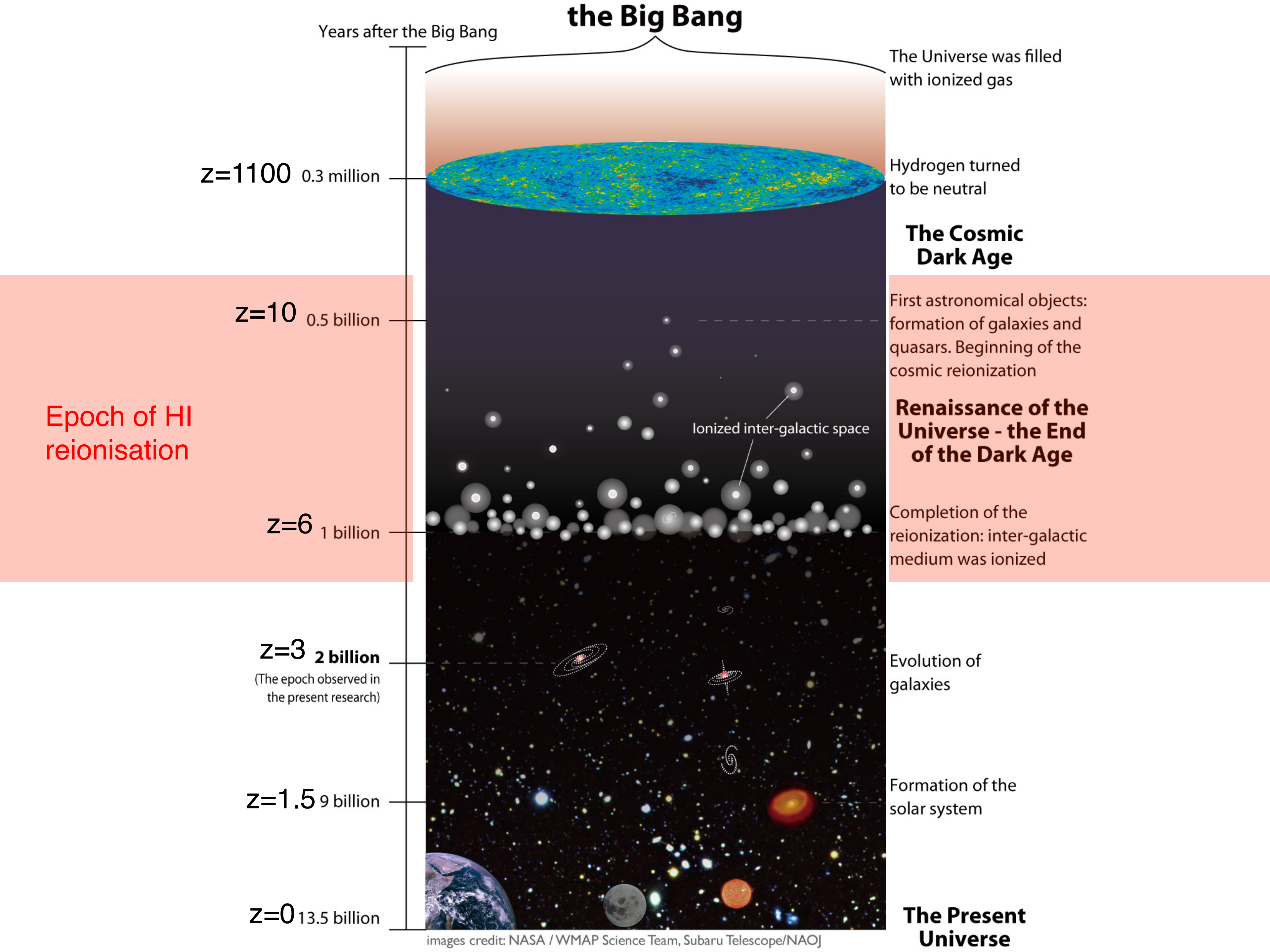
Trieste Joint Seminar, 17.04.13

Reionisation via the Ly-α line

The University of Nottingham

Jamie Bolton

With thanks to:
Benedetta Ciardi (MPA),
George Becker, Martin Haehnelt (Cambridge),
Sudhir Raskutti (Princeton), Stuart Wyithe (Melbourne)

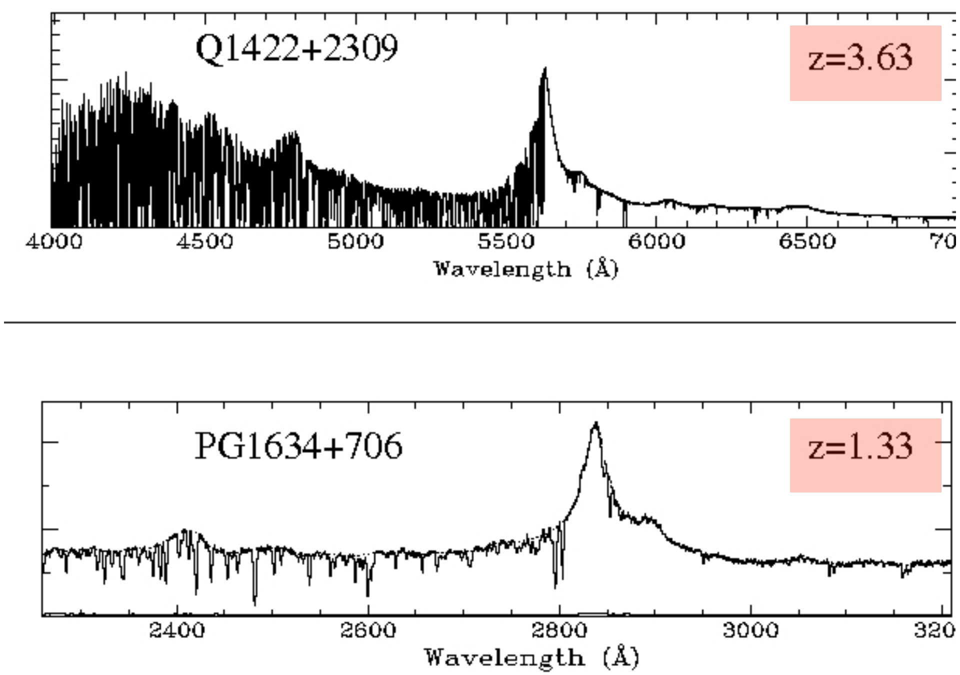


the Big Bang
Years after the Big Bang
The Universe was filled with ionized gas
z=1100 0.3 million
Hydrogen turned to be neutral
The Cosmic Dark Age
z=10 0.5 billion
First astronomical objects: formation of galaxies and quasars. Beginning of the cosmic reionization
Epoch of HI reionisation
Ionized inter-galactic space
Renaissance of the Universe - the End of the Dark Age
z=6 1 billion
Completion of the reionization: inter-galactic medium was ionized
z=3 2 billion
(The epoch observed in the present research)
Evolution of galaxies
z=1.5 9 billion
Formation of the solar system
z=0 13.5 billion
The Present Universe
images credit: NASA / WMAP Science Team, Subaru Telescope/NAOJ

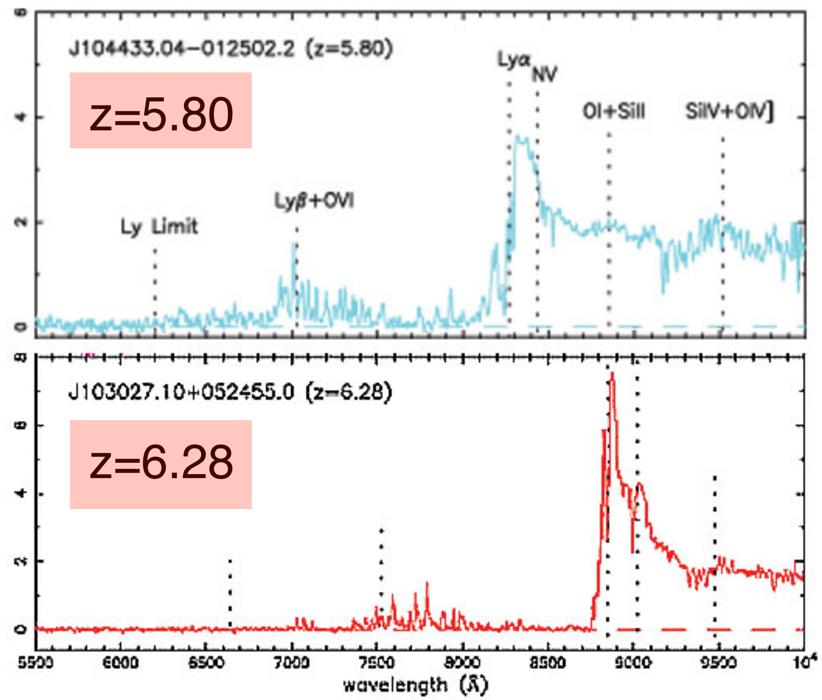
Reionisation: the key evidence

I: The Gunn-Peterson trough

- Gunn-Peterson (1965) trough in QSO spectra implies H-I fraction in IGM is increasing toward higher redshift.



Charlton & Churchill (2000)



Becker et al. (2001)

Reionisation: the key evidence

I: The Gunn-Peterson trough

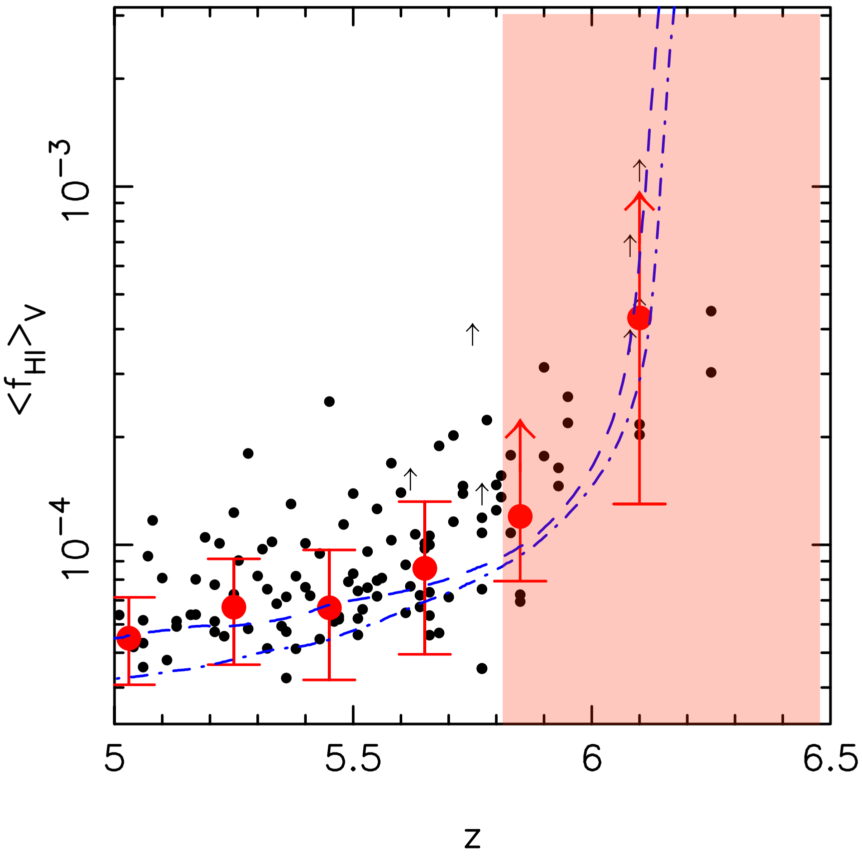
- Observed Ly-α flux at z=6 (SDSS):

$$< F >= e^{-\tau} < 0.004$$

$$\Rightarrow \tau > 5.5$$

- Large Ly-α absorption cross-section limits sensitivity to $f_{HI}<10^{-4}$:

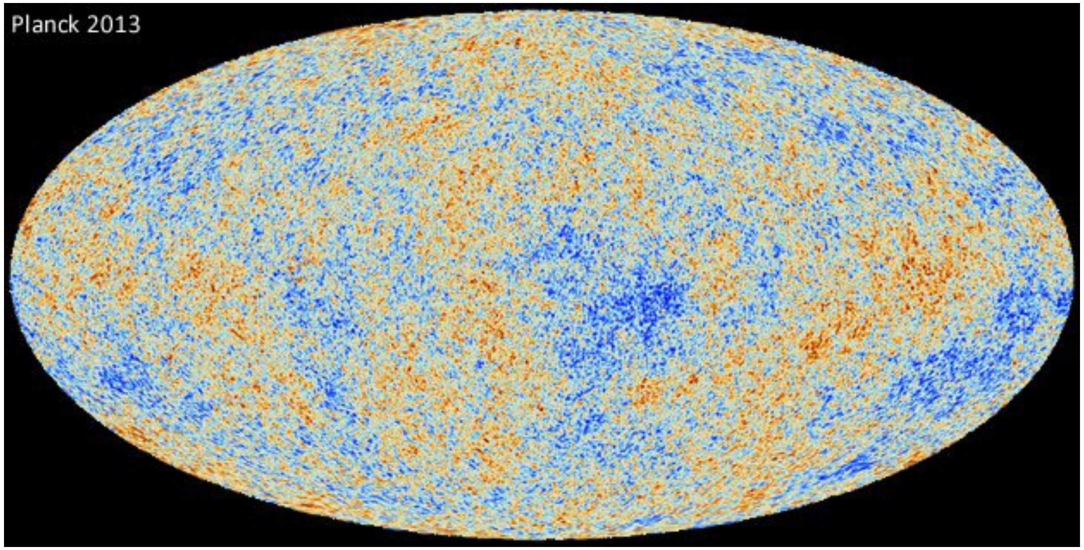
$$\tau \approx 4.3\times 10^{5} f_{HI}\left(\frac{1+z}{7}\right)^{3/2}$$



Fan et al. (2006)

Reionisation: the key evidence

II: Cosmic Microwave Background Data



- Thomson scattering of CMB photons off free electrons modifies the T and TE power spectra;

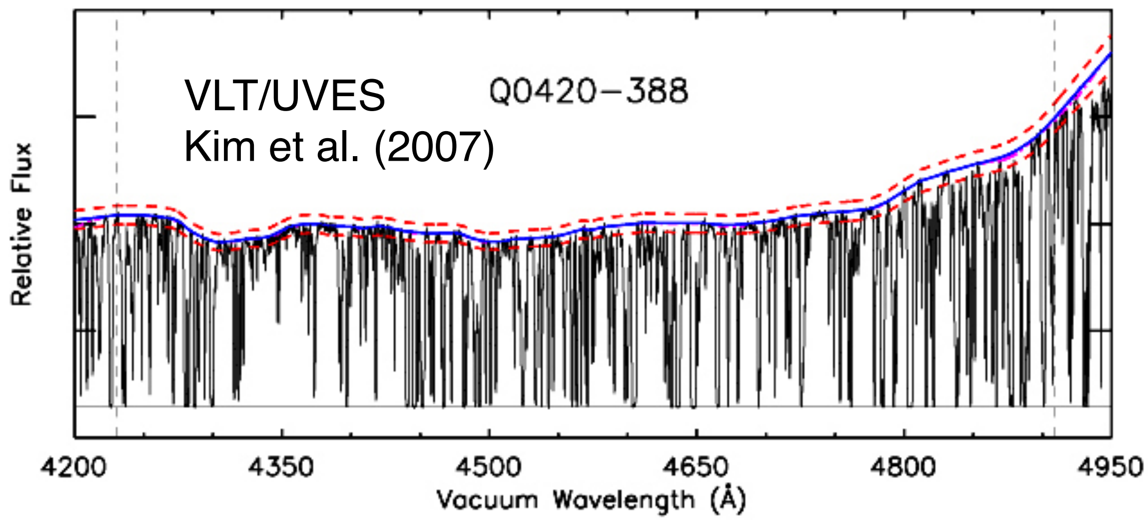
- Only gives a constraint on the integrated reionisation history. Assuming instantaneous reionisation:

$$\tau_e = 0.092 \pm 0.013 \Rightarrow z_r = 11.3 \pm 1.1 \, (68\%)$$

Planck Collaboration XVI (2013)

Reionisation: the key evidence

III. Post-reionisation constraints from the Ly-α forest



- The Ly-α forest encodes information on the ionisation state of the IGM at z<6.

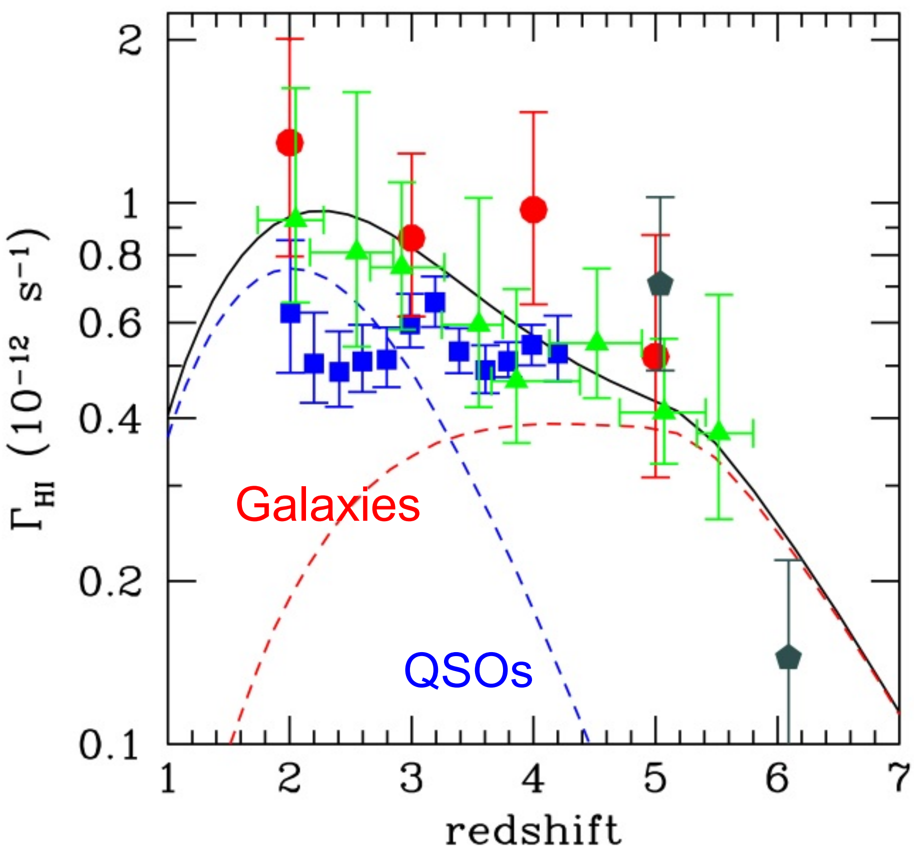
Ly-α opacity

$$\tau = \tau_0 \frac{(1+z)^6 (\Omega_b h^2)^2}{T_0^{0.7} H(z) \Gamma(z)} (1+\delta)^{2-0.7(\gamma-1)}$$

Photo-ionisation rate

Reionisation: the key evidence

III. Post-reionisation constraints from the Ly-α forest

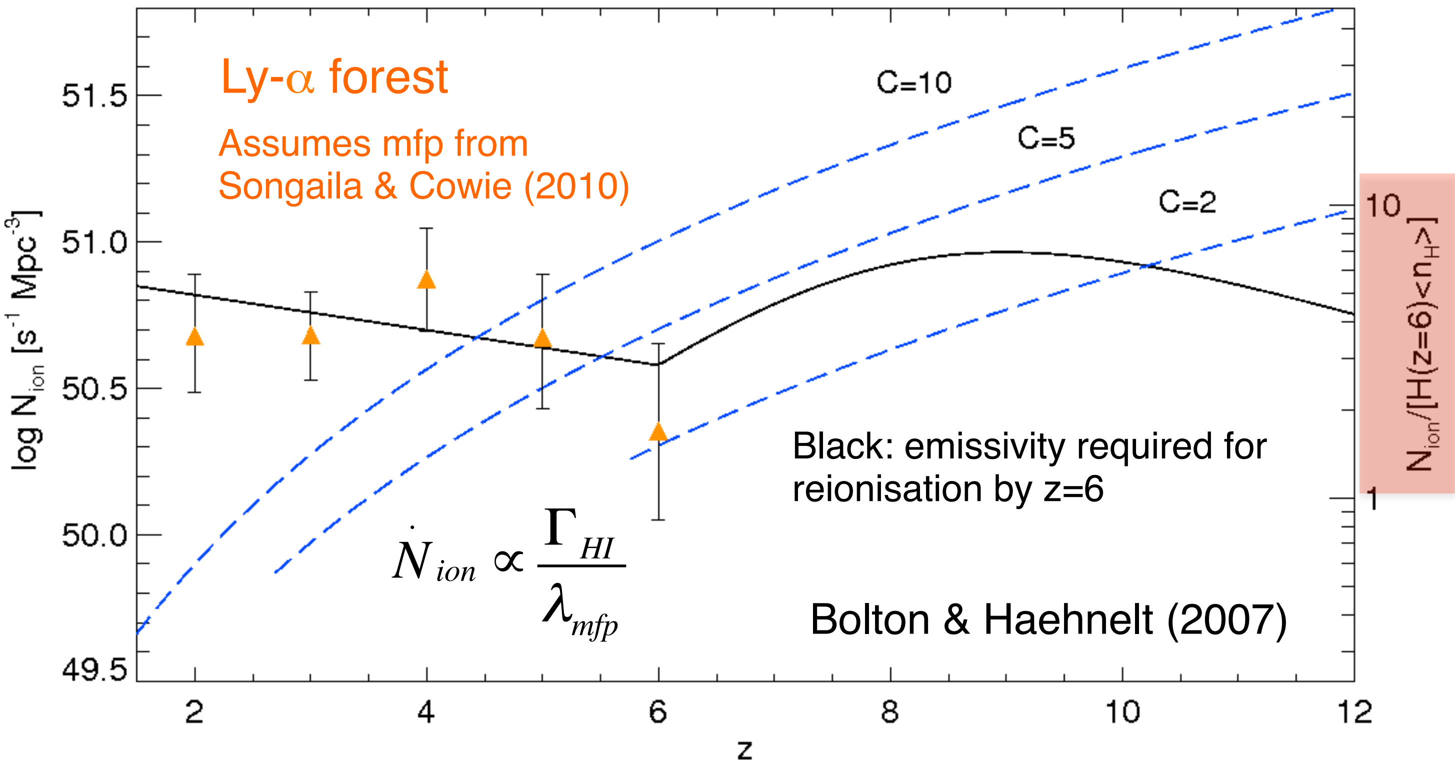


Haardt & Madau (2012)

- Observed quasars do not account for all of the ionising photons required to keep the Universe ionised at z=6 (see also Fontanot et al. 2012).

- Increasingly significant contribution from star forming galaxies required toward higher redshift.

How many photons do we need?



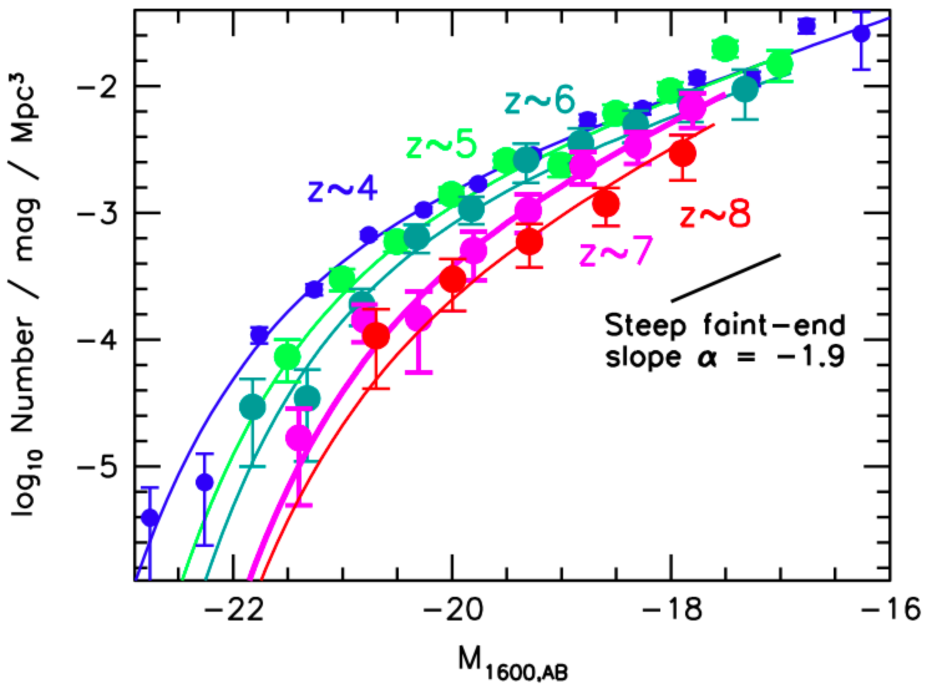
Ionising photons per H atom emitted over a Hubble time at z=6.

- Ly-α forest consistent with only 1-3 ionising photons per HI emitted over a Hubble time at z=6 (see also Miralda-Escude 2003, Kuhlen & Faucher-Giguere 2012);

- Ionising emissivity must remain constant or rise at z>6 for reionisation to complete by z=6.

Reionisation: the key evidence

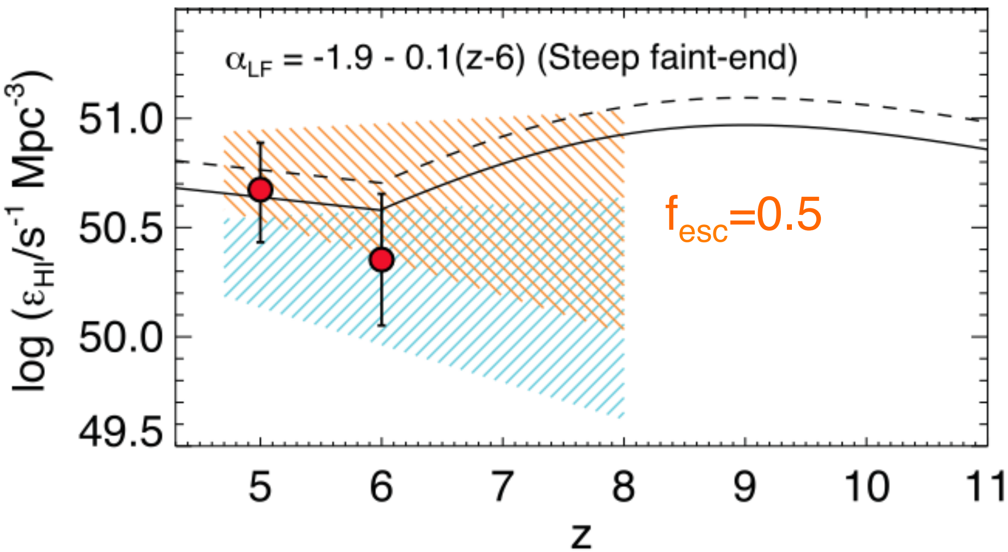
IV. The sources of reionisation at z>6?



- Can now observe bright drop-out galaxies (M<-17) up to z~8 with HST/WFC3.
- Measure luminosity function; estimate star formation rates, stellar masses.
- Number density declines toward higher-z, faint-end steepens.

Bouwens et al. (2012),
see also Schenker et al. (2012) for 2012 UDF

Can galaxies do it?

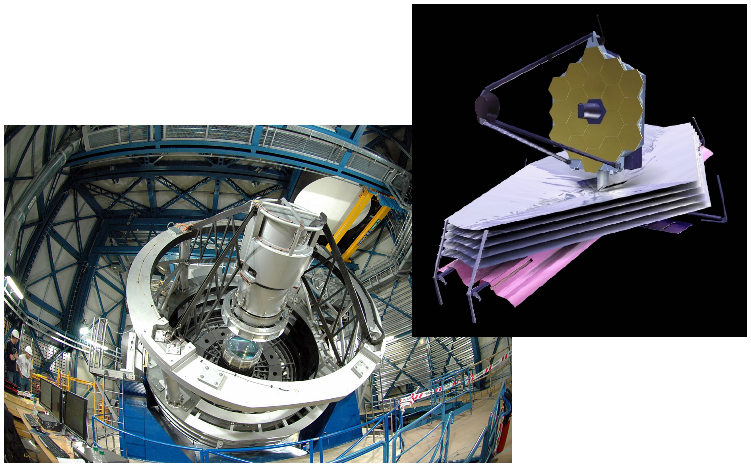


Ciardi, JB et al. (2012)
see also Robertson et al. (2013)

Just about enough ionising photons at z=7-8 if:

- The faint end slope is steep, α<-1.9;
- Escape fraction is large (f_{esc}>0.2-0.5);
- LF extends to fainter magnitudes (M=-10) than observed;
- The IGM clumping factor is low, C<3 (i.e. recombinations occur slowly);

The next decade…



- Infra-red optimised surveys and telescopes will search for quasars and galaxies during reionisation (e.g. VISTA, JWST, Euclid)

- Low frequency radio arrays will search for the redshifted 21cm radiation from neutral hydrogen (e.g. LOFAR, MWA, SKA)

- Ground based 30-m class optical telescopes will enable high resolution spectroscopic analysis of IGM absorption (e.g. E-ELT, TMT, GMT)

Can we learn more in the meantime?

Some additional probes using Lyman-α

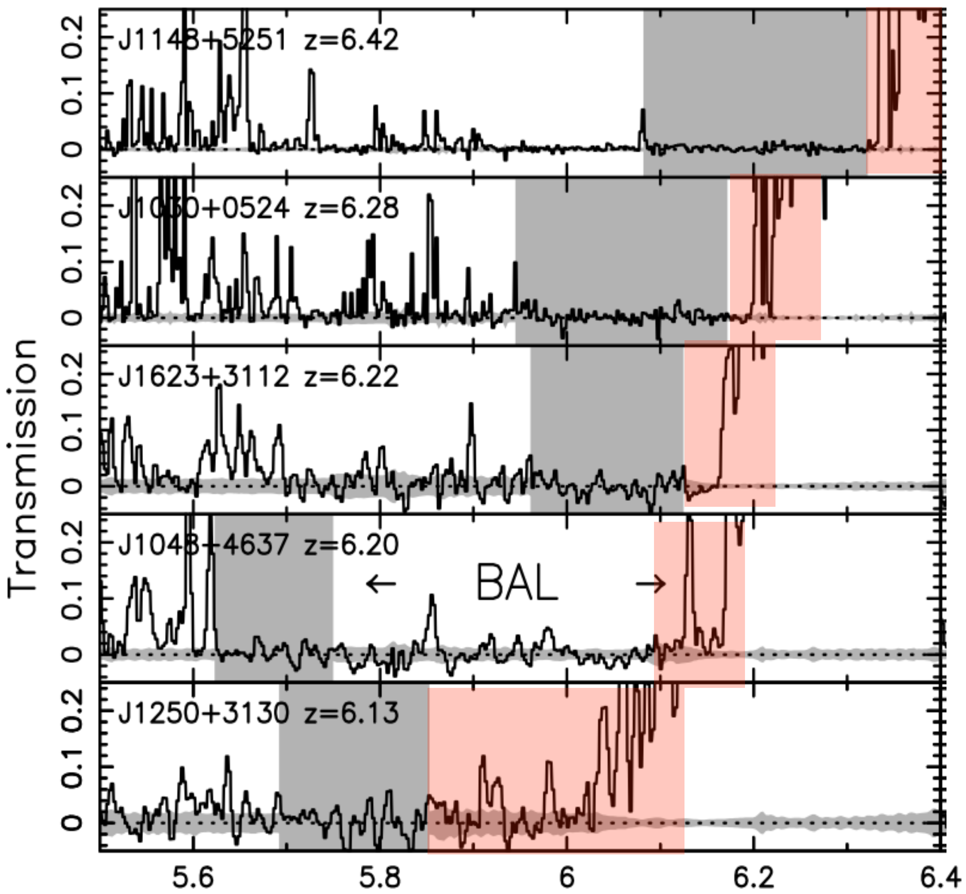
How neutral is the IGM at z~7?

- Quasar near-zones
- Lyman-α emitters

What reionised the IGM?

- The IGM temperature

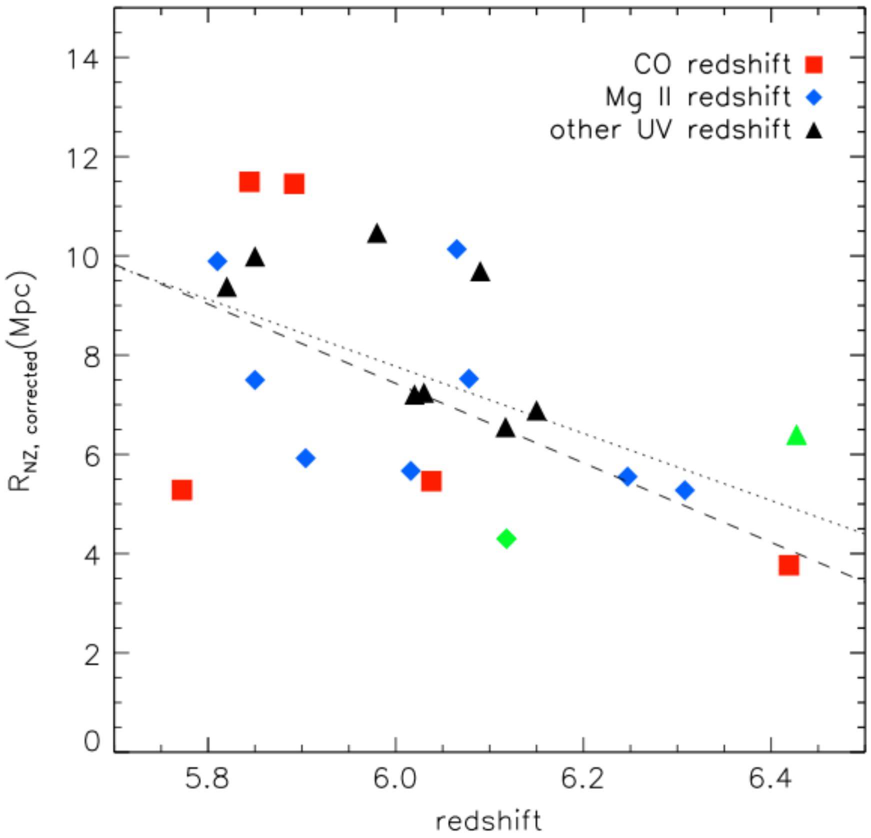
Quasar near-zones



Fan et al. (2006)

- Transmission windows blueward of Ly-α and redward of the Gunn-Peterson trough.
- Arise from enhanced IGM ionisation in close proximity to the QSO.

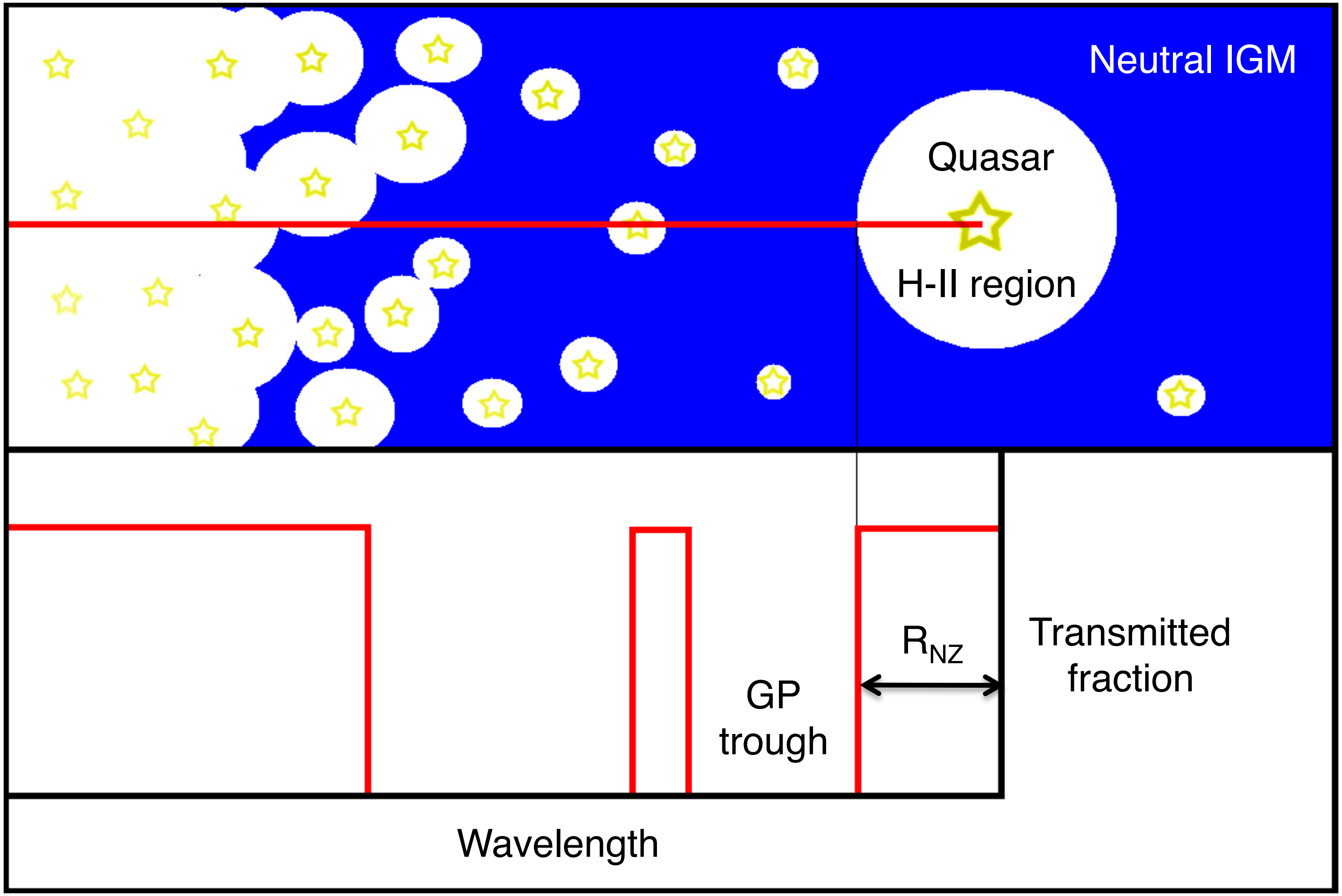
Near-zone size with redshift



- Increasing near-zone size with decreasing redshift at 5.7<z<6.4.
- What drives this evolution?

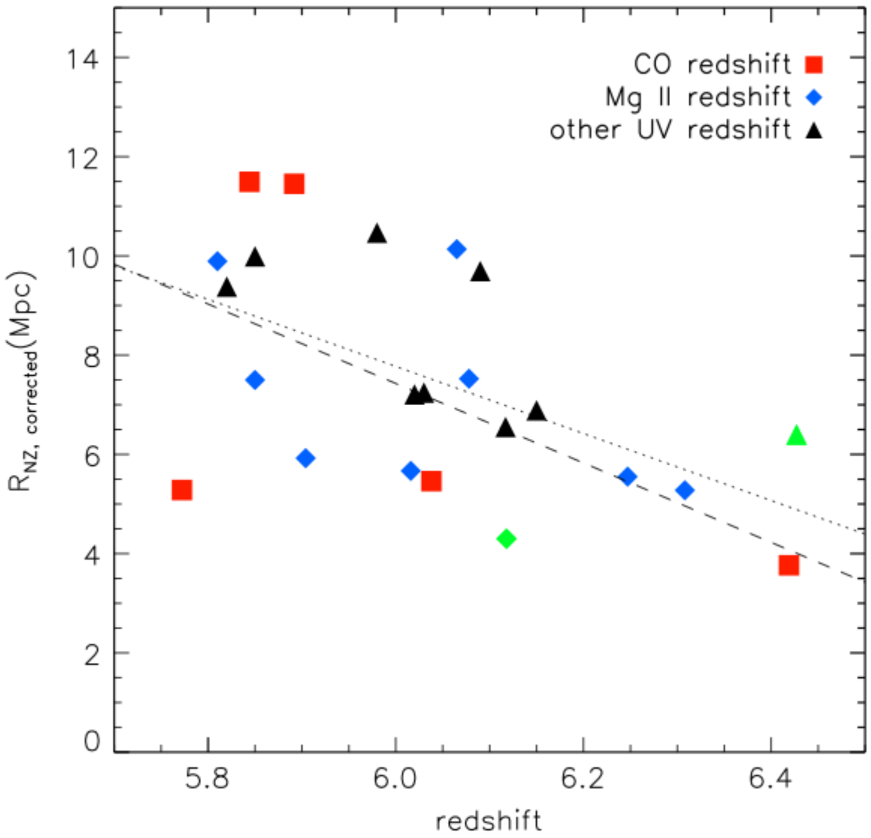
Carilli et al. (2010),
see also Fan et al. (2006)

H-II regions...



$$R_{NZ} \propto \dot{N}^{1/3} t_Q^{1/3} f_{HI}^{-1/3}$$ e.g. Wyithe & Loeb (2004)

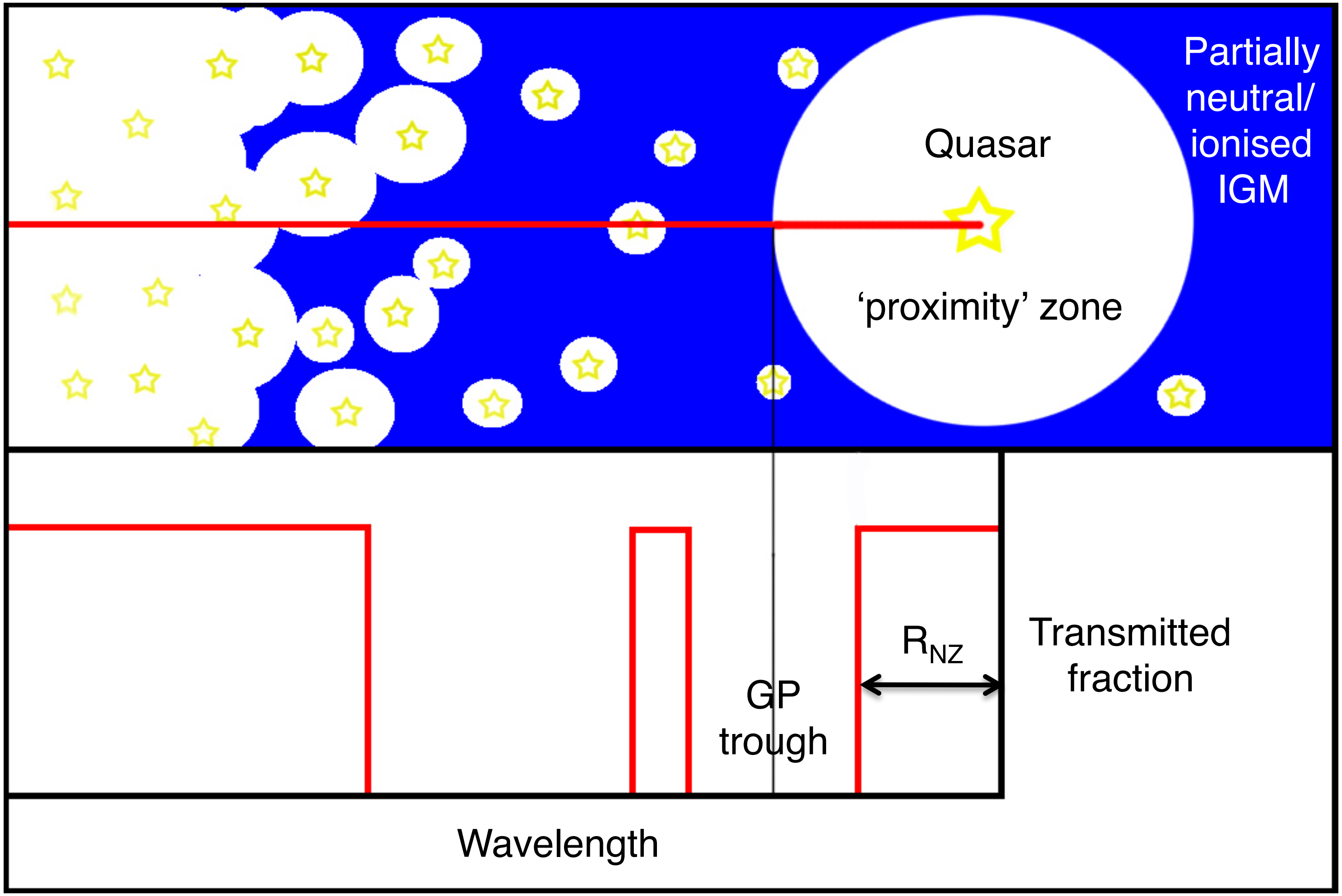
Near-zone size with redshift



Carilli et al. (2010)

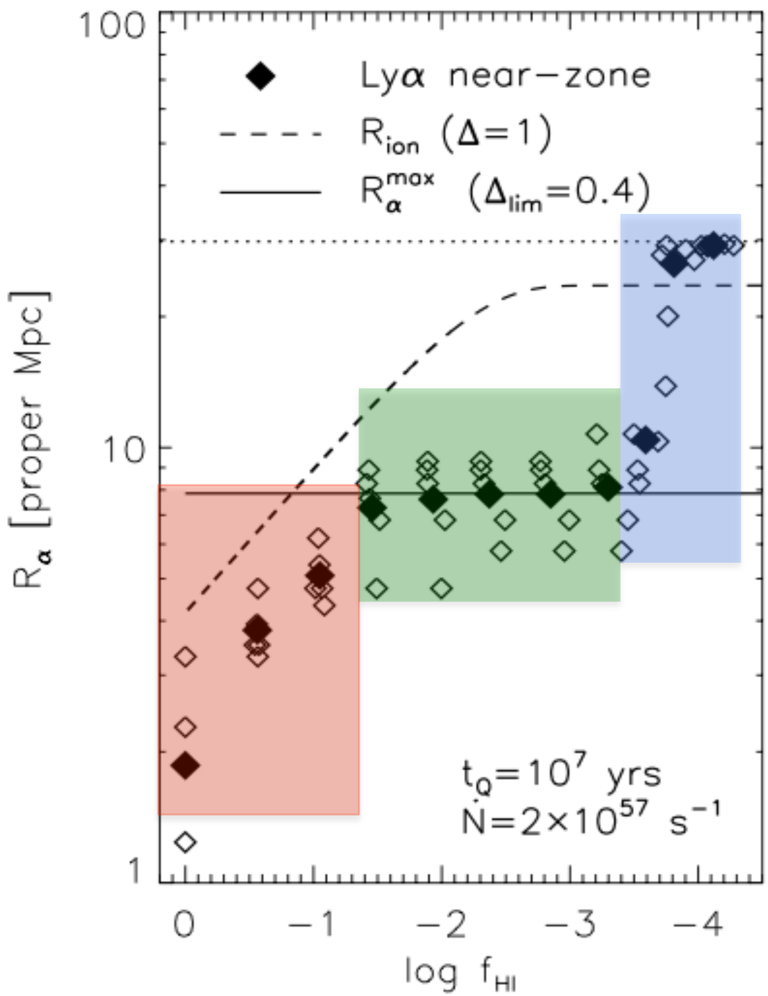
- Assume measured sizes correspond to H-II region boundaries;
- Implies a factor of ~10 increase in IGM H-I fraction from z=5.8 to z=6.4;
- But is this assumption reliable?

...or resonant absorption?



$$R_{NZ} \propto \dot{N}^{1/2}$$

Hydro+RT simulations



Bolton & Haehnelt (2007)

For fixed quasar luminosity and age:

1) Size corresponds to H-II region extent;

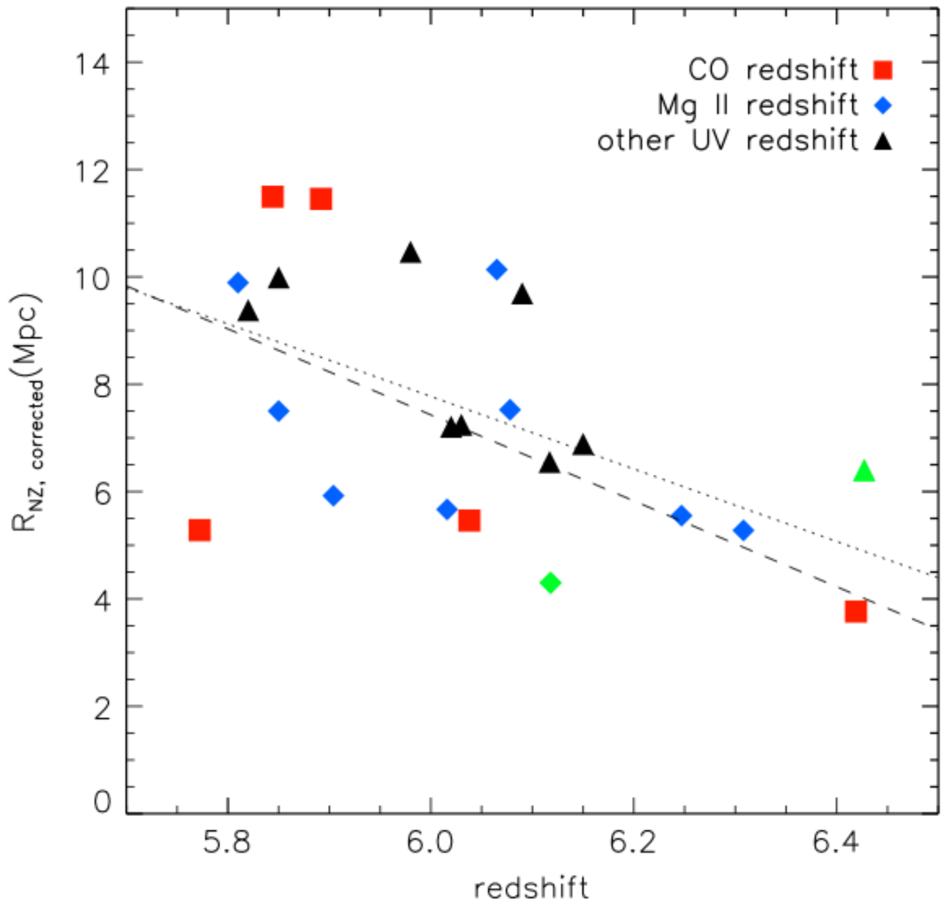
$$R_{NZ} \propto \dot{N}^{1/3} t_Q^{1/3} f_{HI}^{-1/3}$$

2) Size set by resonant absorption;

$$R_{NZ} \propto \dot{N}^{1/2}$$

3) Size set by transmission from thinning Ly-α forest (i.e. the disappearing GP trough).

Near-zone size with redshift

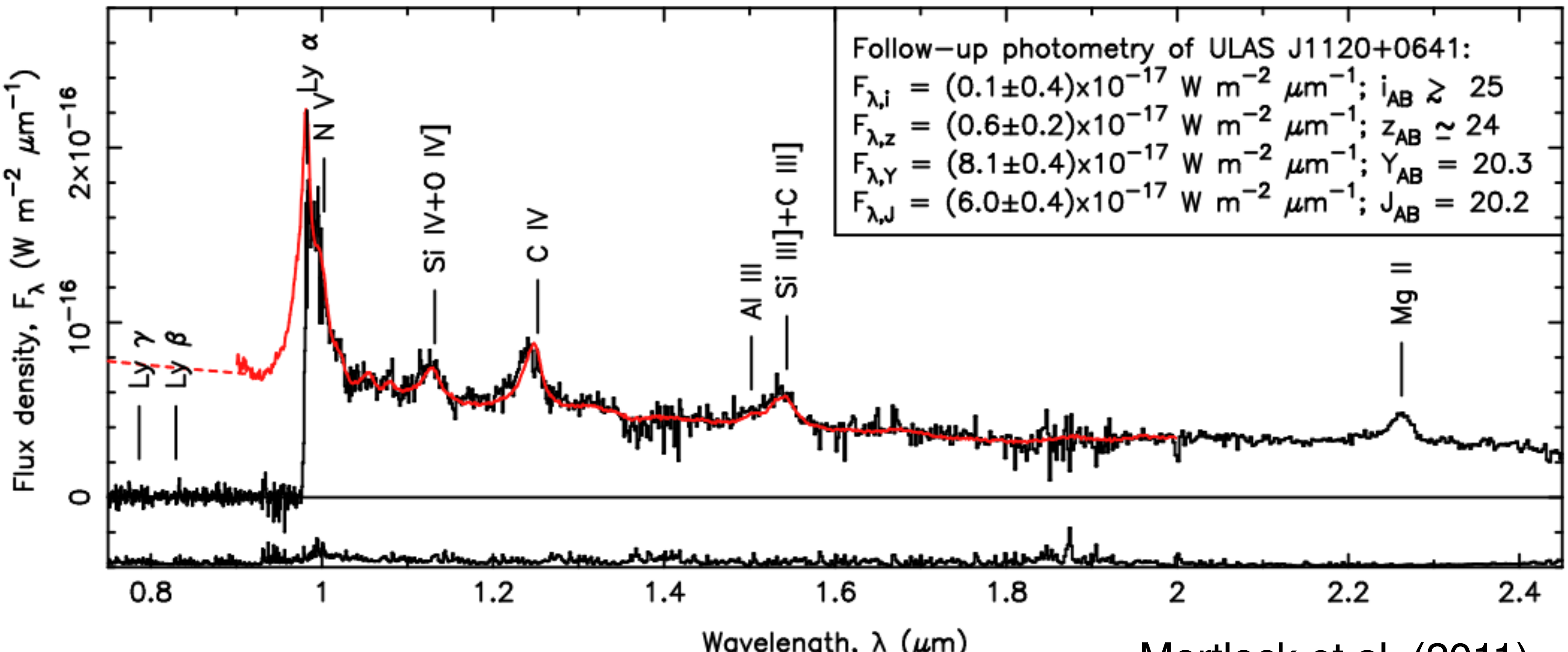


The disappearing GP trough (increasing UV background Intensity)

-> IGM highly ionised at z~6

Carilli et al. (2010), see also Wyithe, JB et al. (2008)

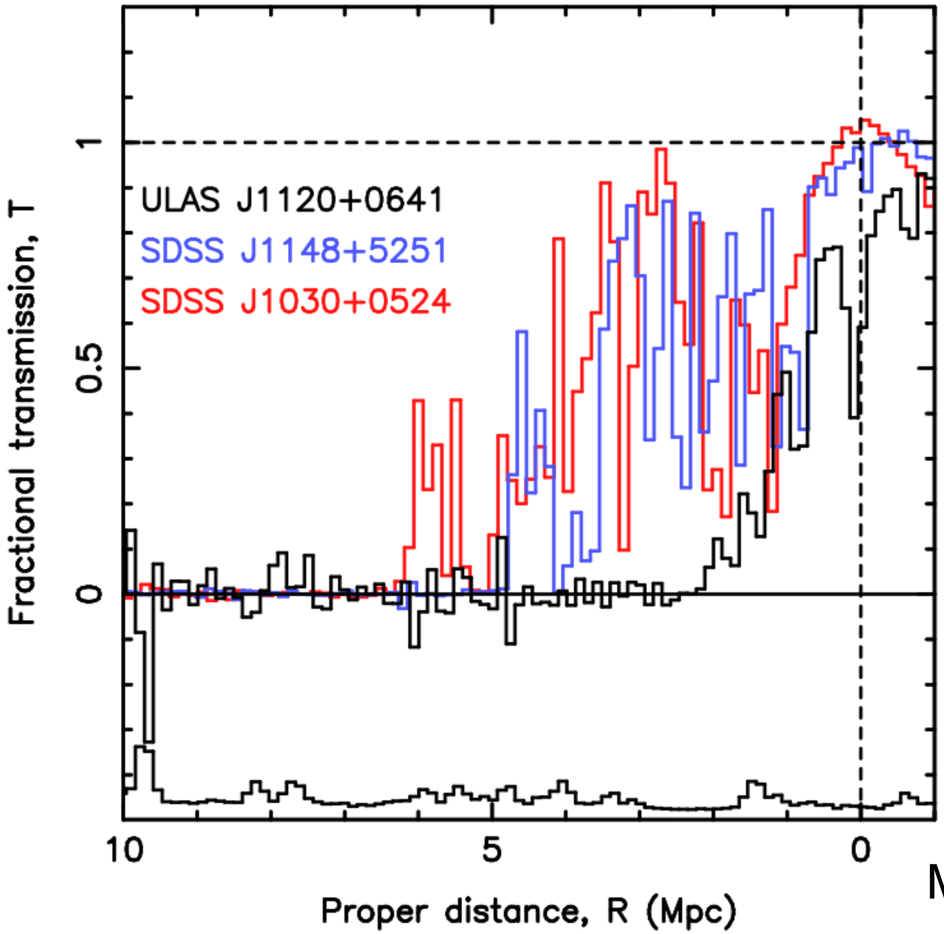
ULAS J1120+0641 at z=7.085



Mortlock et al. (2011)

- Discovered as part of the UKIDSS survey;
- Spectrum obtained with VLT/FORS2 and Gemini/GNIRS;
- Mg-II line width consistent with M_{BH}~2x10^9 M_{sol}

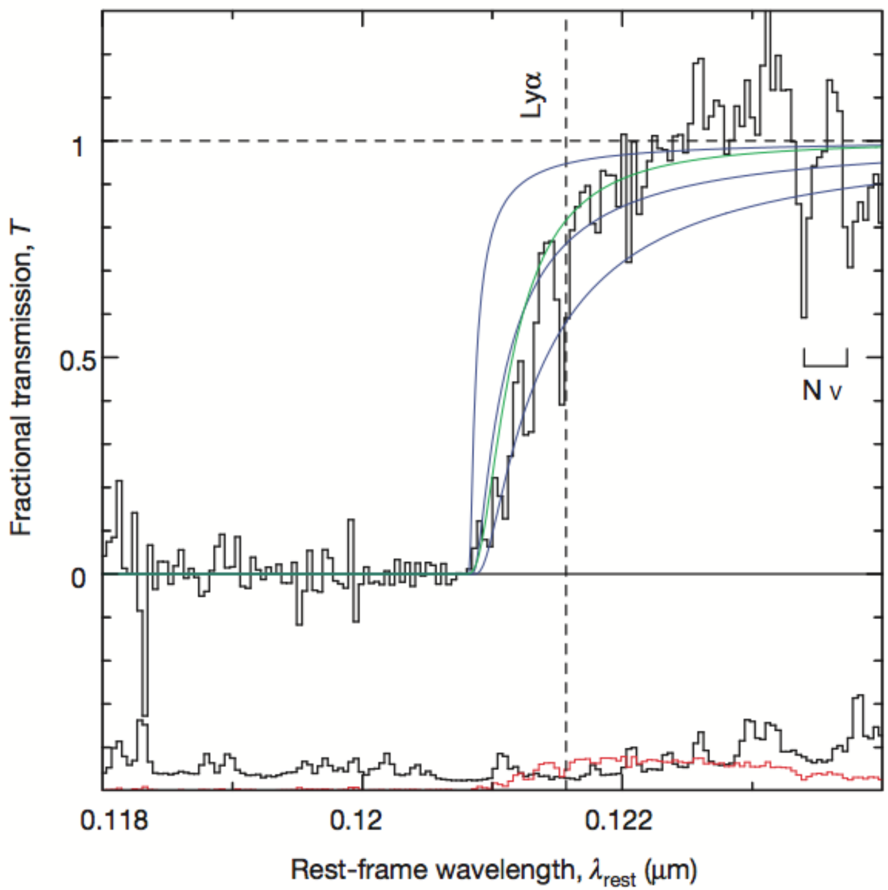
ULAS J1120+0641 at z=7.085



Mortlock et al. (2011)

ULAS J1120+0641 exhibits a rather small near-zone (1.9 proper Mpc) for its bright absolute magnitude (M_{1450}=-26.6)

ULAS J1120+0641 at z=7.085

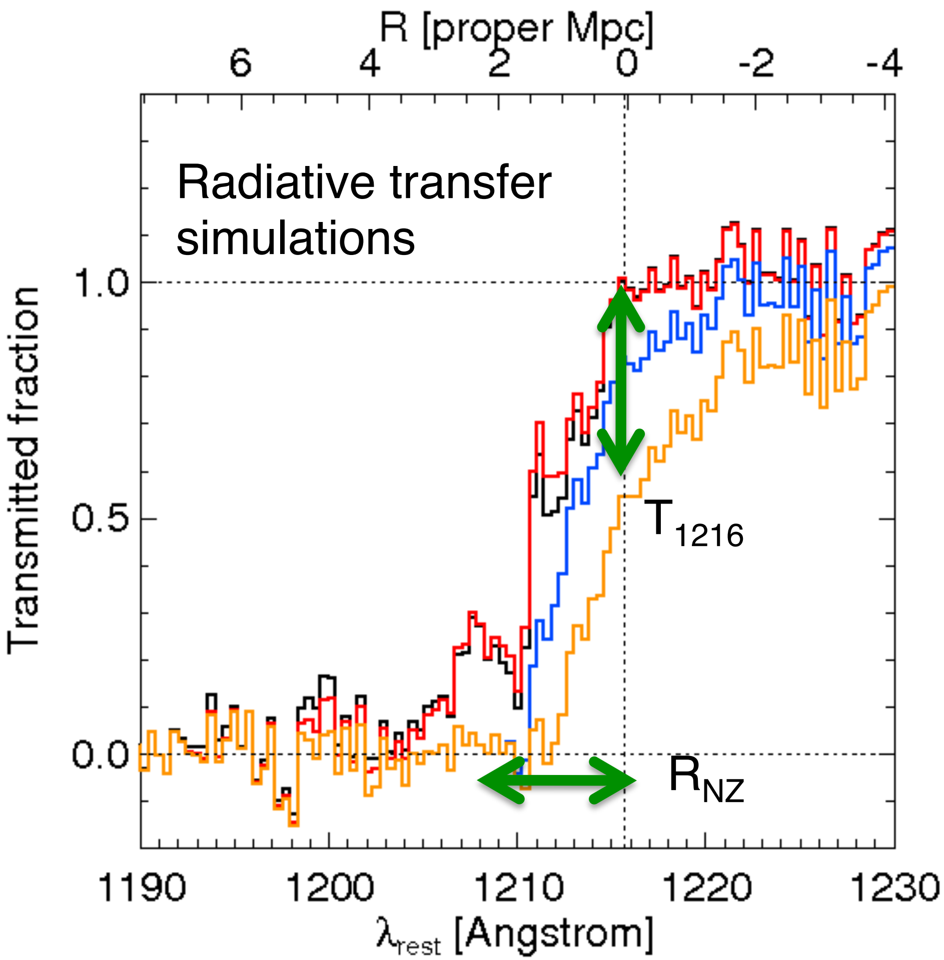


Mortlock et al. (2011)

- Spectrum also has smooth absorption component redward of the Ly-α emission line;

- Consistent with a damping wing from neutral IGM (e.g. Miralda-Escude 1998).

How neutral is the IGM around J1120+0641?

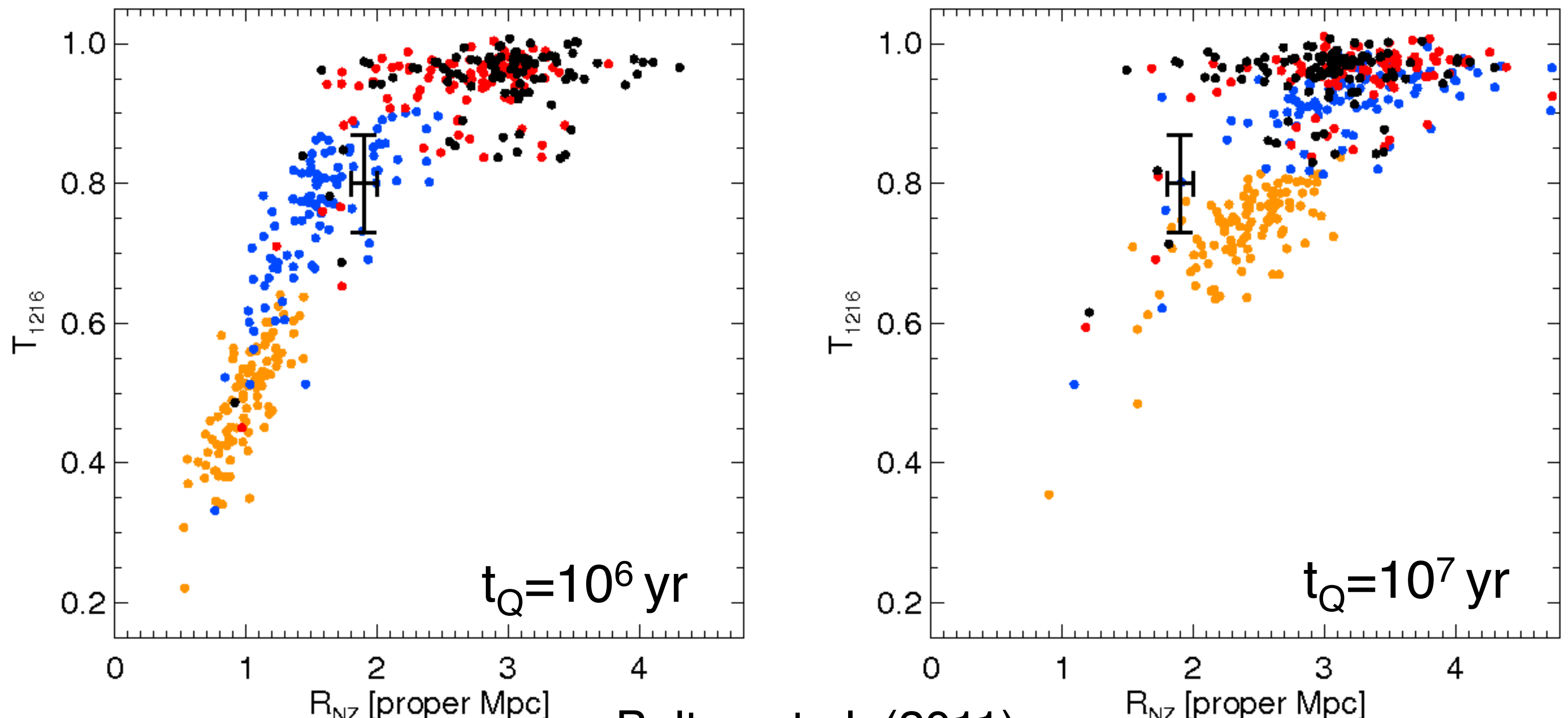


Bolton et al. (2011)

- Characterise the near-zone with R_{NZ} and T_{1216};
- Vary f_{HI} and duration of optically bright phase, t_Q.

$f_{HI} \approx$ 0.0005, 0.006, 0.1, 1.0

How neutral is the IGM around J1120+0641?

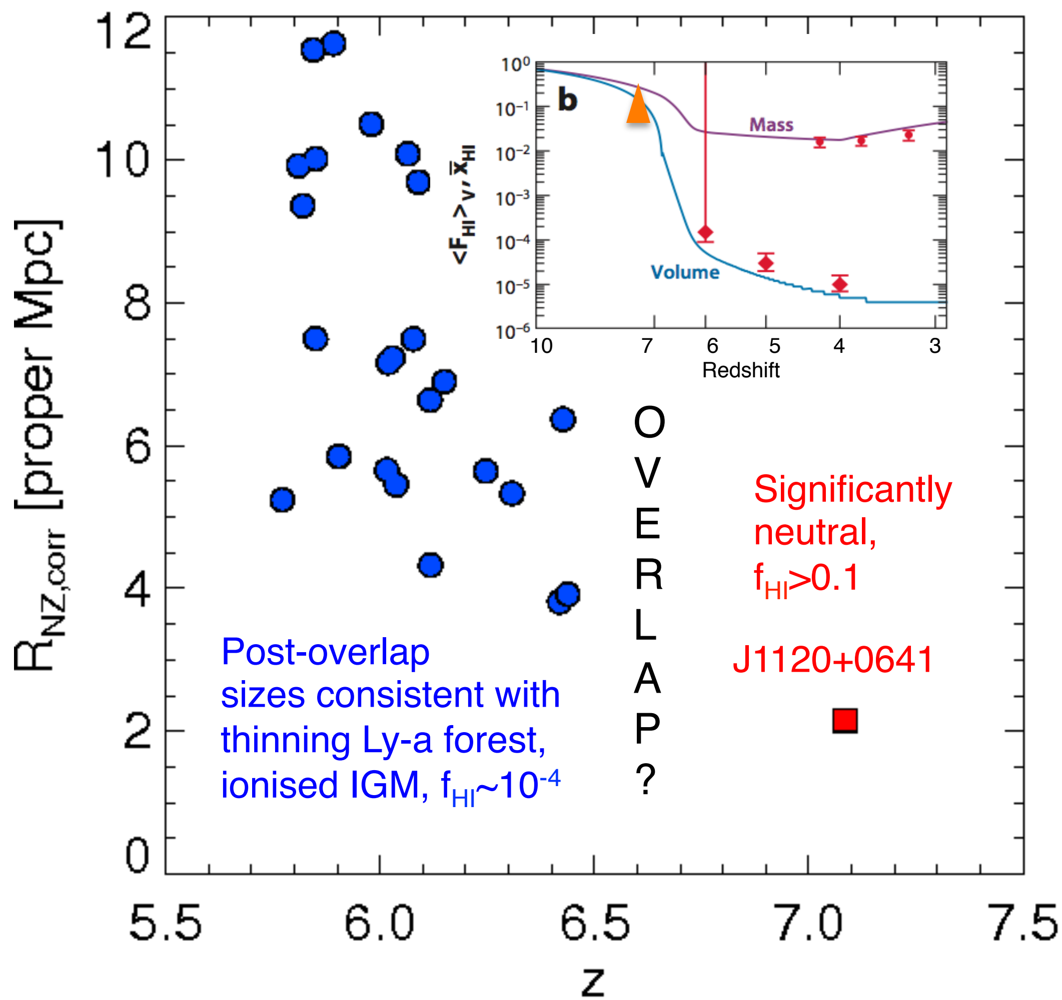


Bolton et al. (2011)

- For an optically bright phase of 10^6 yr (10^7yr) the near-zone size/damping wing is consistent with f_{HI}~0.1 (~1.0);

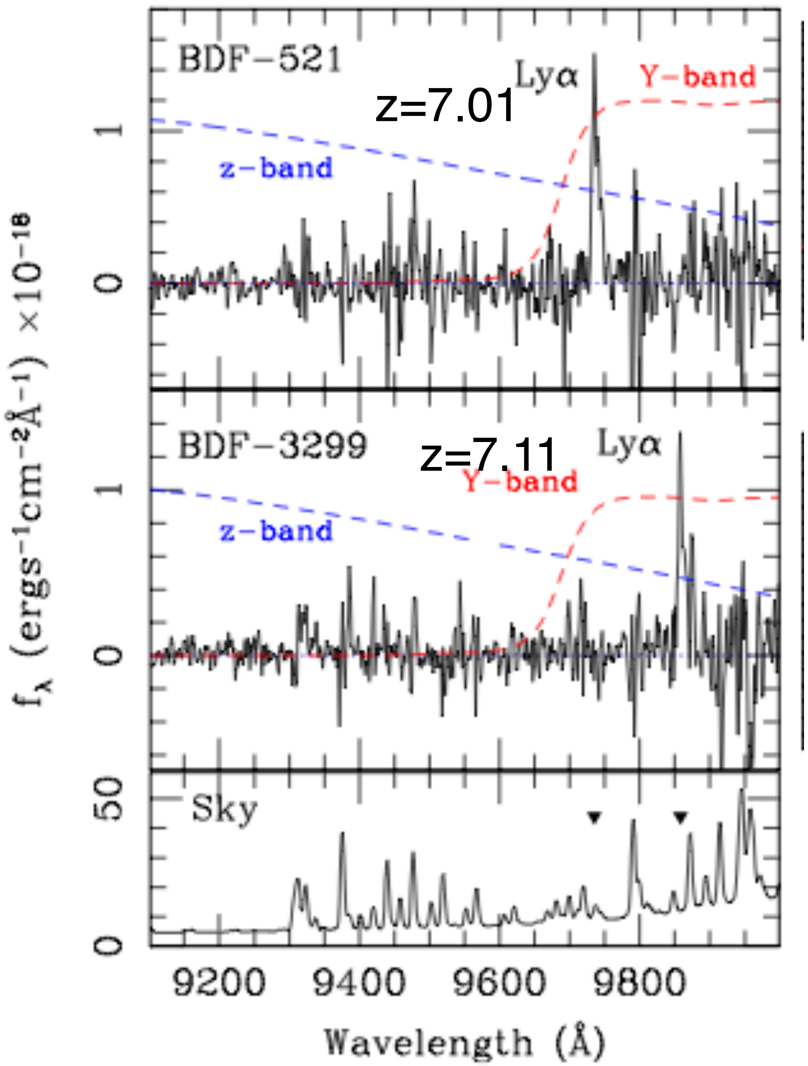
- A highly ionised IGM is also consistent with around 5% of simulated sight-lines due to proximate DLAs (but see also Simcoe et al. 2012)

Implications for the reionisation history?



Caution: Reionisation is inhomogeneous, one object is not the full story (e.g. Mesinger & Furlanetto 2008) and H-I fraction >>10 per cent are difficult to reconcile with other observations.

Lyman-α emitters

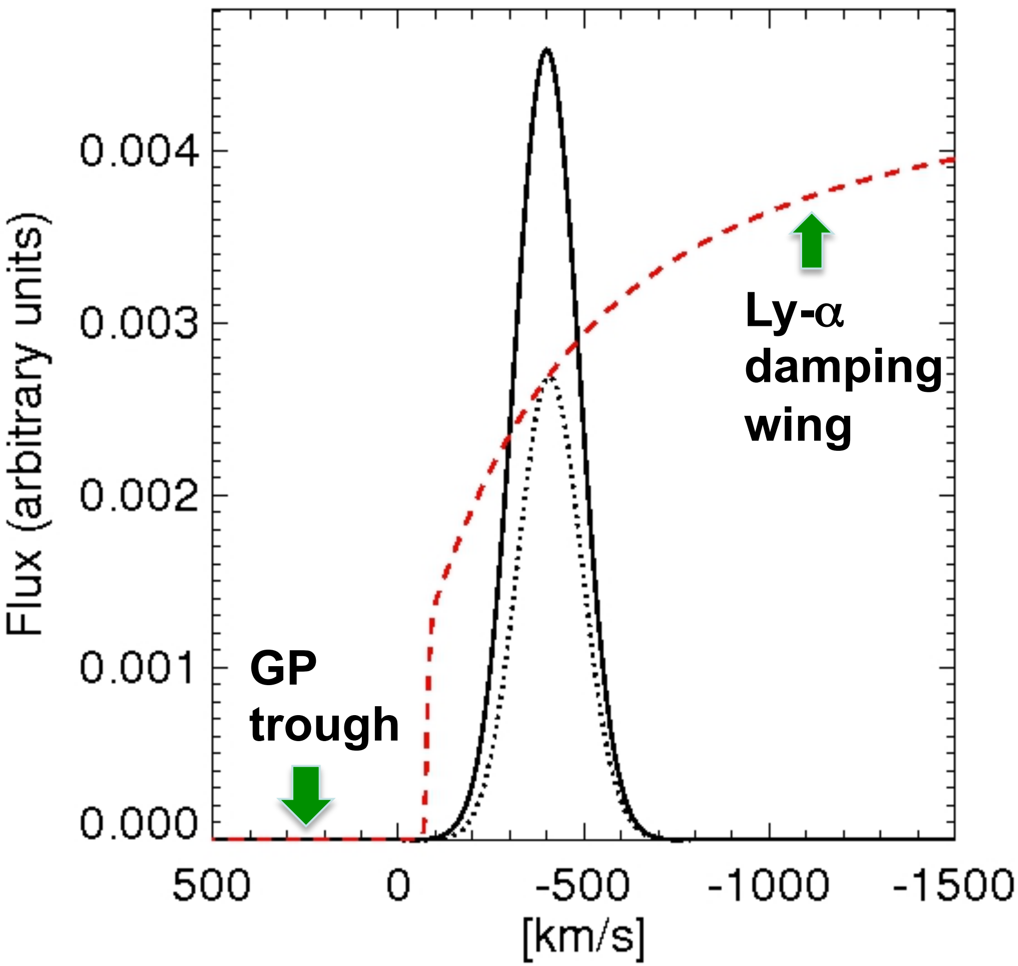


- Hot, blue stars produce hydrogen ionising radiation which photo-ionise neutral hydrogen in ISM;

- Protons and electrons subsequently recombine, but if hydrogen atom is in excited state, line photons are emitted (Ly-α 2/3 of the time).

Vanzella et al. (2011) – FORS2 spectra, VLT/Hawk-I z-band drop outs

The IGM damping wing

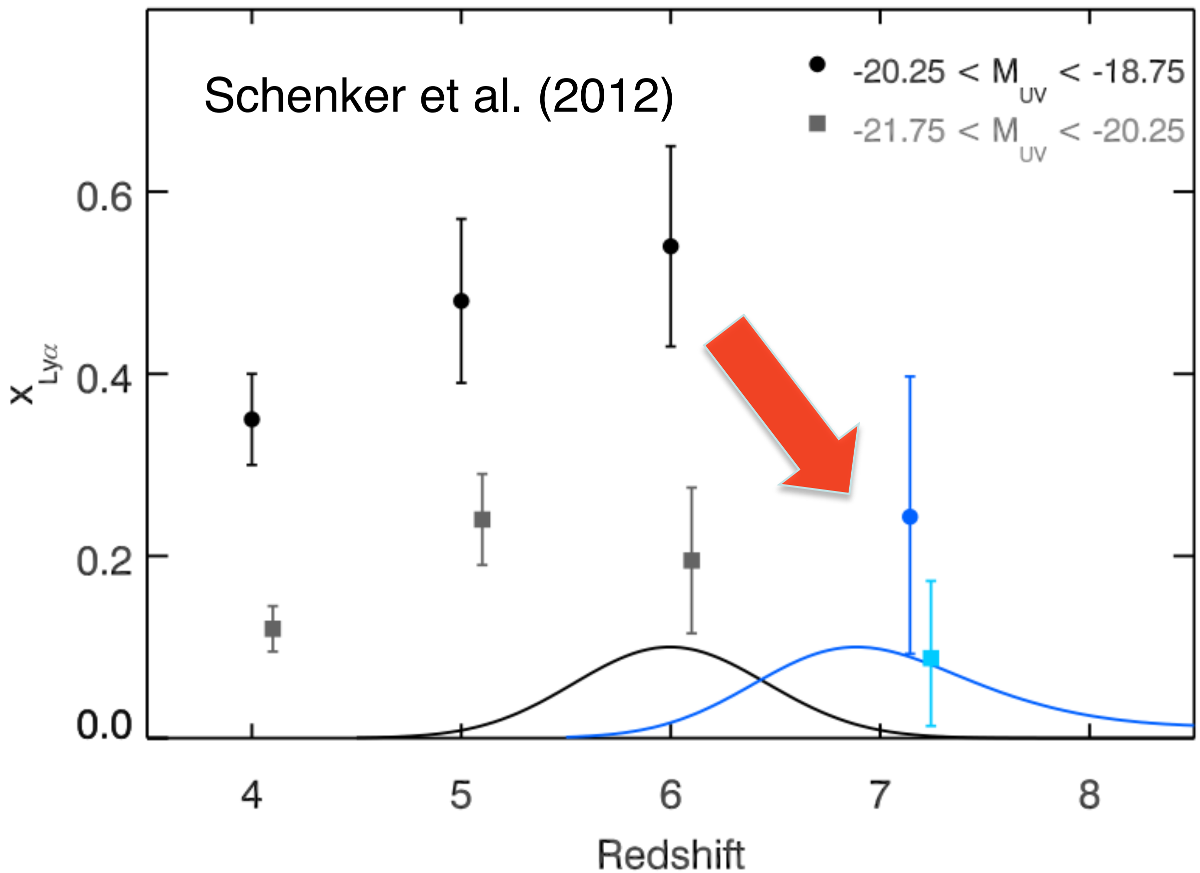


- Lorenzian wing suppresses Ly-α line if IGM significantly neutral

e.g. Miralda-Escude (1998)

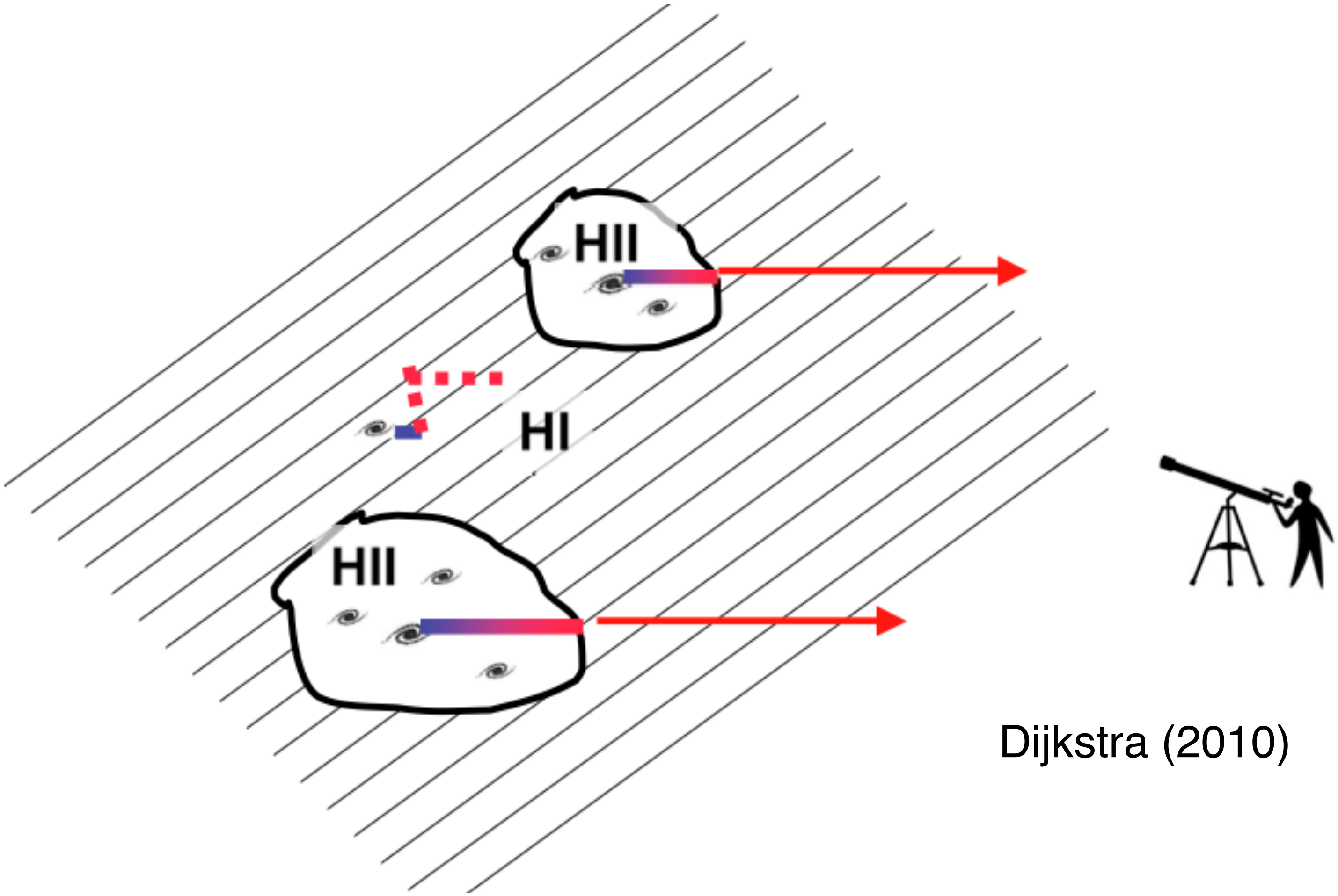
--> Can potentially use Ly-α emitters as probe of H-I fraction/reionisation!

The LBG/LAE fraction



- Significant drop in the fraction of LBGs which exhibit Ly-α emission from z=6 to z=7 (see also Pentericci et al. 2011, Ono et al. 2012).

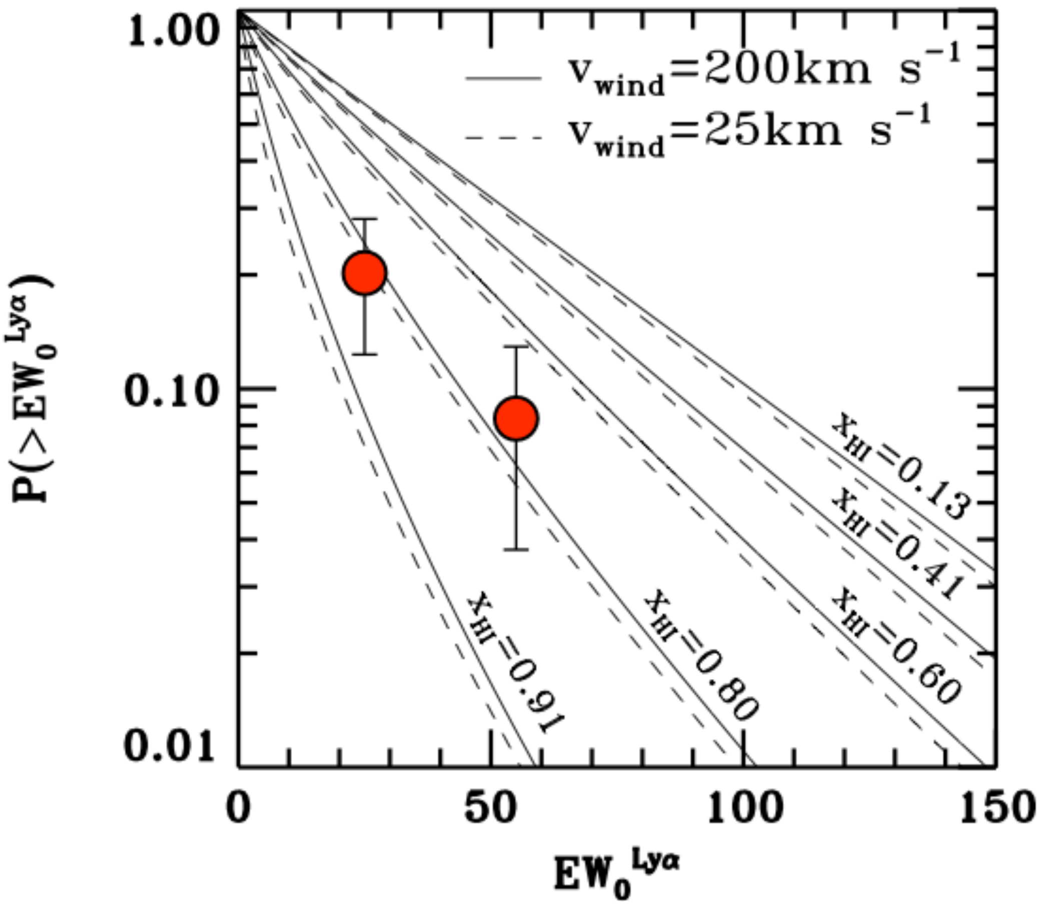
LAE visibility during reionisation



Dijkstra (2010)

But: can still see Ly-α emission if the surrounding IGM is neutral - just need a big enough HII bubble + outflows which aid line scattering.

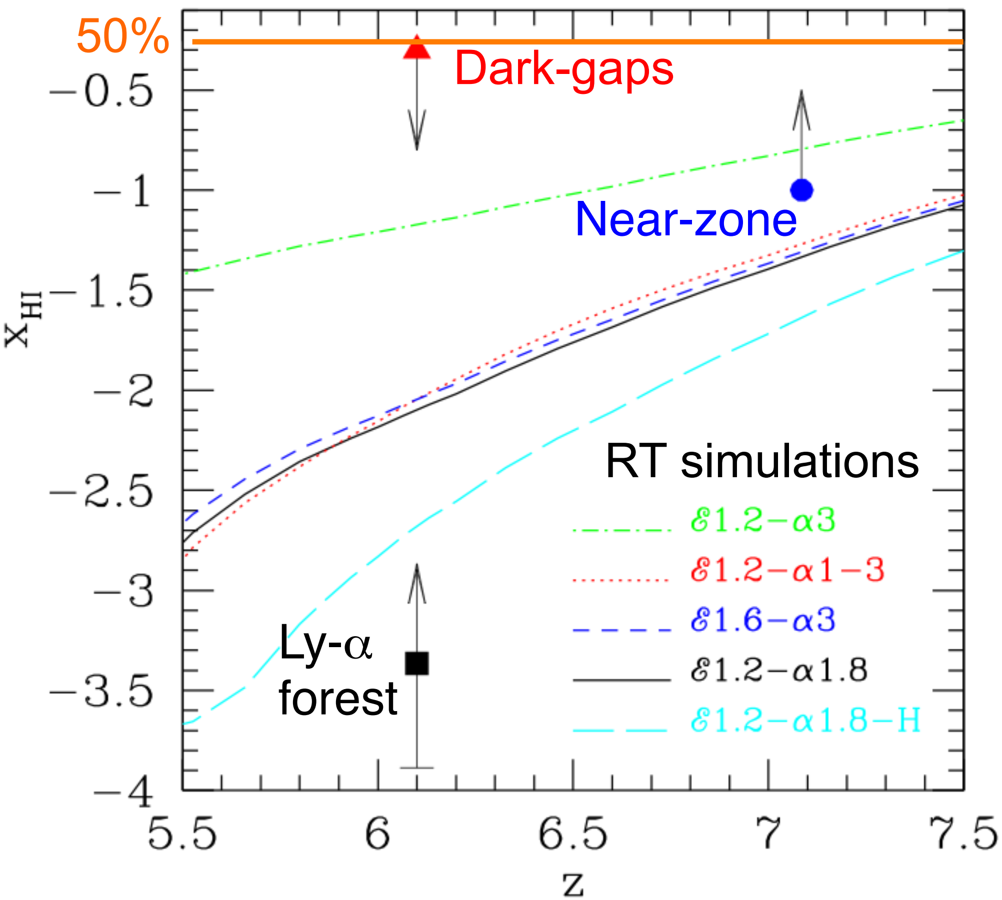
Explaining the Ly-α EW distribution



Ono et al. (2012)
see also Dijkstra et al. (2011)

- Very large HI fractions at z=7 (40-90 per cent) may be required for EW evolution from z=6--7
- Caution: assumes fully transparent IGM at z=6 and no intrinsic LAE evolution, so may be overestimate.

Tension with key constraints?

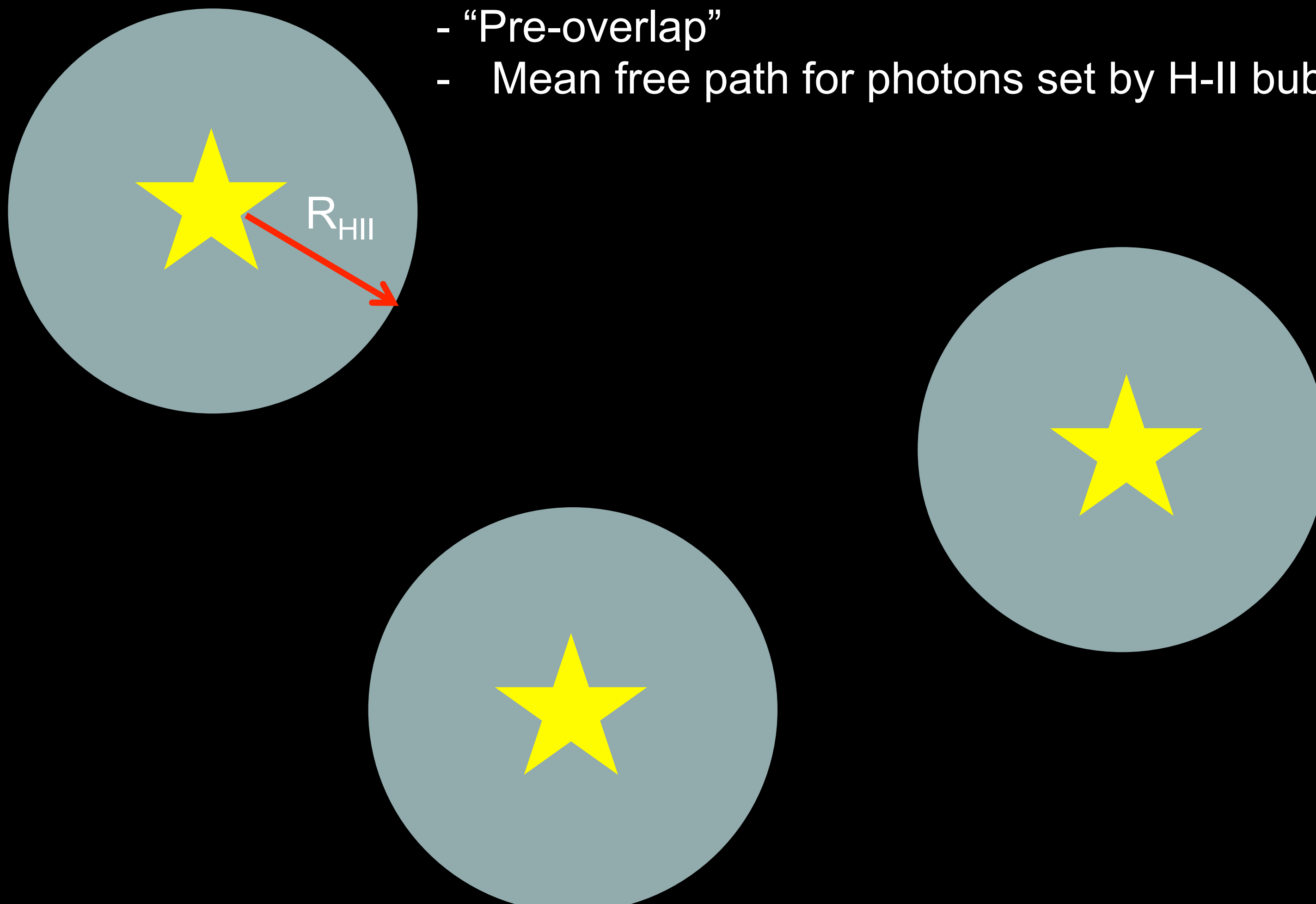


- Difficult to match key constraints (CMB, Ly-α forest) and simultaneously have f_{HI}~0.5 at z=7.1!
- If f_{HI}~0.5, dramatic rise and then fall in ionising emissivity required between 6<z<7.
- Is this large H-I fraction correct, or are large-scale reionisation models missing an important ingredient?

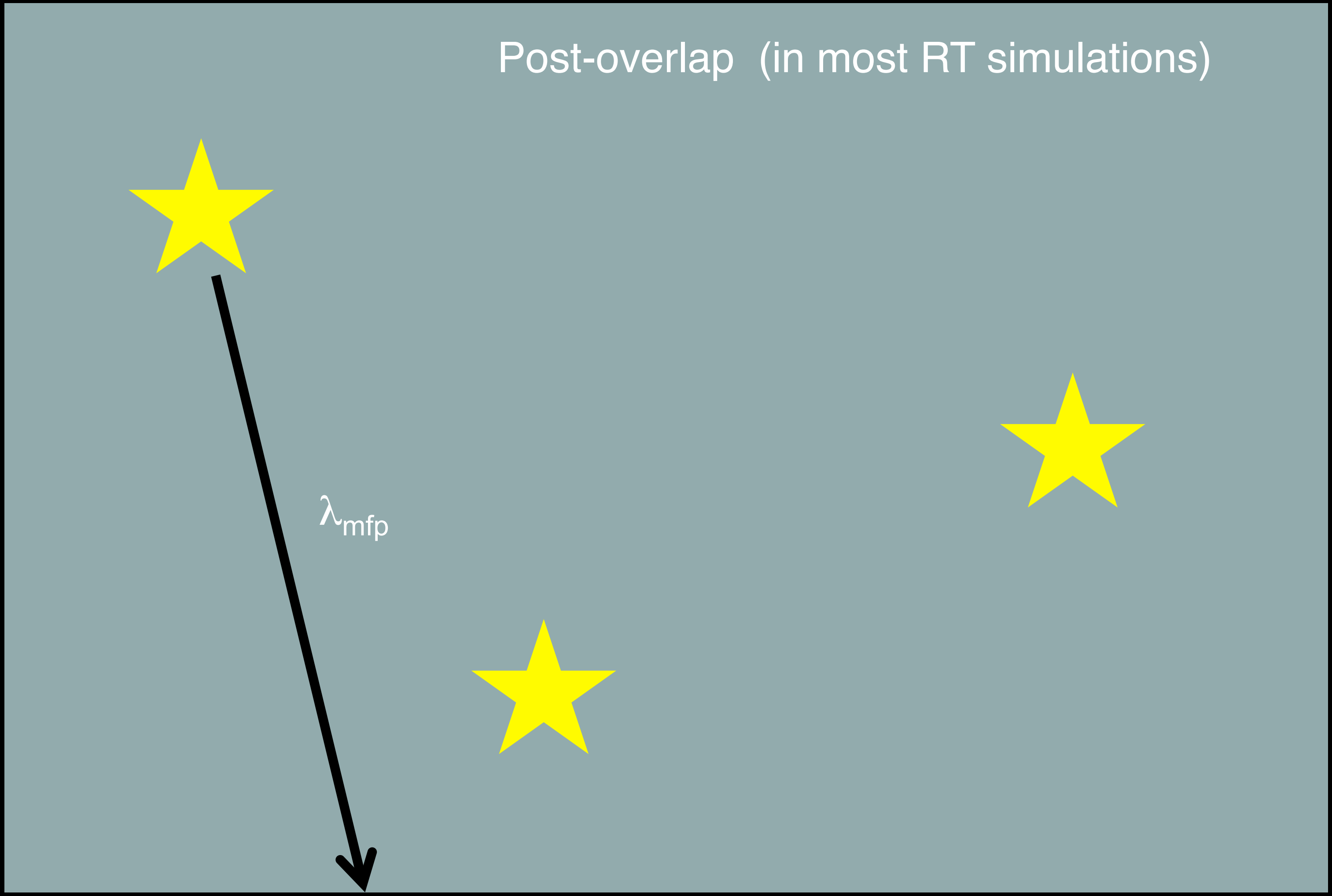
Ciardi, JB et al. (2012)
Data from Fan et al. (2006), McGreer et al. (2011), Mortlock et al. (2012)

Reionisation morphology

- "Pre-overlap"
- Mean free path for photons set by H-II bubble size

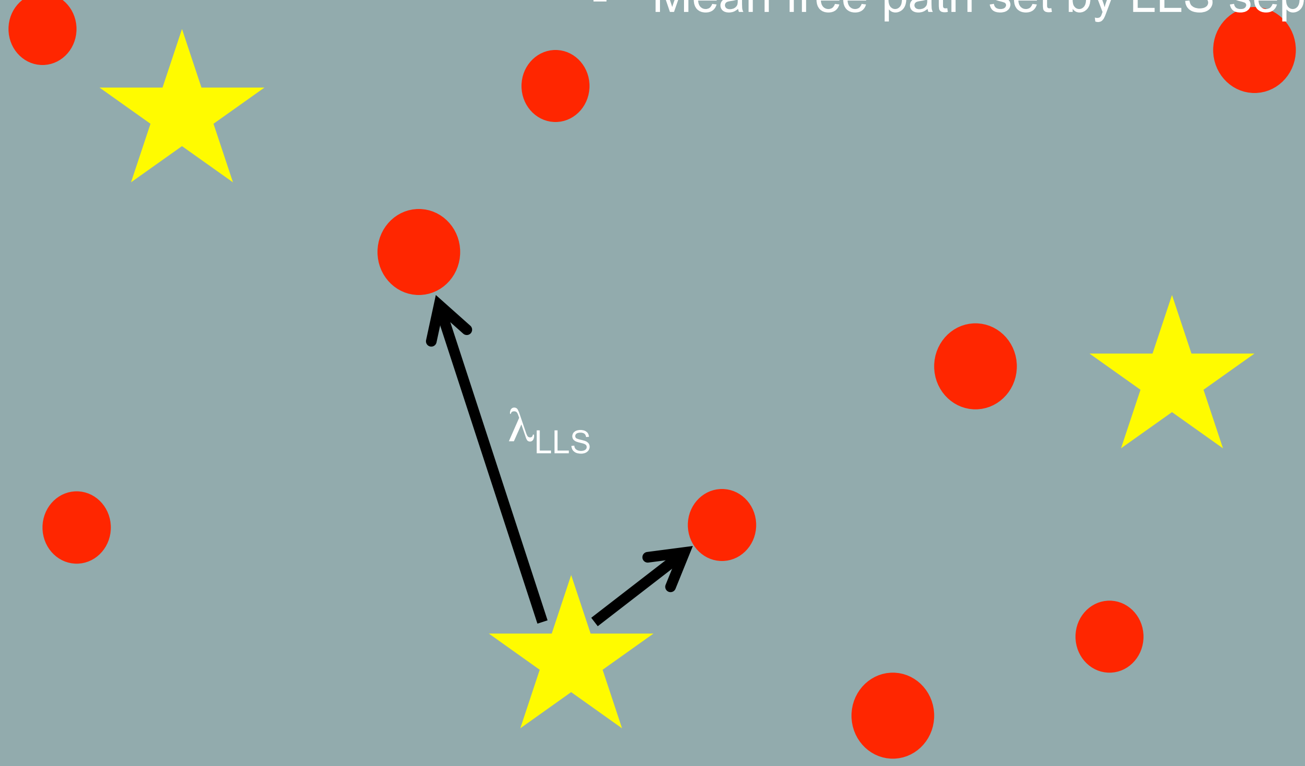


Reionisation morphology



Reionisation morphology

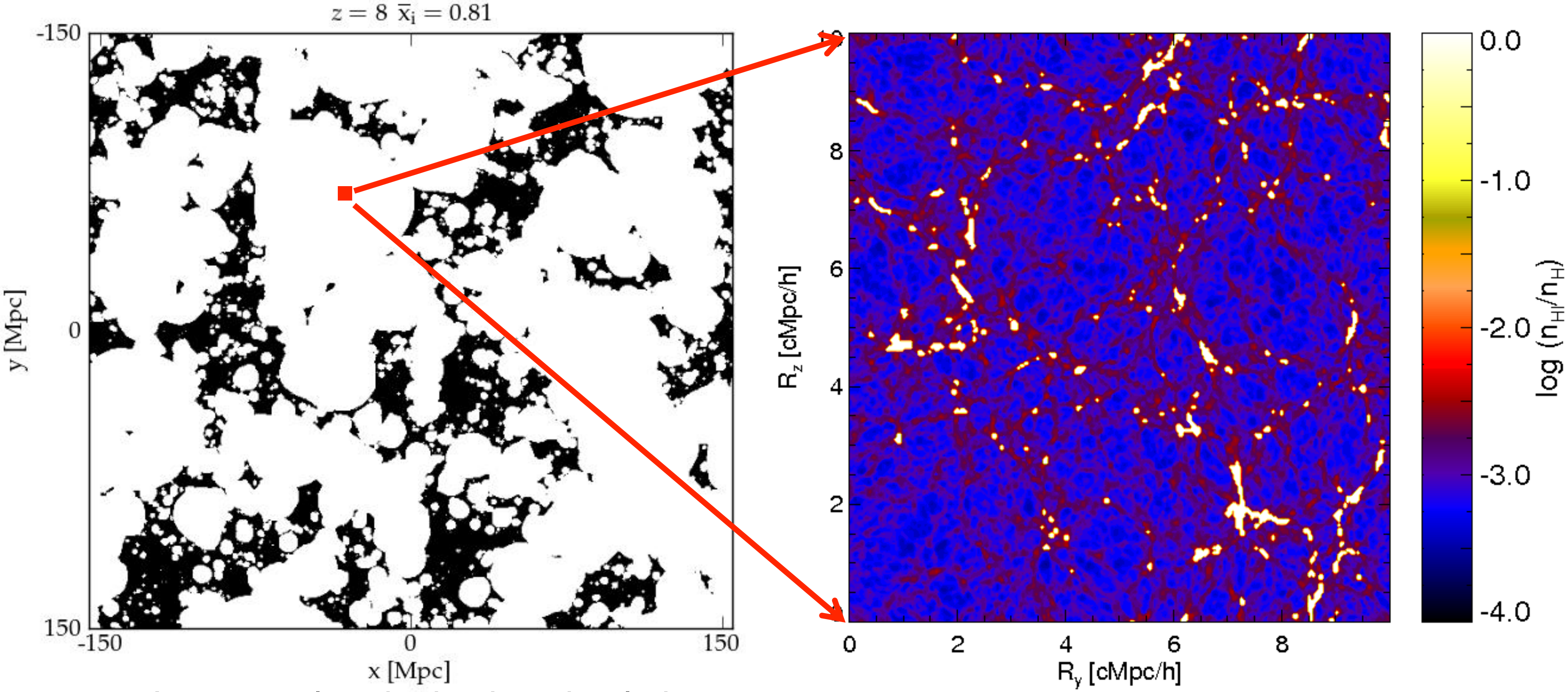
- “Post-overlap”
- Mean free path set by LLS separation



Mean free path set by Lyman limit systems (LLS), $N_{HI}>10^{17.2}$ cm^{-2}

An issue of dynamic range

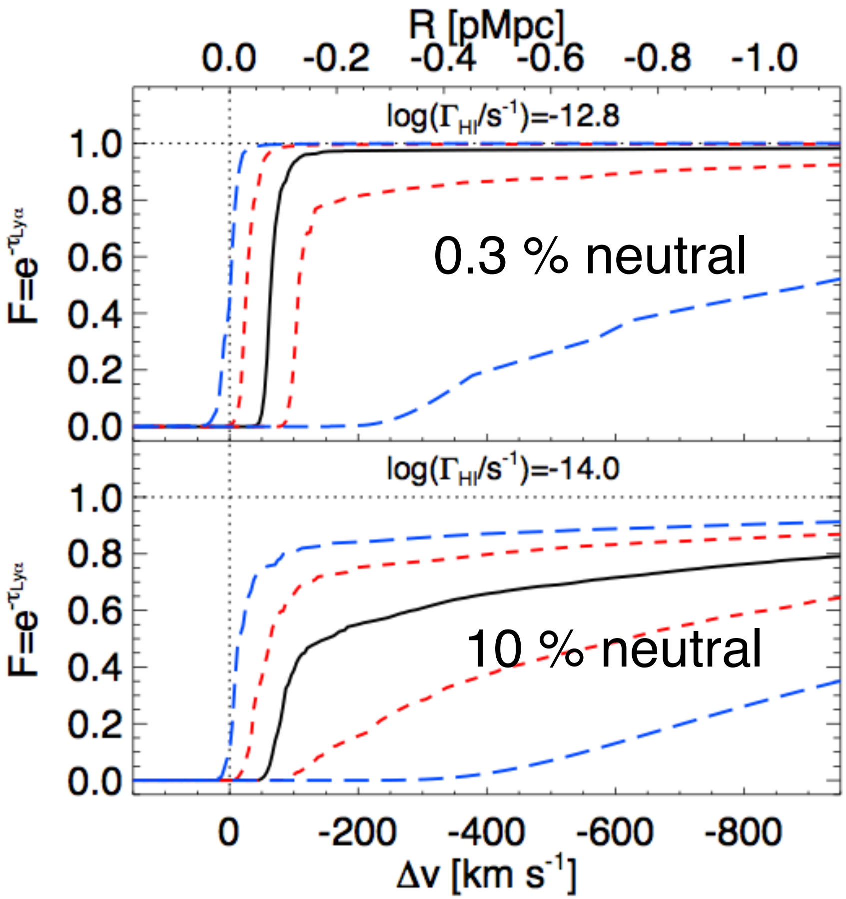
Large scale simulations: L > 100 cMpc.
Lyman-limit systems: L < 20 pkpc



Large-scale reionisation simulation
Santos et al. (2010)

Gadget-3 hydro simulation
+ self shielding

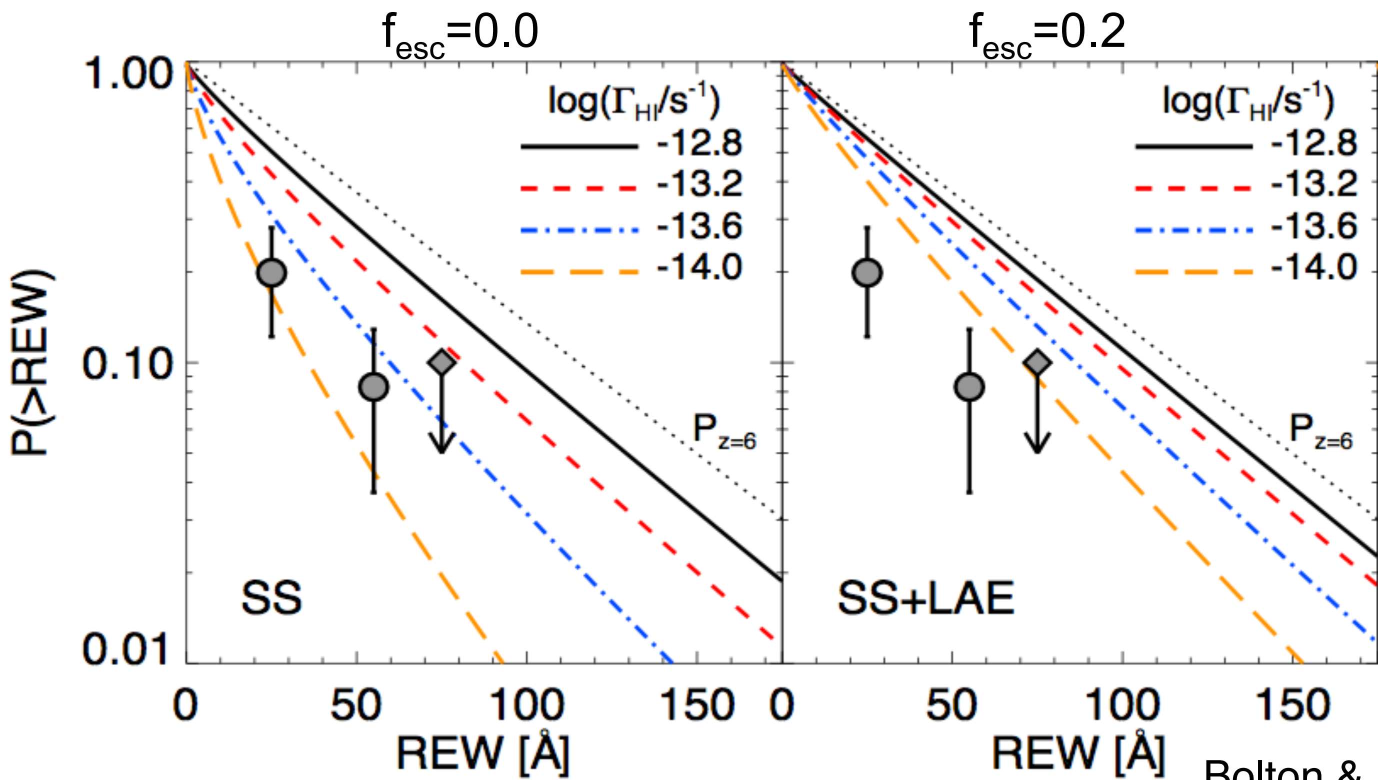
Impact on the IGM damping wing



Bolton & Haehnelt (2013)

- Absorption from these systems varies significantly from one sight-line to another;
- High column density systems are vital for correctly estimating LAE visibility!

Equivalent width distribution

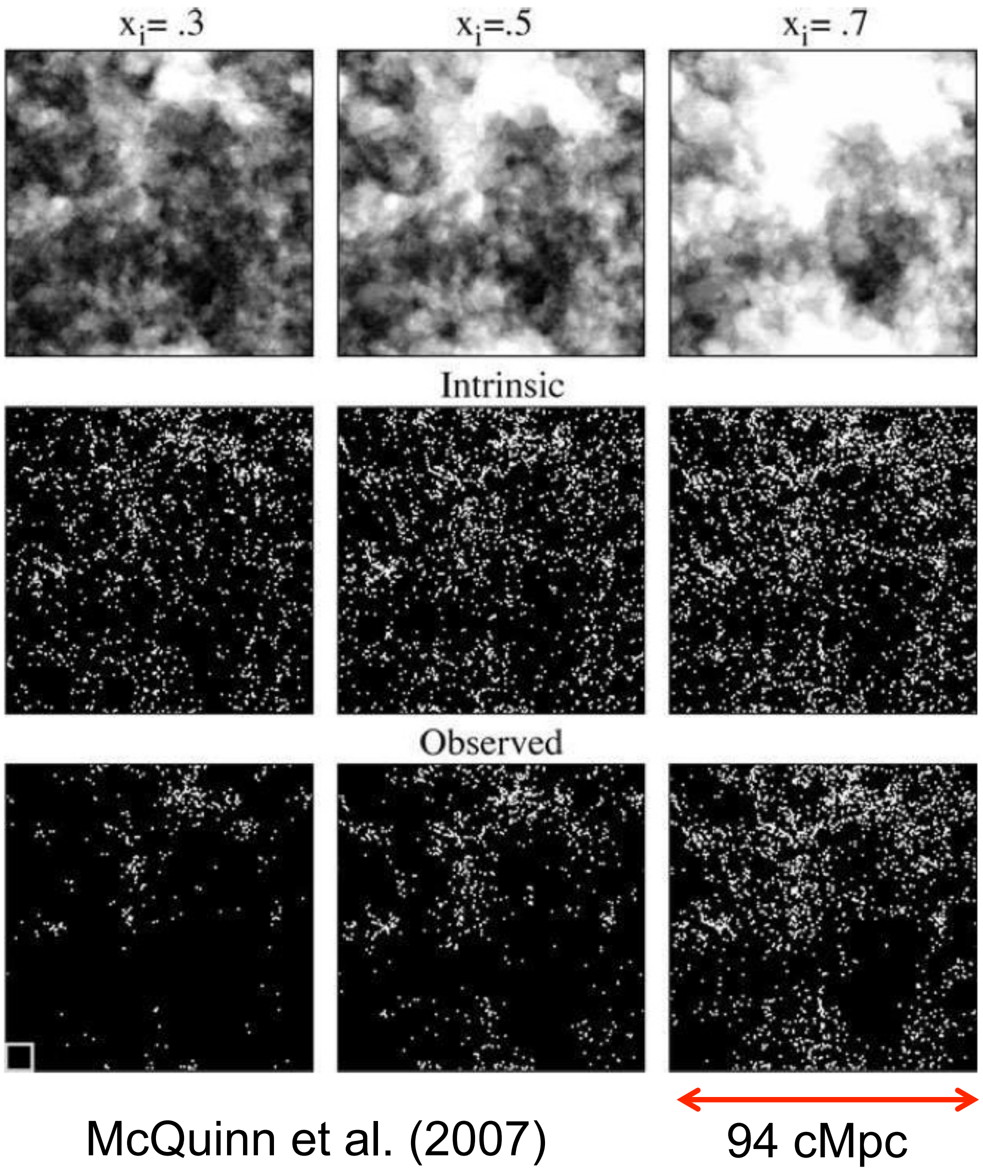


Bolton & Haehnelt (2013)

$\log(\Gamma_{HI}/s^{-1})$	$\langle f_{HI}\rangle_V$
-12.8	2.7×10^{-3}
-13.2	9.2×10^{-3}
-13.6	3.2×10^{-2}
-14.0	1.1×10^{-1}

- Smaller neutral fractions account for data if LyC escape fraction from LAEs is low, partially alleviating tension with other constraints.

Effect on Ly-α emitter clustering?

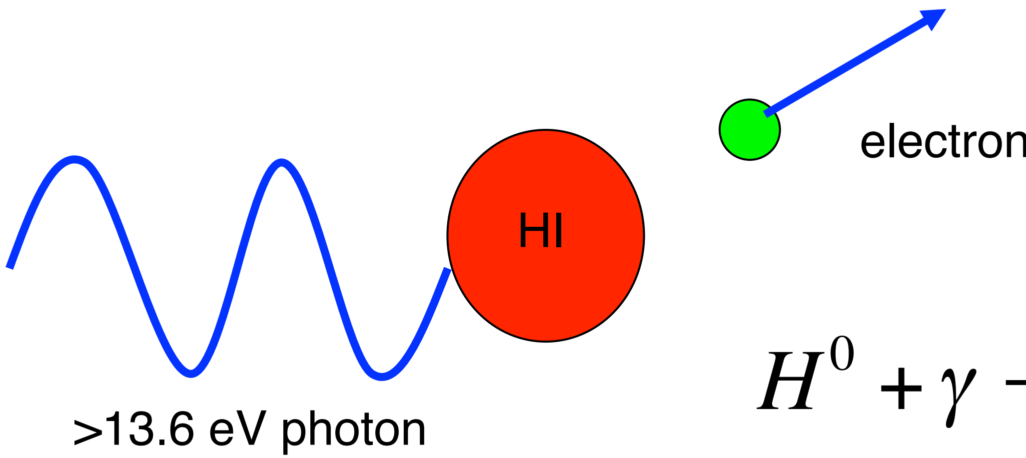


McQuinn et al. (2007)

- Impact on the structure of reionisation (e.g. Choudhury et al. 2009);
- Implications for the intepretation of forthcoming observations (e.g. High-z Ly-α emitter clustering with HyperSuprimeCam)
- Modelling the photon sinks correctly is important!

The IGM temperature

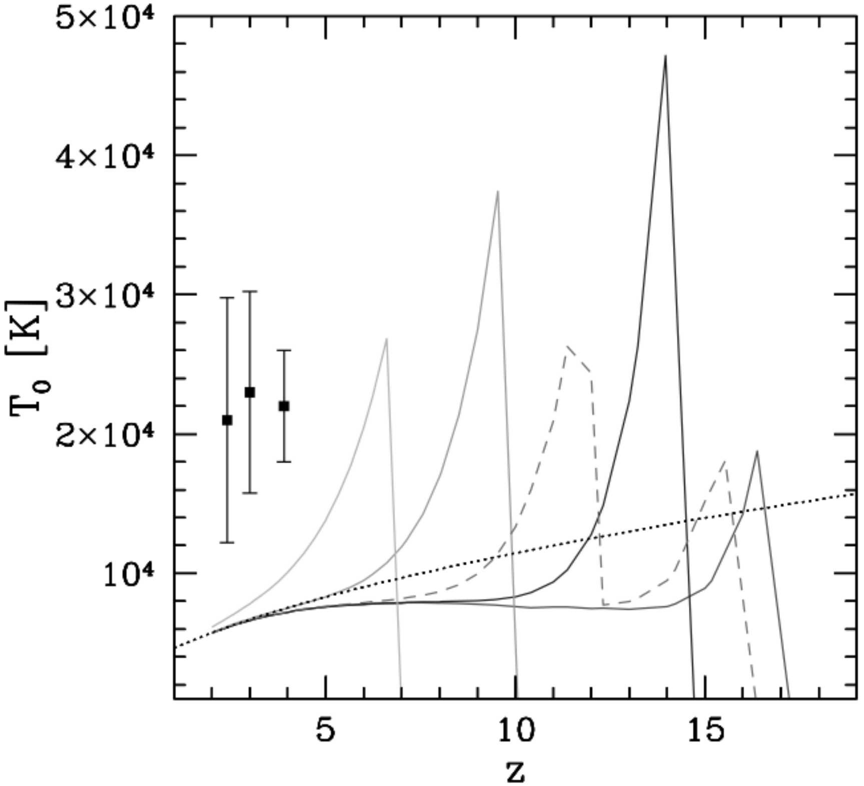
Photons not only ionise – if they have $E > E_{th}$ (H-I=13.6eV, He-II=54.4eV) then they also heat the IGM.



$$H^0 + \gamma \rightarrow H^+ + e^-$$

Ejected electrons share their energy with the baryons via scattering and raise the temperature.

Reionisation and the thermal history



Hui & Haiman (2003)

- Temperature of the low density (δ<10) IGM provides indirect probe of reionisation history;

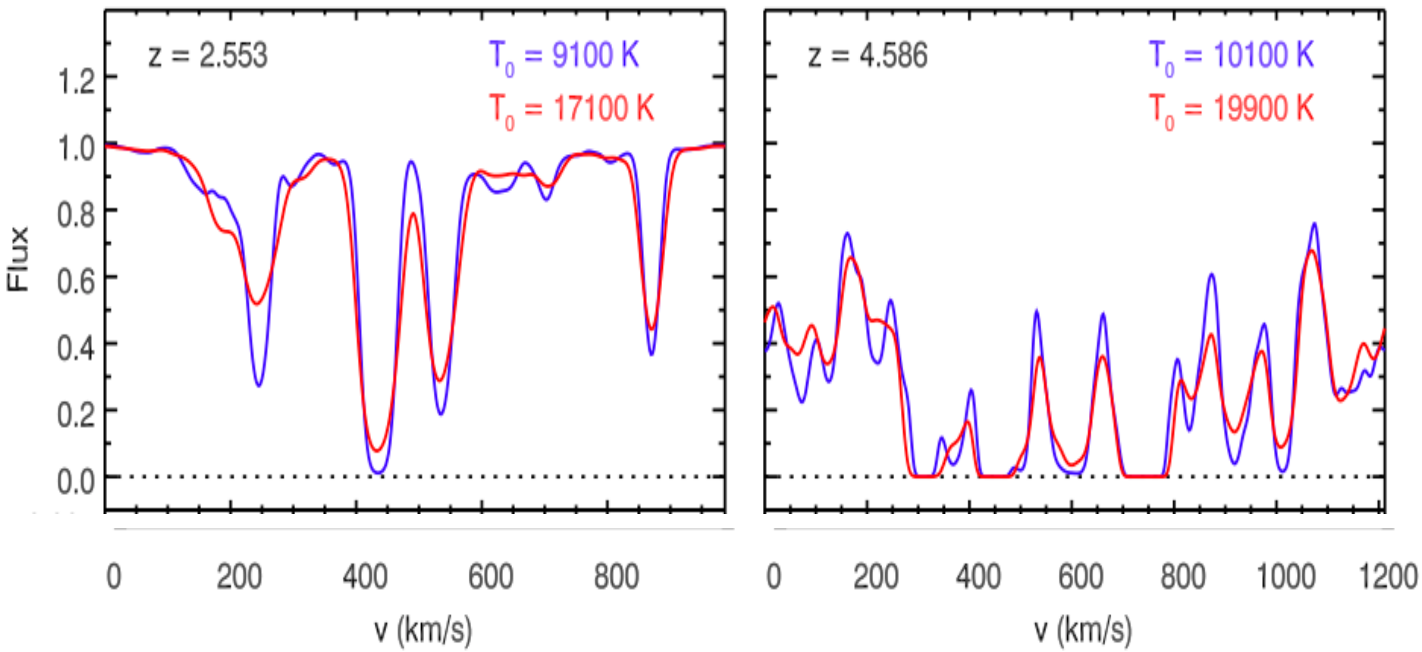
- Long cooling timescale allows IGM to retain thermal memory of reionisation (until thermal asymptote);

The temperature of the IGM depends on:

1) When the IGM was reionised (how much time available to cool?)

2) Spectra of the ionising sources (harder spectra = more heating).

IGM temperature from the Ly-α forest

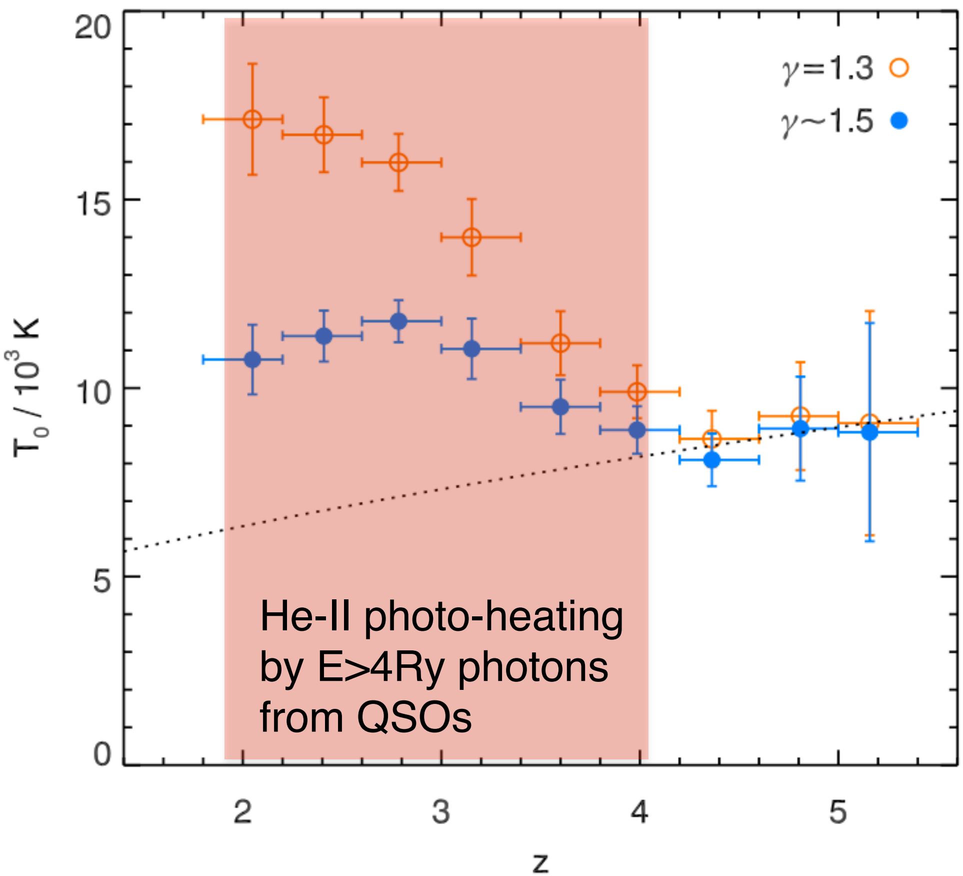


Becker, JB et al. (2011)

Higher temperatures broaden Ly-α forest absorption features through:

1) Thermal broadening by instantaneous temperature (along the line of sight);
2) Jeans (pressure) smoothing by integrated heating history (in three dimensions).

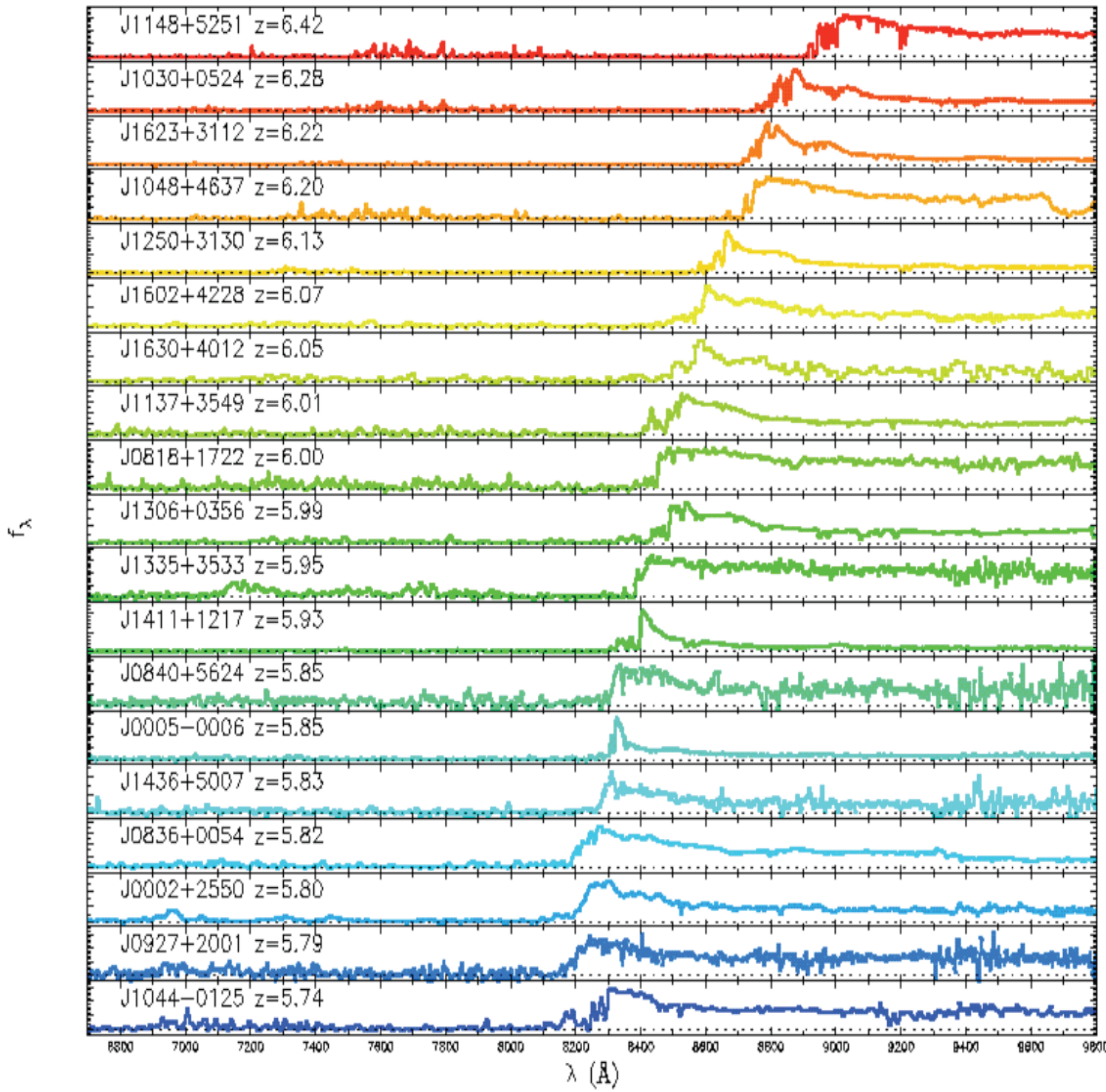
IGM temperature at z<5



Becker, JB et al. (2011)

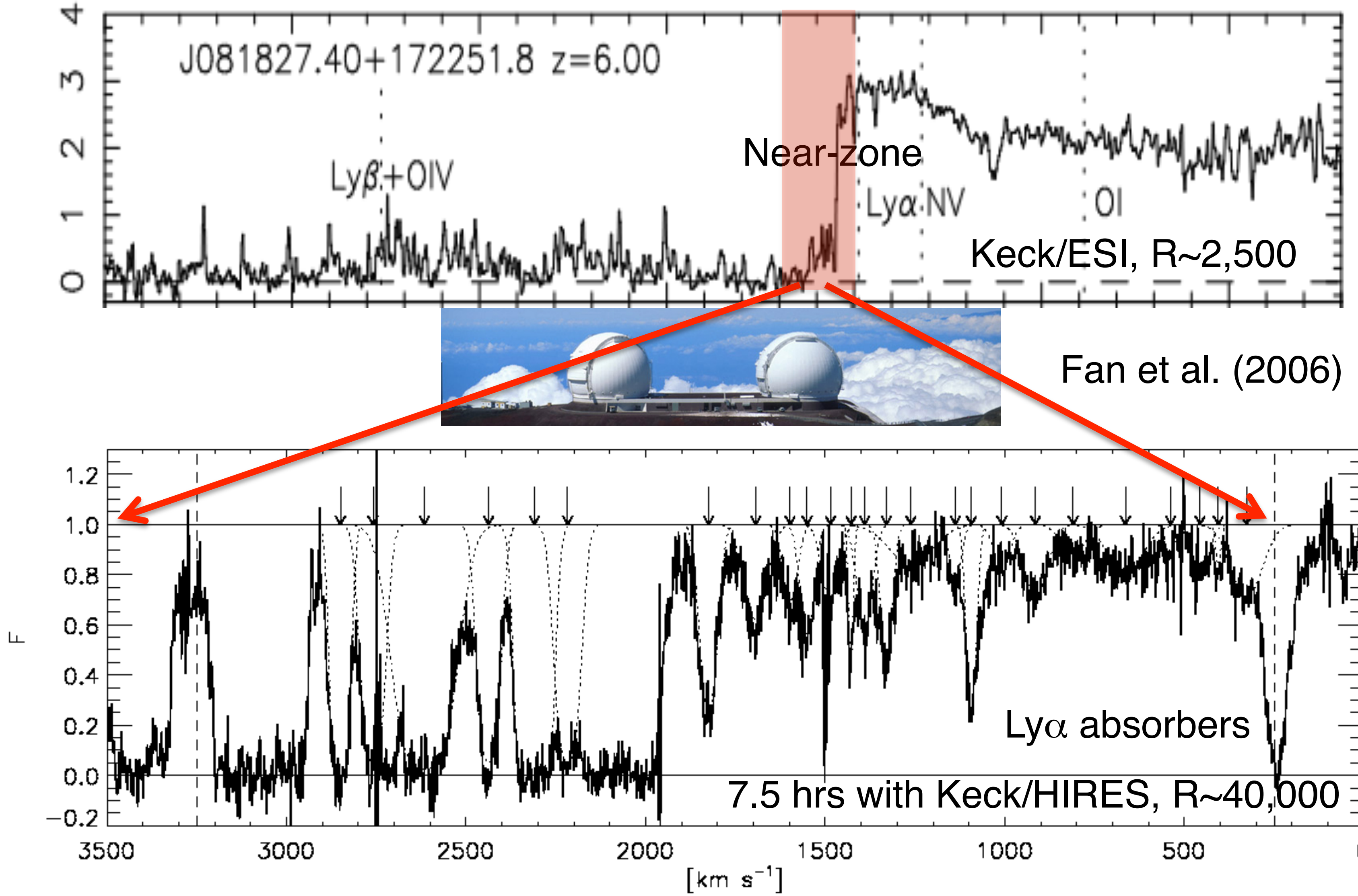
- Temperature increase from z=4 to z=2;
- Signature of extended He-II reionisation at z<4;
- But: He-II heating and thermal asymptote complicates interpretation with respect to H-I reionisation.

The (lack of) Ly-a forest at z>6!

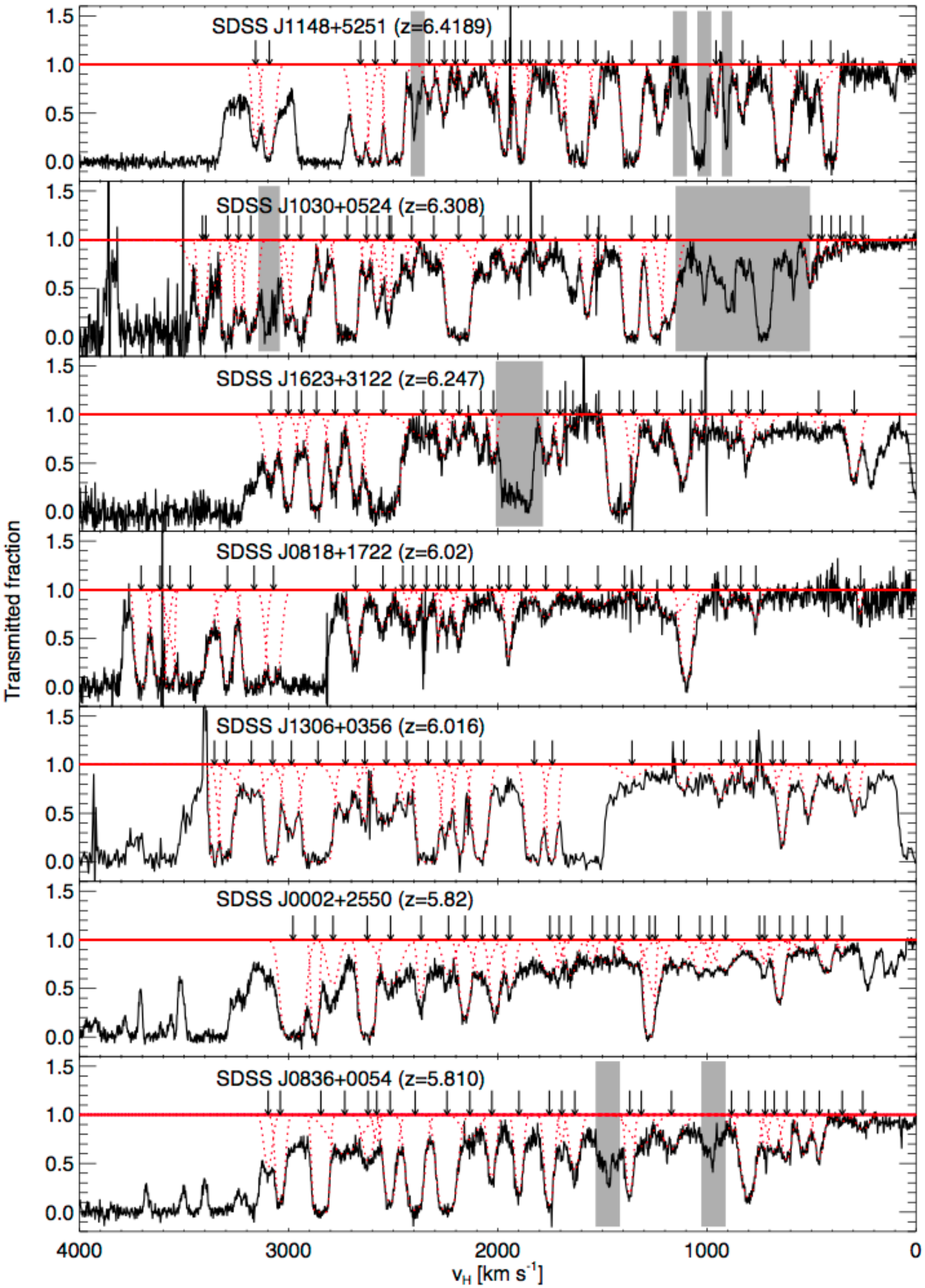


Fan et al. (2006)

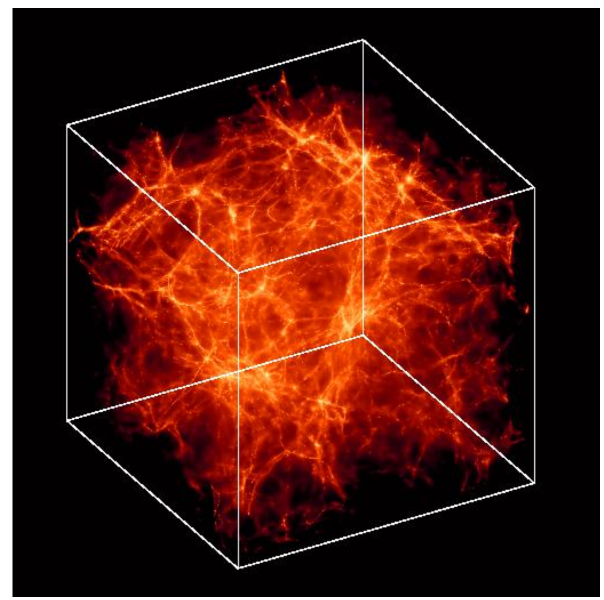
Measuring the IGM temperature at z~6



Becker et al. (2007), Bolton et al. (2010)

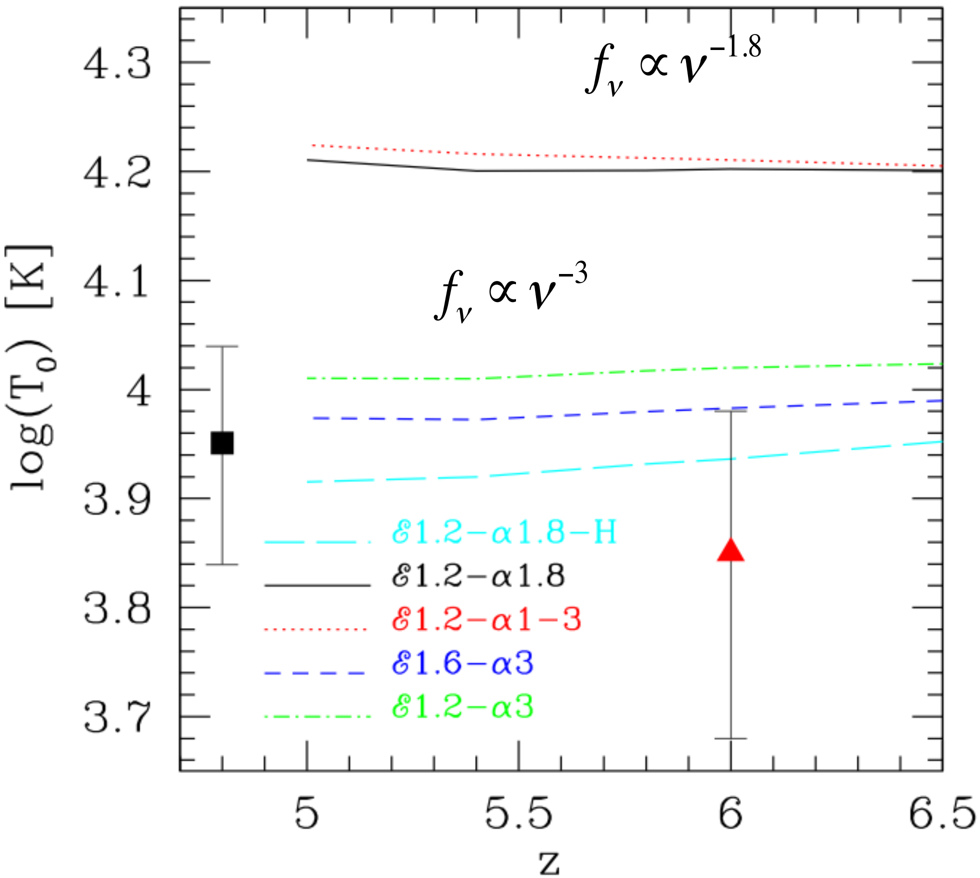


- Seven high resolution quasar spectra at z~6 (Becker et al. 2007);
- Fit Voigt profiles to Ly-α absorption lines (observed and simulated);
- Compare to spectra from hydro+RT simulations with different heating histories – measure temperature!



Bolton et al. (2012)

IGM temperature measurements



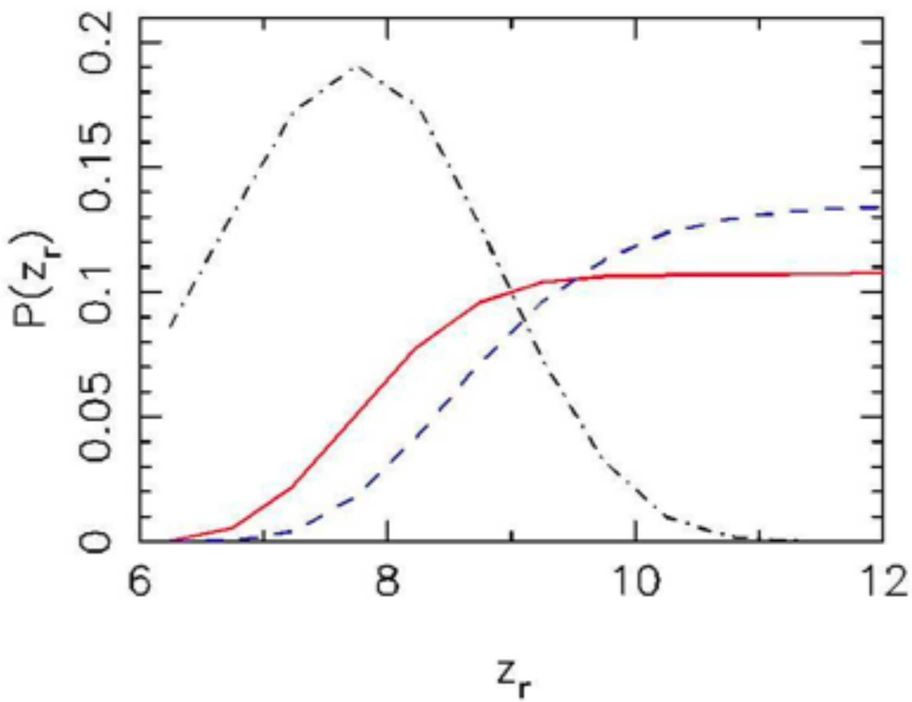
Ciardi, JB et al. (2012)

- CRASH radiative transfer simulations: calibrated to match CMB constraint and ionising emissivity at z=6
- Temperatures at z=5-6 are consistent with the bulk of reionisation being driven by spectra typical of pop-II sources.

Constraint on the end of H-I reionisation

- Temperature data inconsistent with very late end to reionisation (z_r<6.5) for $f_\nu \sim \nu^{-3}$; gas too hot for z_r~6-7, but limited constraining power for larger z_r due to thermal asymptote.

- Lower limit on z_r: higher temperatures from e.g. harder stellar sources/X-rays/ significant spectral filtering favour larger z_r (more time for gas to cool).



Raskutti, JB et al. (2012)

RED SOLID CURVE
Constraint from temperature measurements

BLACK DOT-DASH CURVE
Constraint from photo-ionisation rates + CMB

Summary: reionisation

- Started no later than z~12, and ended around z~6, likely an extended process (CMB and GP trough);
- Ionising emissivity must remain constant or rise at z>6 - only 1-3 photons per H-I emitted over a Hubble time at z=6; (Ly-α forest);
- Too few quasars to dominate the ionising photon budget at z>4 (quasar luminosity function, Ly-α forest);
- Star forming galaxies can potentially drive the bulk of reionisation (HUDF luminosity functions), but other sources cannot be fully ruled out.

Summary: Ly-α probes

- Current constraints on the timing and nature of reionisation are still weak, however, and not all are in agreement;

- The recent discovery of the first quasar and LAEs at z>7, plus high resolution spectra of z~6 quasars, have provided tantalising (but confusing!) glimpses into this distant era:

- Near-zone and LAE/LBG fraction suggest IGM may be ~10 per cent neutral at z=7: the bulk of reionisation may occur at z>7;

- IGM temperature at z=6 consistent with heating by (primarily) soft ionising spectra typical of star-forming galaxies; reionisation largely over by z=6.5.

- Further observations are key, but z>7 data are already helping to better inform theoretical models of reionisation.