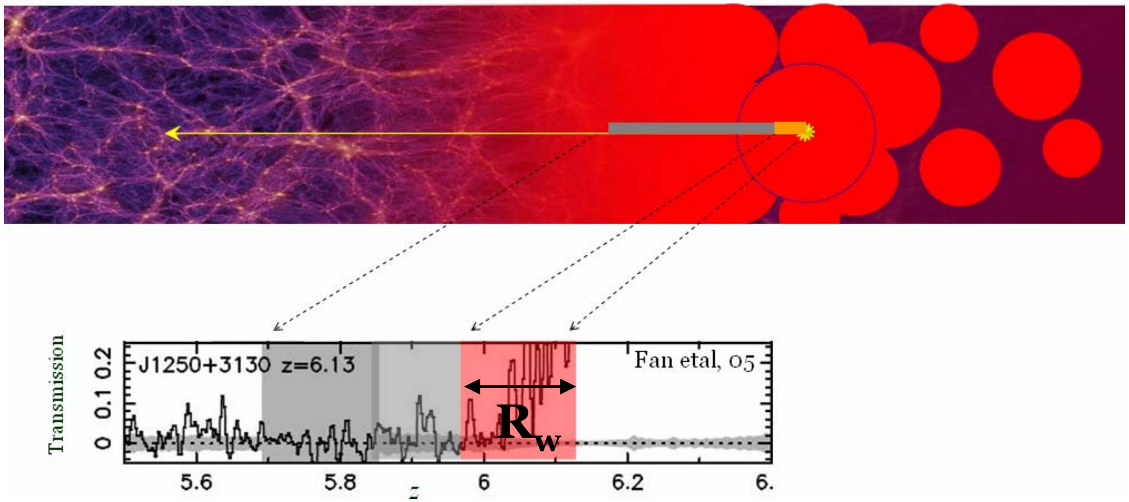
Wyithe & Loeb 04

Wyithe, Loeb & Carilli 04

Fan etal. 06; Yu & Lu 04

The PE Regime Constraints on Reionization

Proximity Effect (PE) Regime



R_w can be **much smaller** than the **H_{II} region** size

R_w & R_{HII} independent

In PE Regimes **R_w don't constraint x_{HI}**.

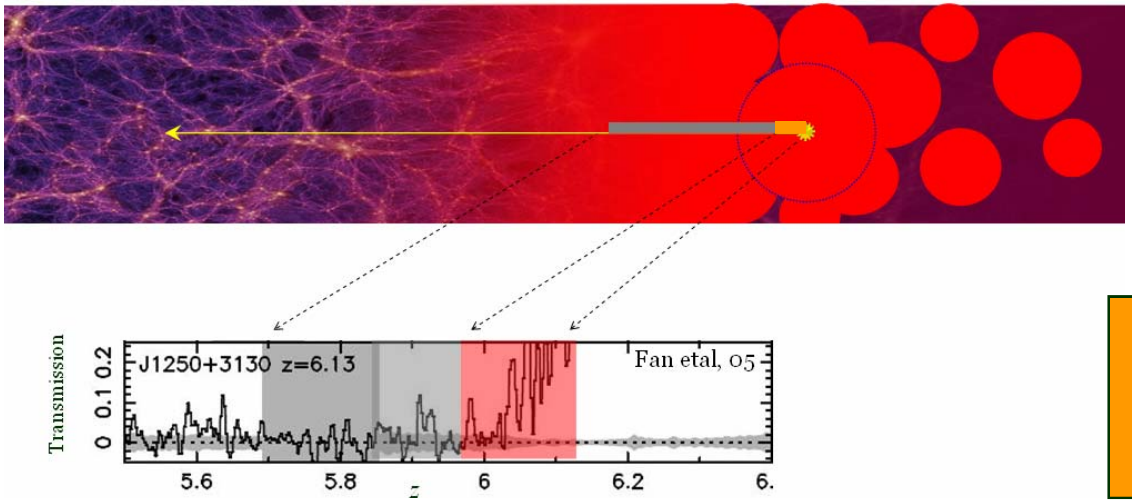
Current observations are consistent with a **highly ionized IGM at z~6**

Bolton & Haehnelt 07

AM et al.07

The Apparent Shrinking Effect

ie. Why R_w does not grow as R_{HII}



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

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

$$x_{\rm HI} < 0.1 \longrightarrow R_{\rm HII} > 10 \text{ Mpc com} \qquad (R_{\rm HII} \propto x_{\rm HI}^{-1/3})$$

$$\Gamma_Q \propto R^{-2} \longrightarrow$$

At large distances Γ_Q becomes too small to produce enough extra ionization and to keep the IGM transparent

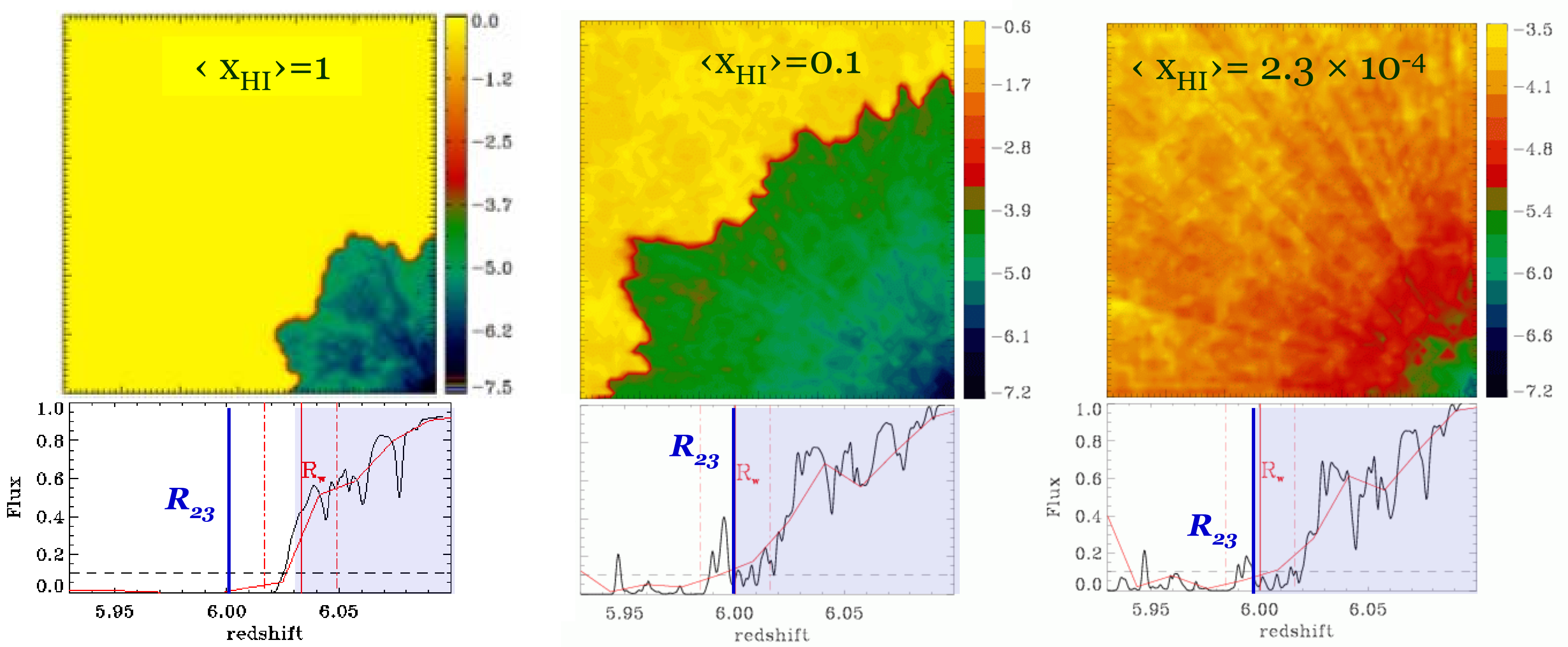
The Apparent Shrinking Effect

SPH + 3D Radiative Transfer (Gadget2 + CRASH)

(Ciardi et al.01; AM et al. 03, 08)

(***CRASHα*** *see Pierleoni, AM, Ciardi 07; Poster*)

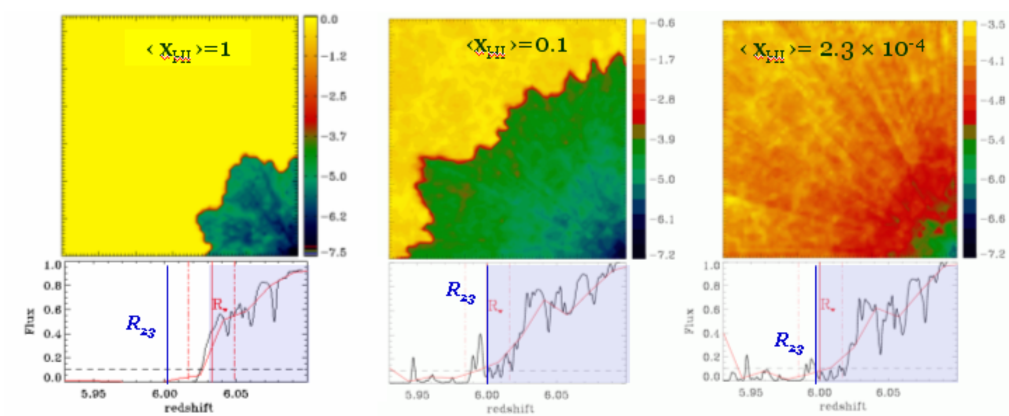
$N_\gamma = 2 \times 10^{57} s^{-1}$
$t_Q = 10^7$ yr
$z_Q = 6.1$



- $R_{\rm HII} \propto x_{\rm HI}^{-1/3}$
- $\boldsymbol{R_w \leq R_{HII}}$
- $\boldsymbol{R_w}$ saturates at a fixed distance from the QSO, independent from $\boldsymbol{x_{HI}}$ → $\boldsymbol{R_{23}}$

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

- ***R_w*** : extent of the transmission window
- ***R_{23}*** : maximum distance from the QSO where transmitted flux can be detected



The "Apparent Shrinking" Criterion

R_{23} : maximum distance from the QSO where transmitted flux can be detected (distance from the quasar at which $\tau > 2.3$, i.e. $F < 0.1$)

R_{23} can be derived semi-analytically requiring ***$F(R_{23}) = 0.1$*** in the following set of equations:

$$F(R) = \int_0^\infty e^{-\tau_\Delta(R)} P_\Delta(\Delta) d\Delta$$

$$\tau_\Delta(R) = 2.9 \times 10^5 h^{-1} \left(\frac{\Omega_m}{0.26}\right) \left(\frac{\Omega_b h^2}{0.0241}\right) \left(\frac{1+z}{7}\right)^{3/2} x_{\mathrm{HI}}(\Delta, R)$$

$$\Gamma(R) = \Gamma_B + \Gamma_Q(R) + \Gamma_G(R)$$

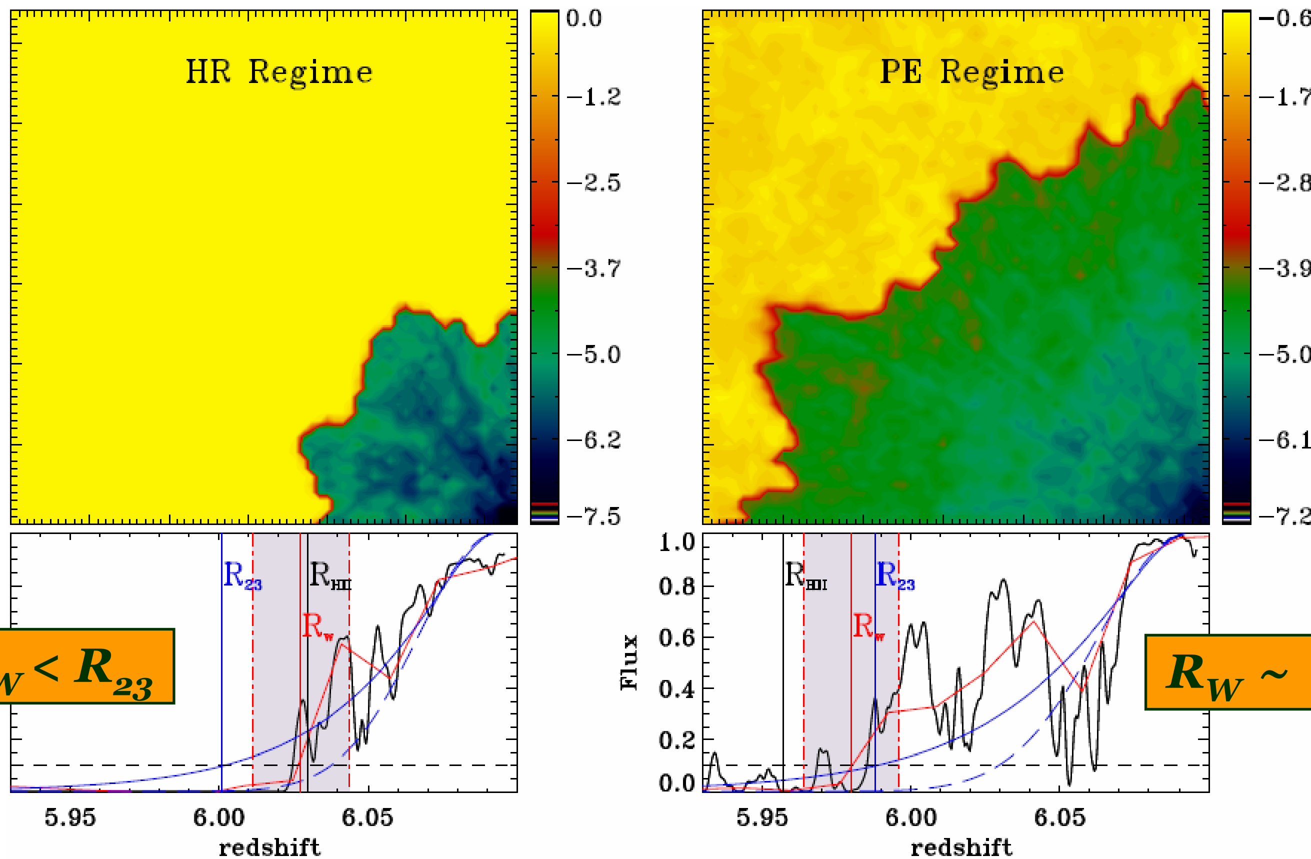
R_{23} depends on: ***T*** (temperature), ***Γ_Q*** (quasar luminosity), ***Γ_B*** (UVB), ***Γ_G*** (galaxies clustered)

- T and Γ_B are constrained from Lyα forest observations and reionization models
- $\Gamma_Q = \frac{\dot{N}_\gamma \bar{\sigma}_H}{4\pi R^2}$ with $\dot{N}_\gamma = \dot{N}_\gamma(M_{1450}, S_\nu)$ and $R_{HII} \rightarrow \infty$
- R_{23} is determined assuming a zero contribution from galaxy clustering ($\Gamma_G = 0$)

The "Apparent Shrinking" Criterion

- $R_w < R_{23}$: HR Regime → $R_w = R_{HII}$ and x_{HI} can be constrained.
- $R_w = R_{23}$: PE Regime → the $\Gamma_G = 0$ assumption is confirmed observationally
- $R_w > R_{23}$: PE Regime → $\Gamma_G \neq 0$ and Γ_G can be estimated by imposing $F(R_w) = 0.1$

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



$R_W < R_{23}$

$R_W \sim R_{23}$

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

Testing the ASC with Numerical Simulations

- $R_w < R_{23}$: HR Regime → $R_w = R_{HII}$ and x_{HI} can be constrained.
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$\dot{N}_{\gamma,57}$	$\bar{x}_{\rm HI}$	t_Q [10^7 yr]	R_{23} [Mpc]	R_w [Mpc]	Regime
0.56	0.1	1	2.51(2.96)	2.74 ± 0.96	PE
0.56	$10^{-4.2}$	1	2.30(2.43)	2.74 ± 1.60	PE
2	0.1	1	4.83(5.35)	5.50 ± 1.47	PE
2	$10^{-4.2}$	1	4.51(4.93)	5.66 ± 1.86	PE
2	1	1	3.4(4.7)	3.70 ± 0.64	HR
2	1	2	4.2(5.7)	4.55 ± 0.89	HR

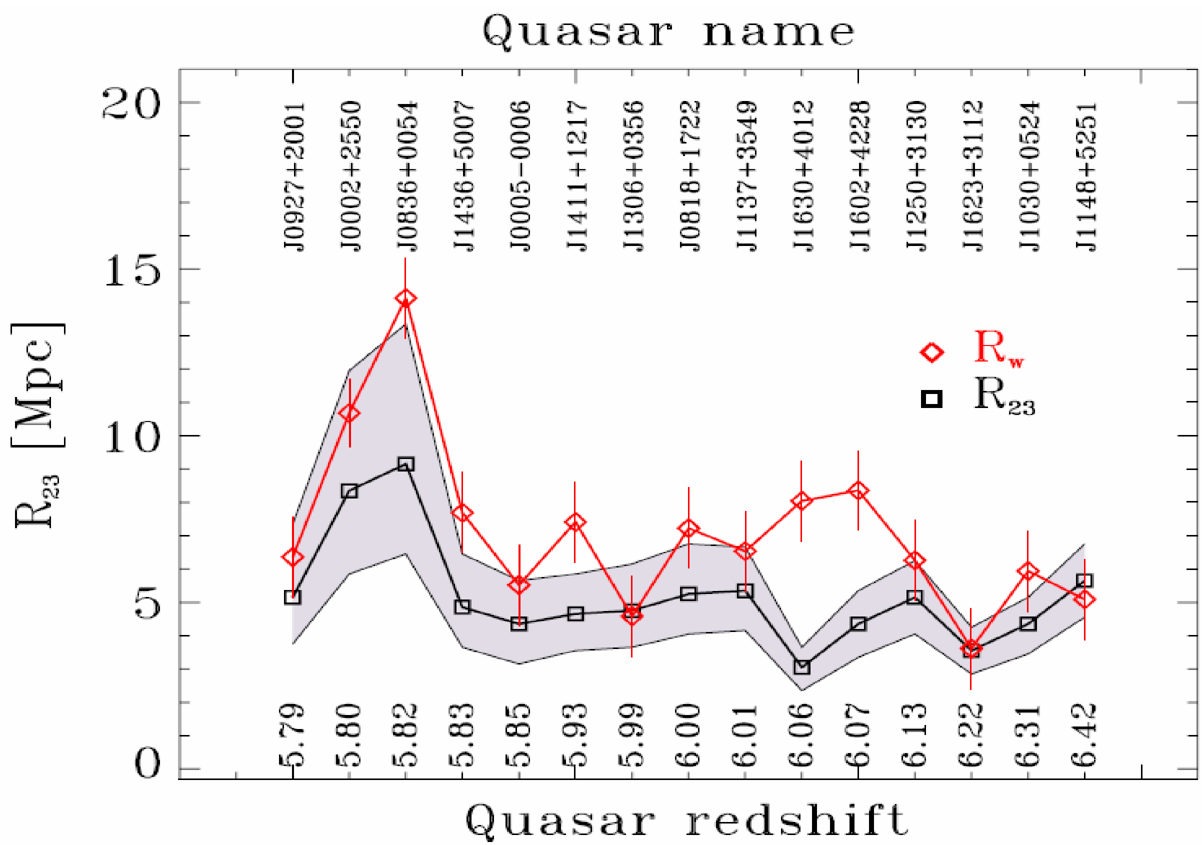
x_{HI} at photoionization equilibrium

(NO inner opacity; NO flux drop-off at the ionization front)

x_{HI} from RT simulations

- The R_{23} semi-analytical estimate formulated is highly accurate.
- The effects of the residual H_I inside the H_{II} region can be safely neglected.

The ASC applied to observed Spectra



R_w : Observations (Fan et al. 06)

R_{23}: Analytical Estimate

$T = (1\pm0.5)\times10^4$ K

Γ_B Gallerani et al. 07 ER Model

Reionization is complete by z≈ 7

Consistent with the Bolton et al. 07 upper limit of $\Gamma_B < 0.34 \times 10^{-12}$ s^{-1}

1. **The PE regime applies in all cases: current data do not allow to constraint x_{HI}.**
2. **Current data are consistent with a highly ionized IGM at z≈6.4 , i.e. consistent with "Early Reionization"**

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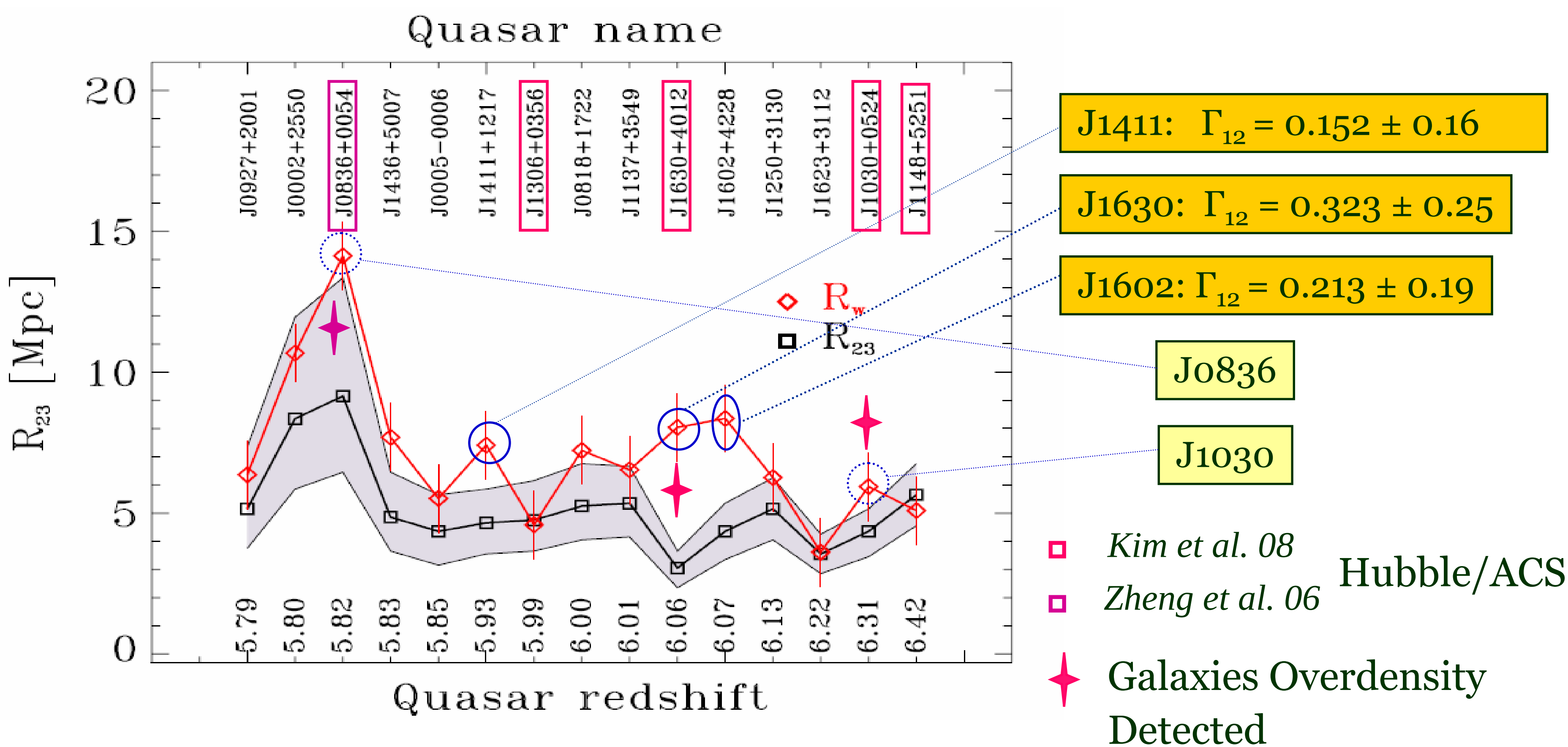

1. **The PE regime applies in all cases: current data do not allow to constraint x_{HI}.**
2. **Current data are consistent with a highly ionized IGM at z≈6.4 , i.e. consistent with "Early Reionization"**
3. **Three QSO spectra show evidence for a local enhanced galaxy clustering**

Conclusions

- The **Apparent Shrinking Criterion (ASC) :**
  Semi-analytic method which allows to discriminate between H_{II} Region (HR) and Proximity Effect (PE) Regime for each observed high redshift quasar.

- All observed quasars spectra are in the PE regime and are consistent with a highly ionized Universe up to z ~ 6.4.

- Five quasars show evidence for a locally enhanced galaxy clustering, in agreement with galaxy counts in fields centred on the same objects *(Kim et al. 08)*.

- ASC powerful tool for probing the ionization state of the high redshift universe. Fainter quasars at higher redshift are more probable to be found in HR regime.