Cosmological reionisation, HRI Allahabad, 16/02/10

Reionisation and the Ly-α forest

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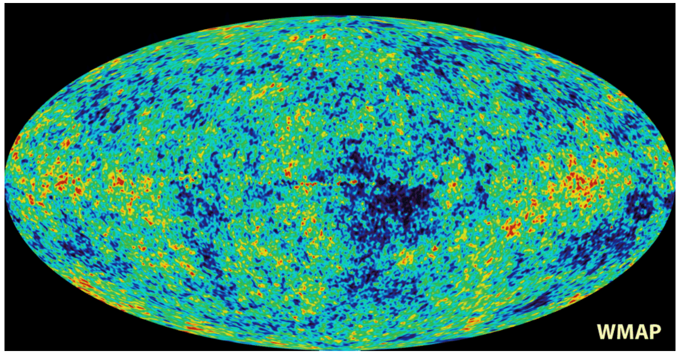
The key evidence

I: CMB polarisation data



In the limit of instantaneous reionisation:

$$\tau_e = 0.088 \pm 0.015 \Rightarrow z_r = 10.5 \pm 1.2\ (68\%)$$

Parameter	7-year Fit	5-year Fit
Fit parameters		
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	2.273 ± 0.062
$\Omega_c h^2$	0.1109 ± 0.0056	0.1099 ± 0.0062
Ω_Λ	0.734 ± 0.029	0.742 ± 0.030
$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.41 \pm 0.11) \times 10^{-9}$
n_s	0.963 ± 0.014	$0.963^{+0.014}_{-0.015}$
τ	0.088 ± 0.015	0.087 ± 0.017
Derived parameters		
t_0	13.75 ± 0.13 Gyr	13.69 ± 0.13 Gyr
H_0	71.0 ± 2.5 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc
σ_8	0.801 ± 0.030	0.796 ± 0.036
Ω_b	0.0449 ± 0.0028	0.0441 ± 0.0030
Ω_c	0.222 ± 0.026	0.214 ± 0.027
z_{eq}	3196^{+134}_{-133}	3176^{+151}_{-150}
z_{reion}	10.5 ± 1.2	11.0 ± 1.4

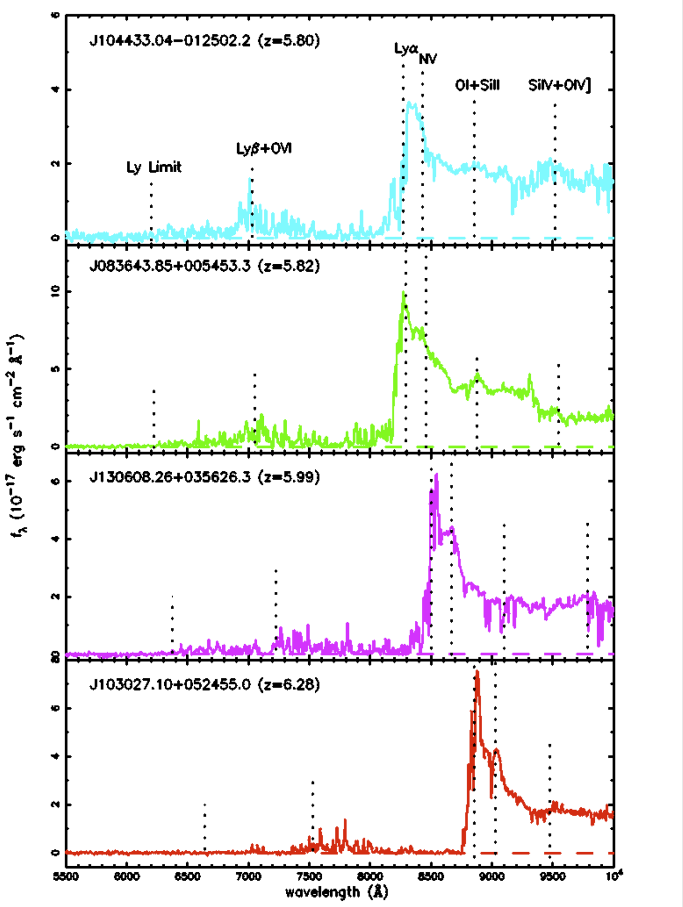
WMAP-7 analysis now includes helium reionisation

Dunkley *et al.* (2007), Larson *et al.* (2010)

The key evidence

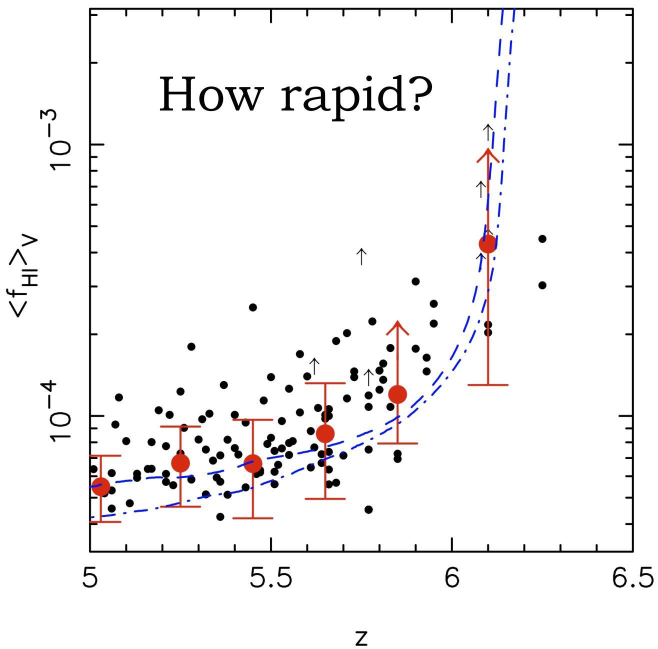
II: SDSS quasar absorption spectra

The Gunn-Peterson (1965) trough at $z>6$ implies f_{HI} is increasing towards higher redshift.

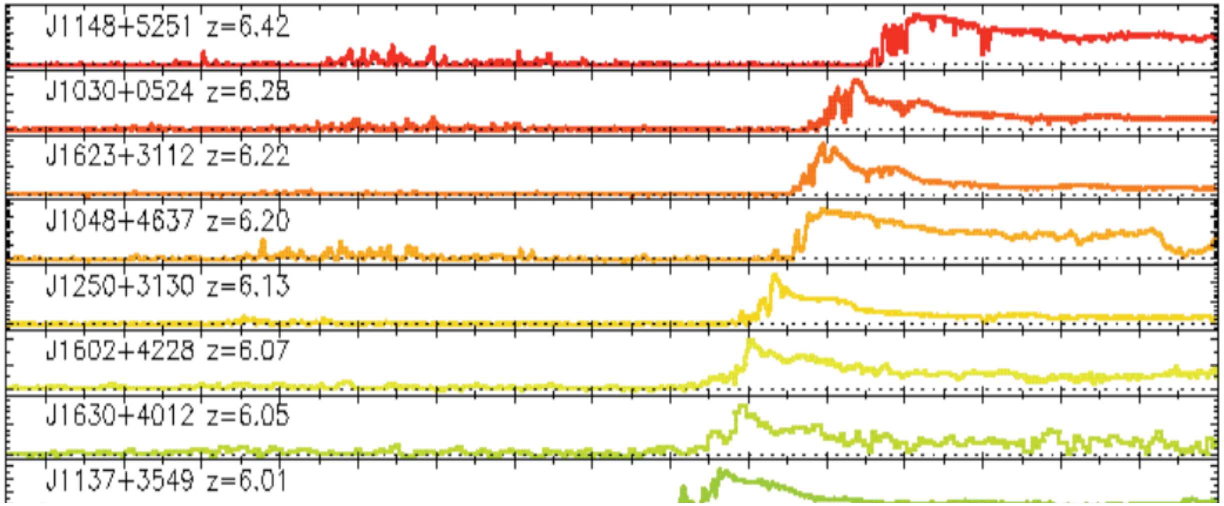


Becker *et al.* (2001)

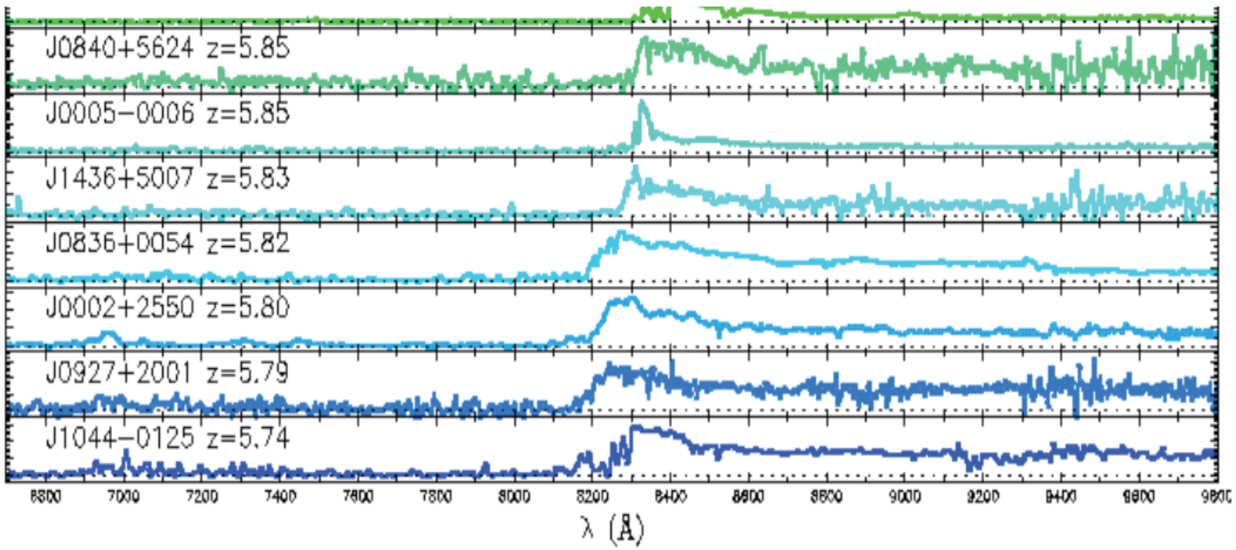
$z_r > 6$



Fan *et al.* (2006), but see Becker *et al.* (2007)



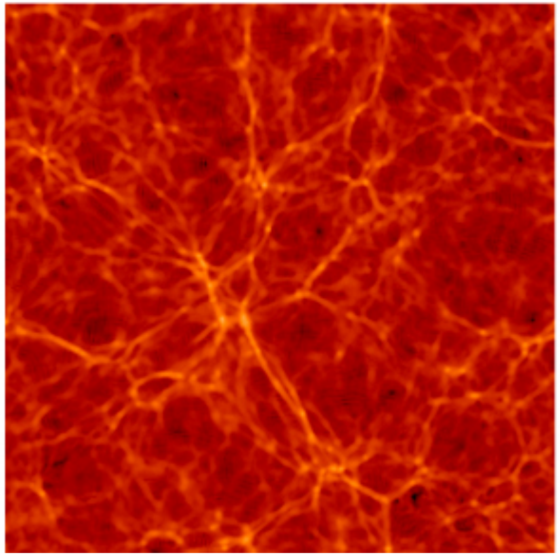
$$\tau_{GP} \approx 4.3\times10^{5} f_{HI}\Delta\left(\frac{\Omega_b h^2}{0.024}\right)\left(\frac{\Omega_m h^2}{0.135}\right)^{-1/2}\left(\frac{1+z}{7}\right)^{3/2}$$

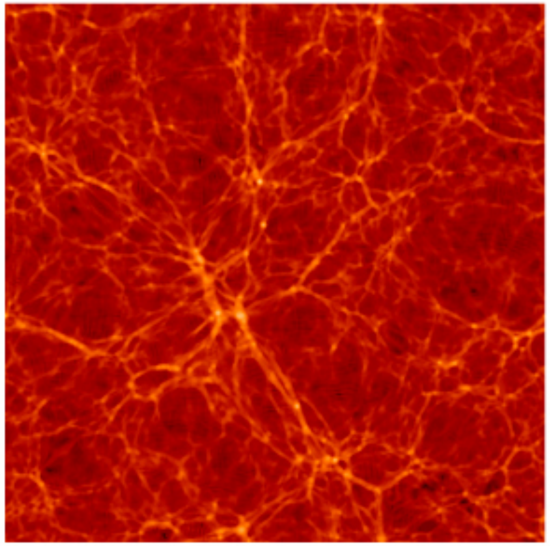


Fan *et al.* (2006)

Ly-α forest - theory

Baryons
at z=3





Dark matter
at z=3

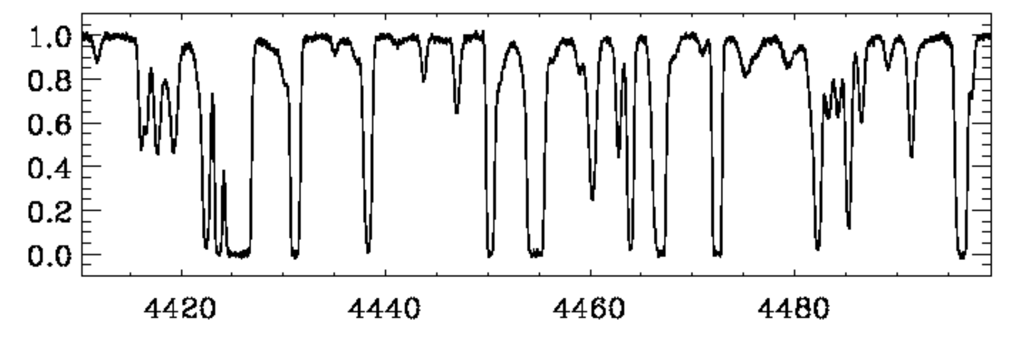
Credit: M. Viel

- The Ly-α forest originates from, warm, photoionised underdense to moderately overdense hydrogen gas in the IGM which closely traces the dark matter.

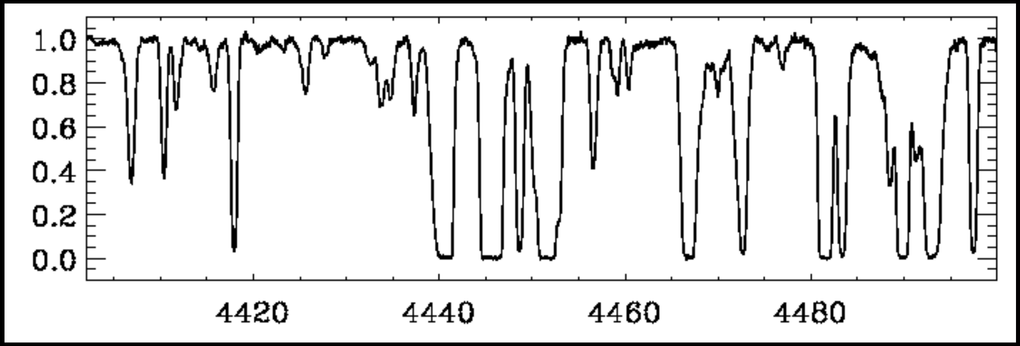
- Absorption lines arise from the residual HI in the density field associated with the filaments and sheets of the 'cosmic web'.

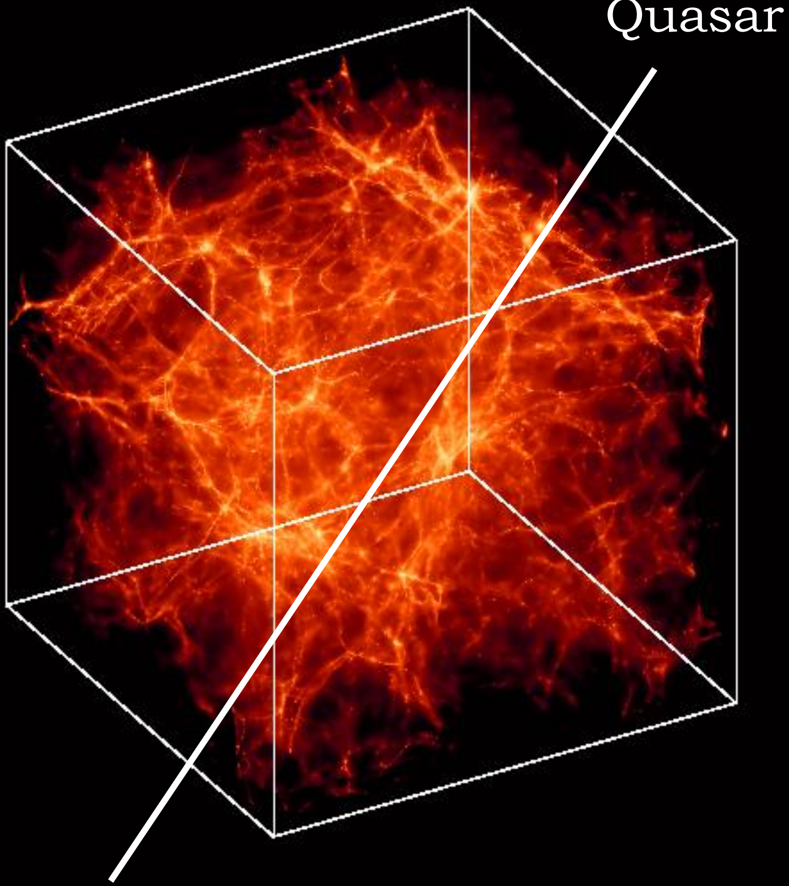
Ly-α forest - simulations

Hydrodynamical simulation



Q0420-388 (VLT/UVES)





The Fluctuating Gunn-Peterson Approximation

Assuming HI photo-ionisation equilibrium and a temperature-density relation for low density gas, $T=T_0(1+\delta)^{\gamma-1}$

$$\tau_{Ly\alpha} = \tau_0 \frac{(1+z)^6(\Omega_b h^2)^2}{T_0^{0.7}(z)H(z)\Gamma_{HI}(z)}(1+\delta)^{2-0.7(\gamma-1)}$$

The Ly-α forest opacity is closely linked to the IGM temperature, intensity of UV background…

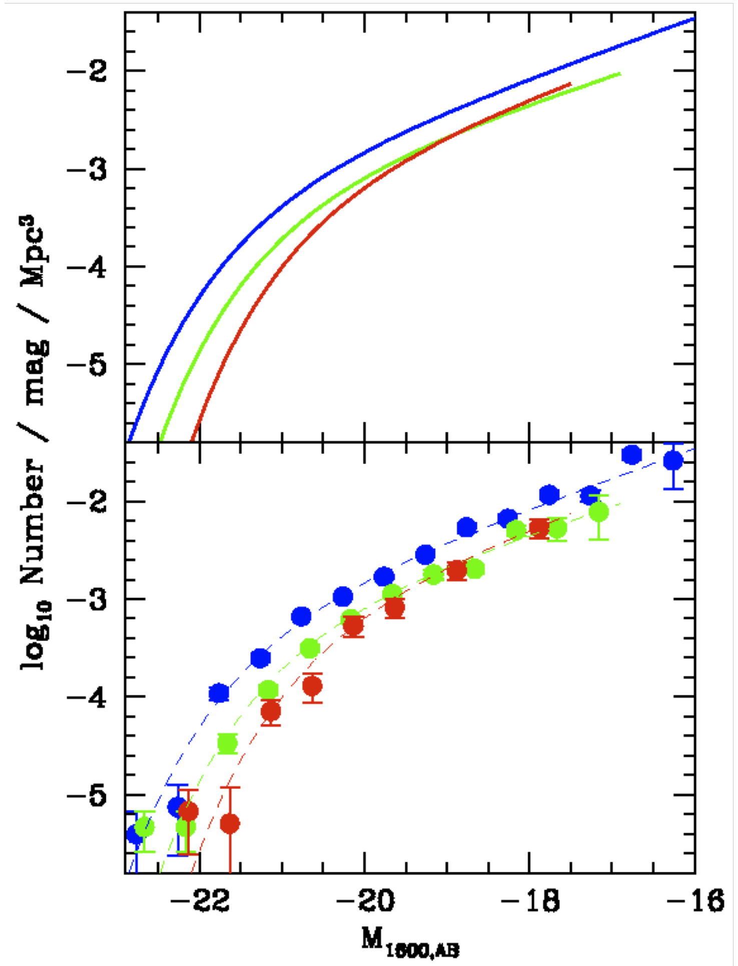
I: The metagalactic ionising background

with Martin Haehnelt (IoA, Cambridge)

Ionising photons from sources

Comoving emissivity typically obtained from galaxy and quasar luminosity functions.

$$\dot{N}_{ion} = \int_{\nu_{HI}}^{\infty} \frac{\varepsilon_\nu}{h\nu} d\nu \quad [s^{-1} Mpc^{-3}]$$



Bouwens *et al.* (2007)

Ionising photons from sources

$$\dot{N}_{ion} \approx 10^{49.7}\left(\frac{\varepsilon_L}{10^{25}\,erg\,s^{-1}\,Hz^{-1}\,Mpc^{-3}}\right)\left(\frac{\alpha_s}{3}\right)^{-1}\left(\frac{f_{esc}}{0.1}\right)s^{-1}\,Mpc^{-3}$$

Lyman limit emissivity:
depends on magnitude limit of survey
and the spectral shape at >912 Å
(need stellar population models)

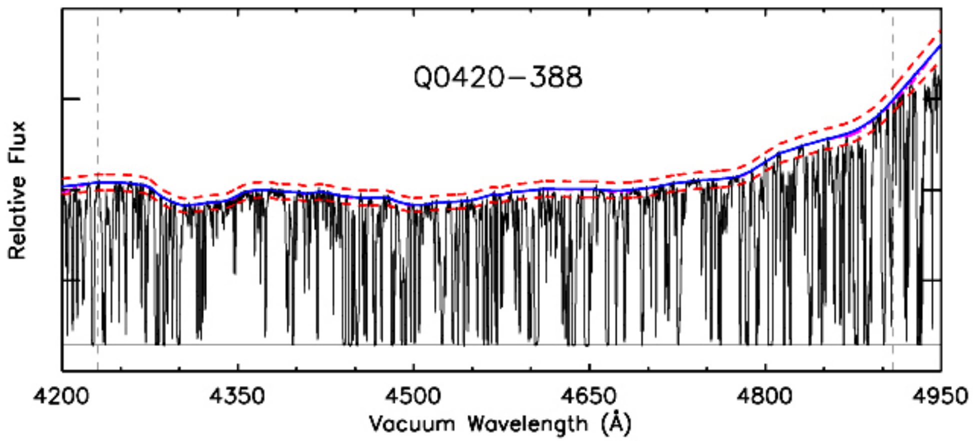
Source spectral
shape below the
Lyman limit.

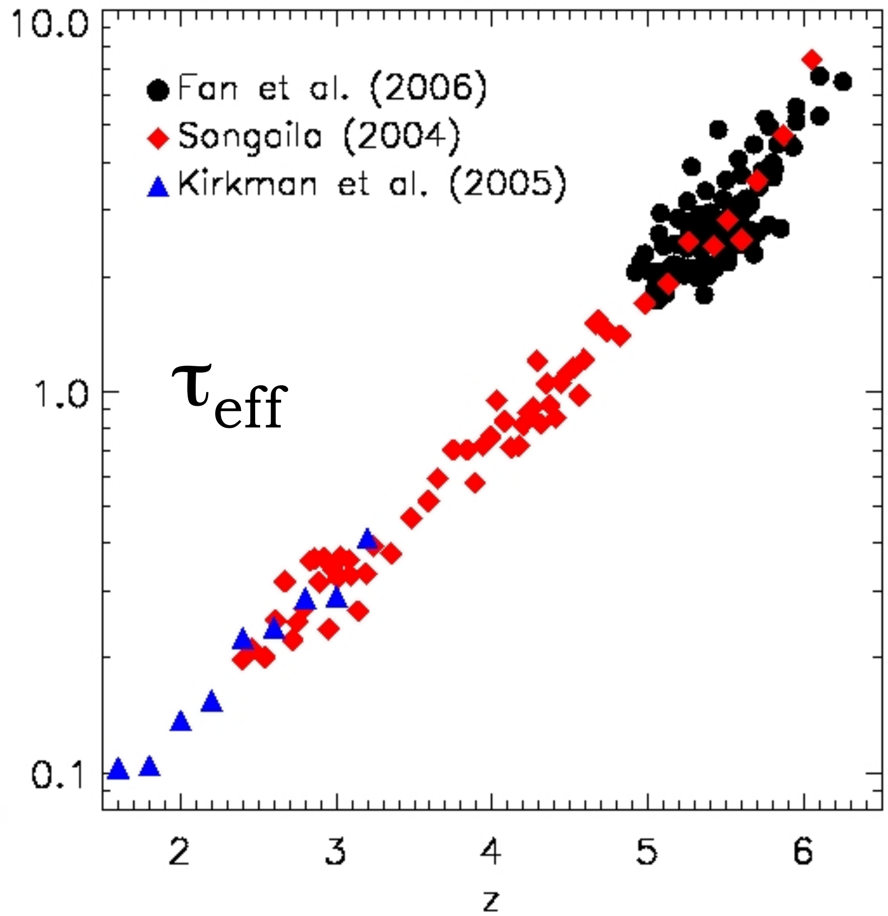
The fraction of
ionising photons
escaping from the
ISM into the IGM
- very uncertain.

Ionising photons in the IGM

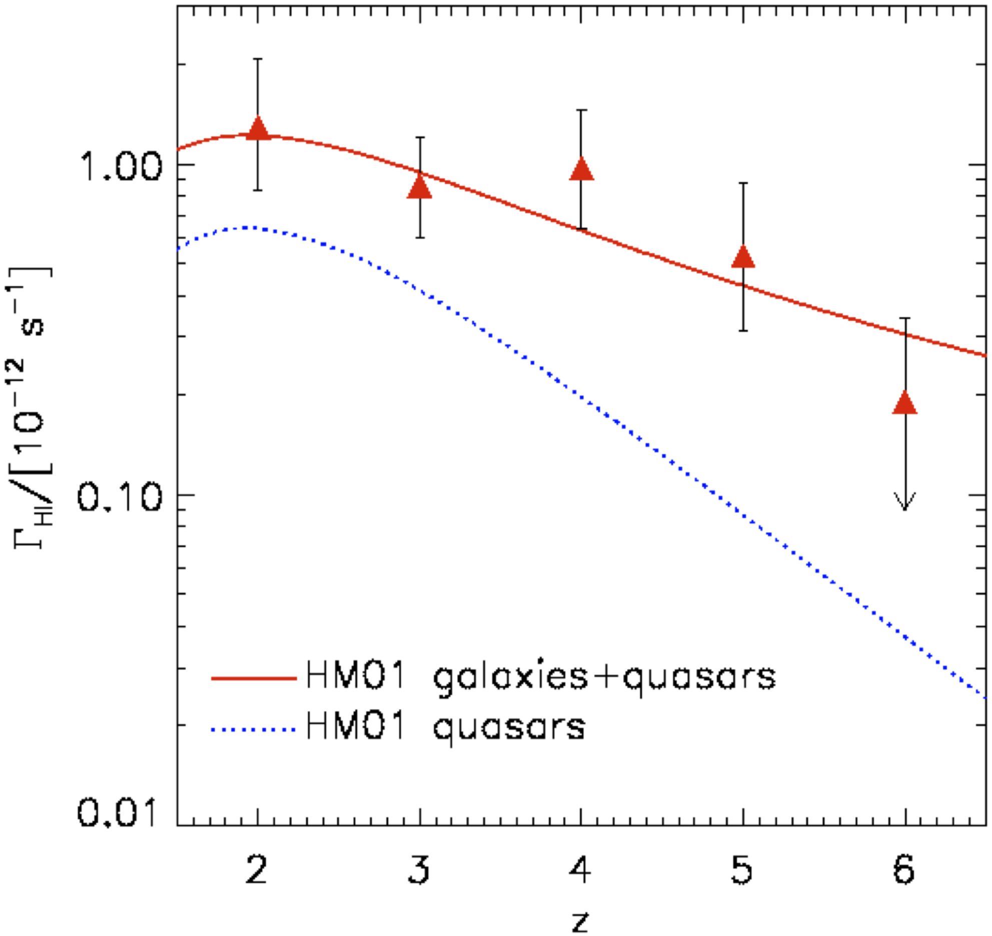
$$\Gamma_{HI} = \int_{\nu_{HI}}^{\infty} \frac{\varepsilon_\nu}{h\nu} \sigma_\nu \lambda_\nu \, d\nu$$

Recall that $\tau_{Ly\alpha} \propto \dfrac{1}{\Gamma_{HI}}$





Measuring Γ_{HI} at 2<z<6



Bolton *et al.* (2005, 2007), Faucher-Giguere *et al.* (2008, 2009)

Match the observed Ly-α opacity to a suite of hydrodynamical sims, carefully consider systematics

- Quasars fall short of providing the requisite number of ionising photons, especially towards z=6
- A significant contribution from star forming galaxies required to maintain the photon budget at z~6 (consistent with Haardt & Madau 2001 UVB models)
- But the PI rate can also tell us something interesting about the reionisation history at z>6…

Ionising photons in the IGM

Can only measure at z<6

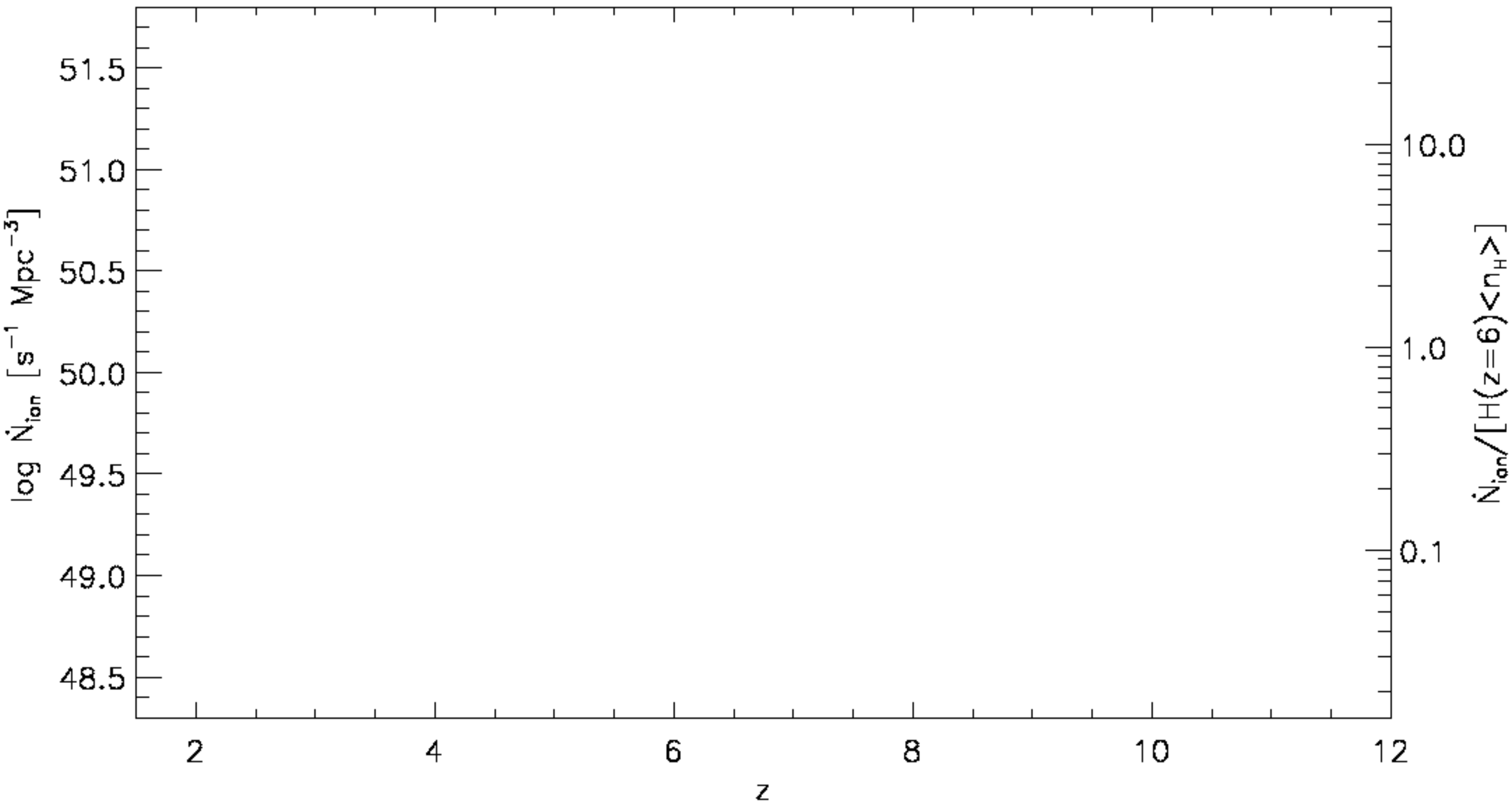
$$\dot{N}_{ion} \approx 10^{51.2}\,\Gamma_{-12}\left(\frac{\alpha_s}{3}\right)^{-1}\left(\frac{\alpha_b+3}{6}\right)\left(\frac{\lambda_{mfp}}{40\,Mpc}\right)^{-1}\left(\frac{1+z}{7}\right)^{-2} s^{-1}\,Mpc^{-3}$$

Source and UVB spectral shape.
Need stellar population and UVB models
e.g. Leitherer *et al.* 1999,
Faucher-Giguere *et al.* 2009)

Ionising photon mean free path
(Lyman limit systems, *e.g.*
Prochaska *et al.* 2009)

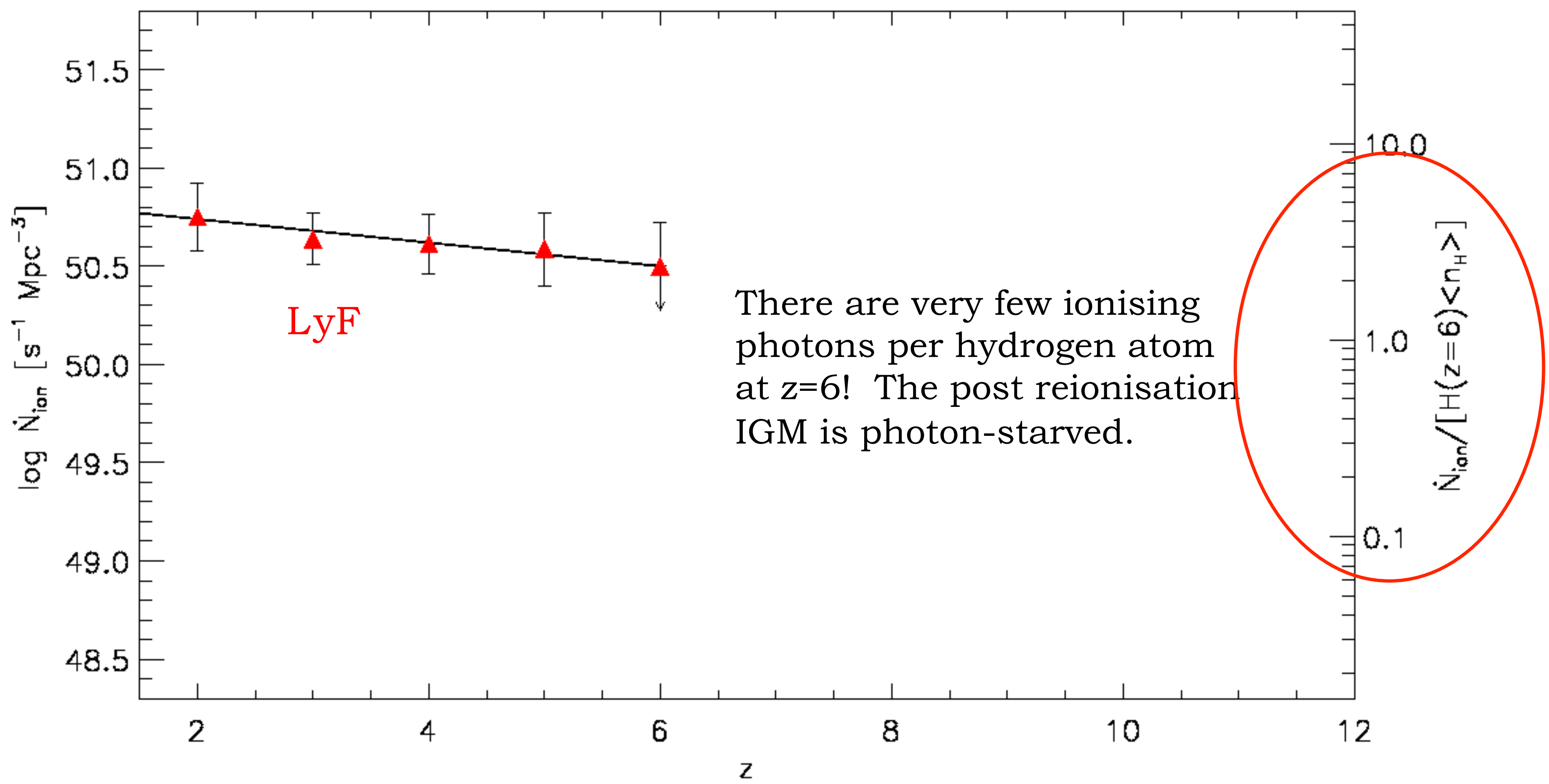
- Independent of the escape fraction
- Not affected by missing sources
- Only possible at z<6

Constraints on the Ionising Emissivity



Bolton & Haehnelt (2007)

Constraints on the Ionising Emissivity

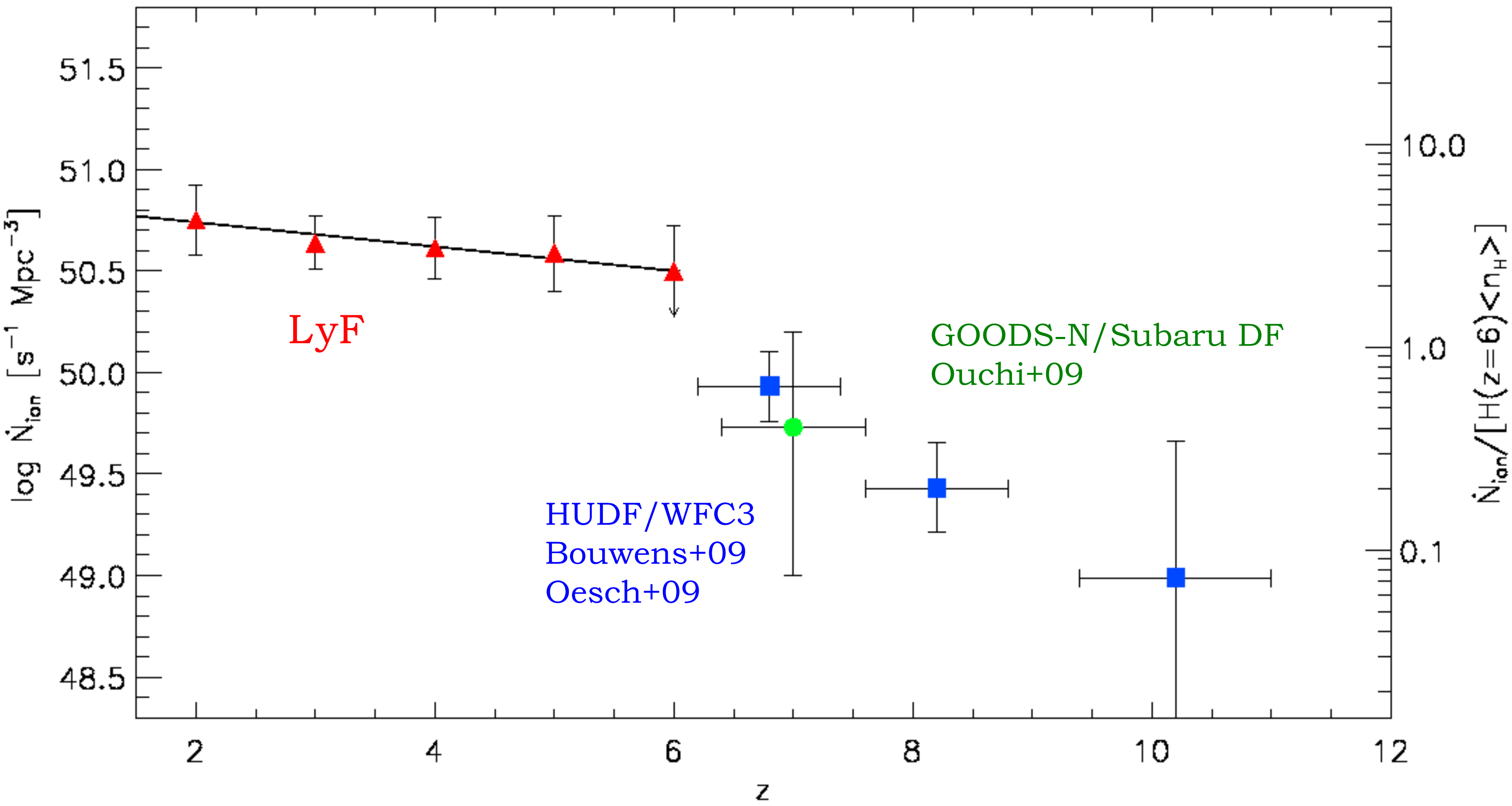


There are very few ionising photons per hydrogen atom at z=6! The post reionisation IGM is photon-starved.

Bolton & Haehnelt (2007)

Constraints on the Ionising Emissivity

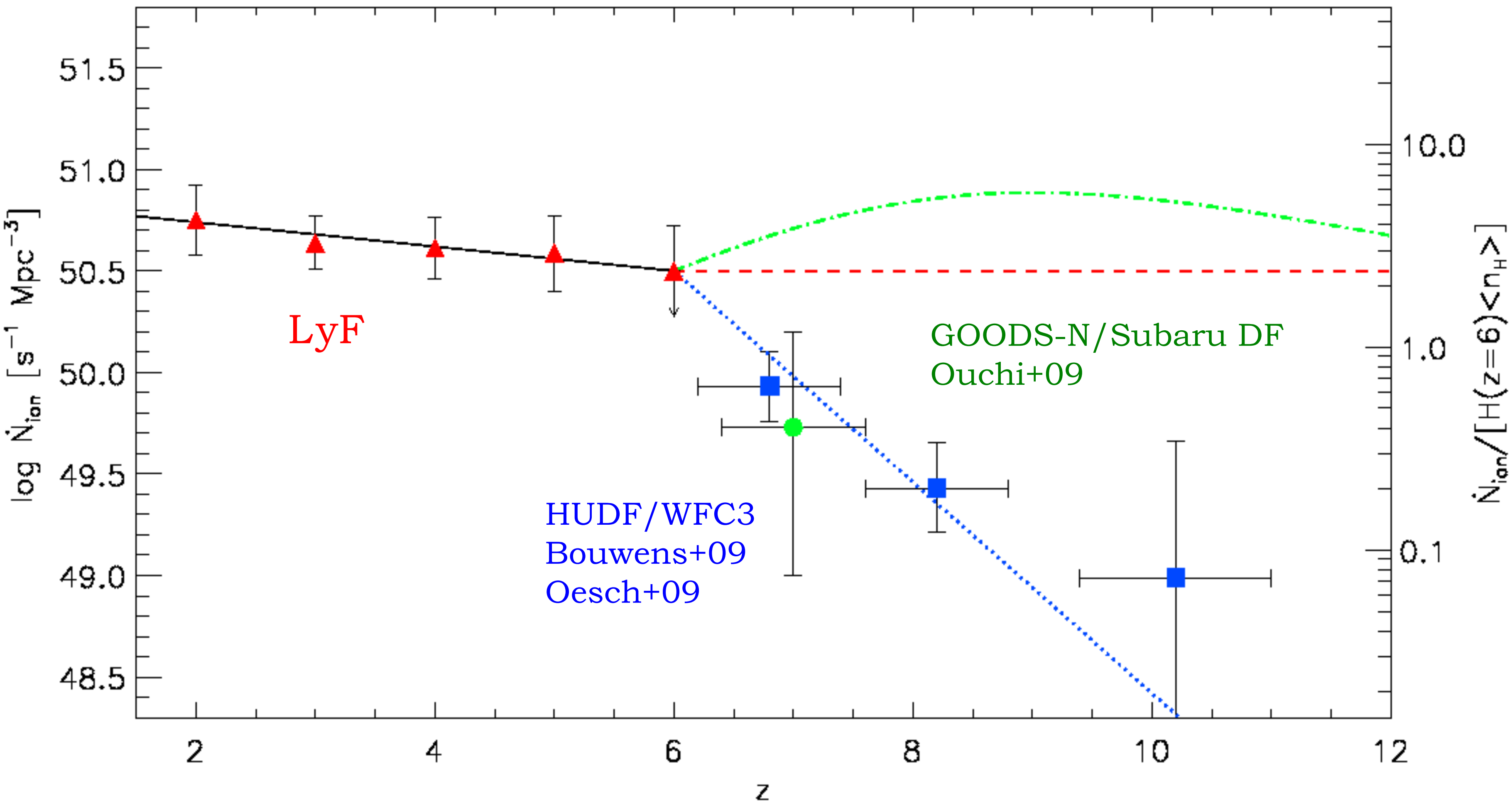
See also Bunker+09, McClure+09, Yan+09, Finkelstein+10...



$$f_{esc} = 0.2, \alpha_s = 3, M_{UV} = -18.3$$

Bolton & Haehnelt (2007)

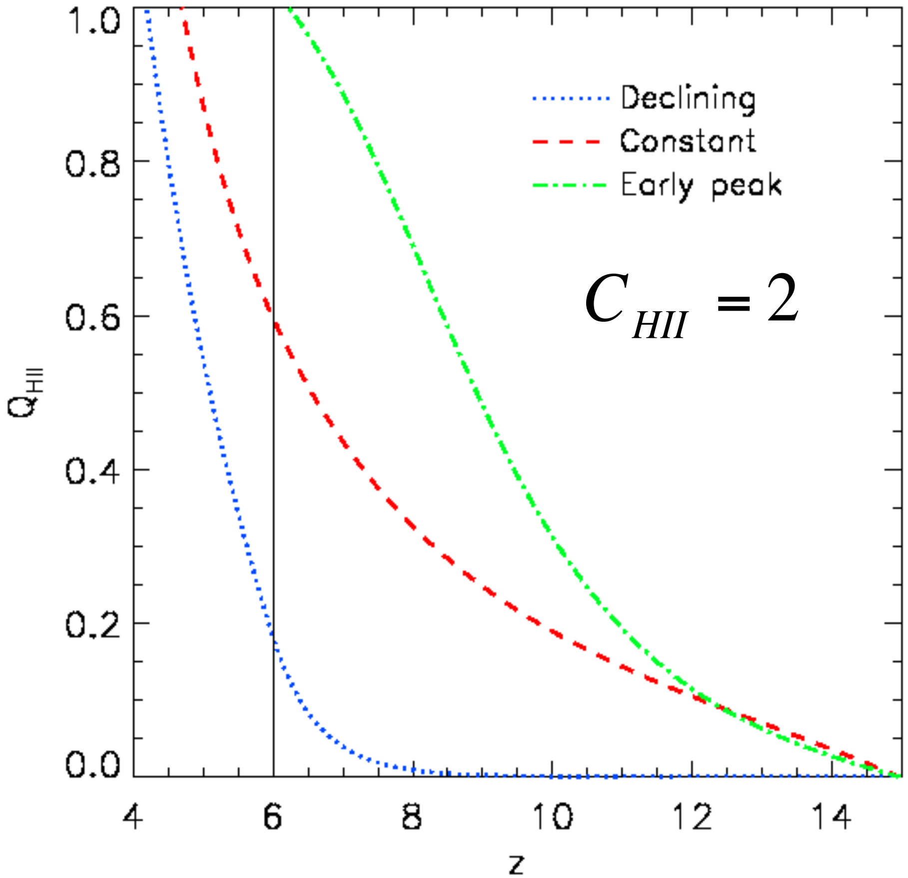
Constraints on the Ionising Emissivity



$$f_{esc} = 0.2, \alpha_s = 3, M_{UV} = -18.3$$

Bolton & Haehnelt (2007)

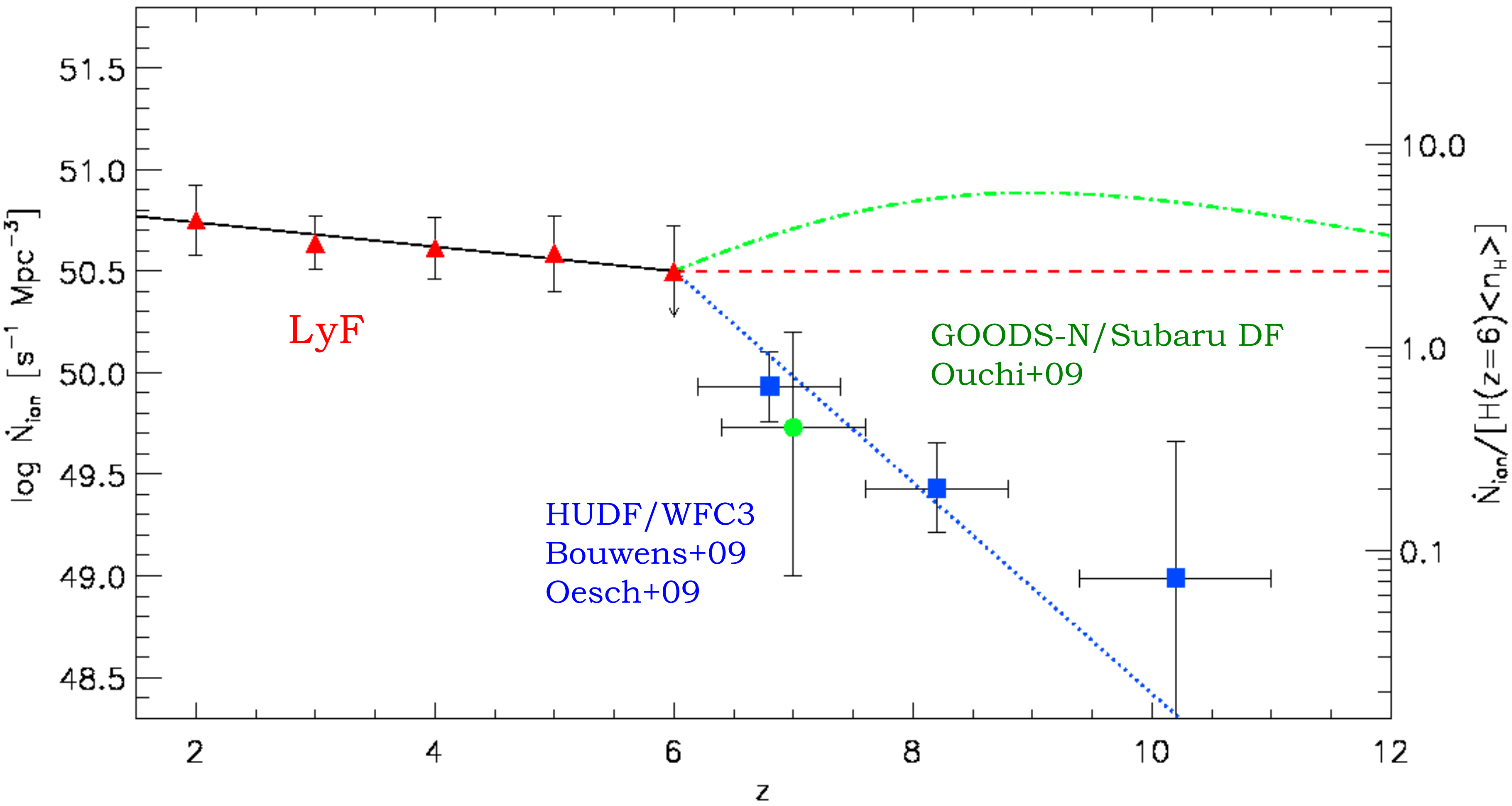
The filling factor of HII



$$\frac{dQ_{HII}}{dt} = \frac{\dot{N}_{ion}}{\langle n_H \rangle} - Q_{HII} C_{HII} \frac{\langle n_H \rangle}{a^3} \alpha_B(T)$$

Implications for ionising sources

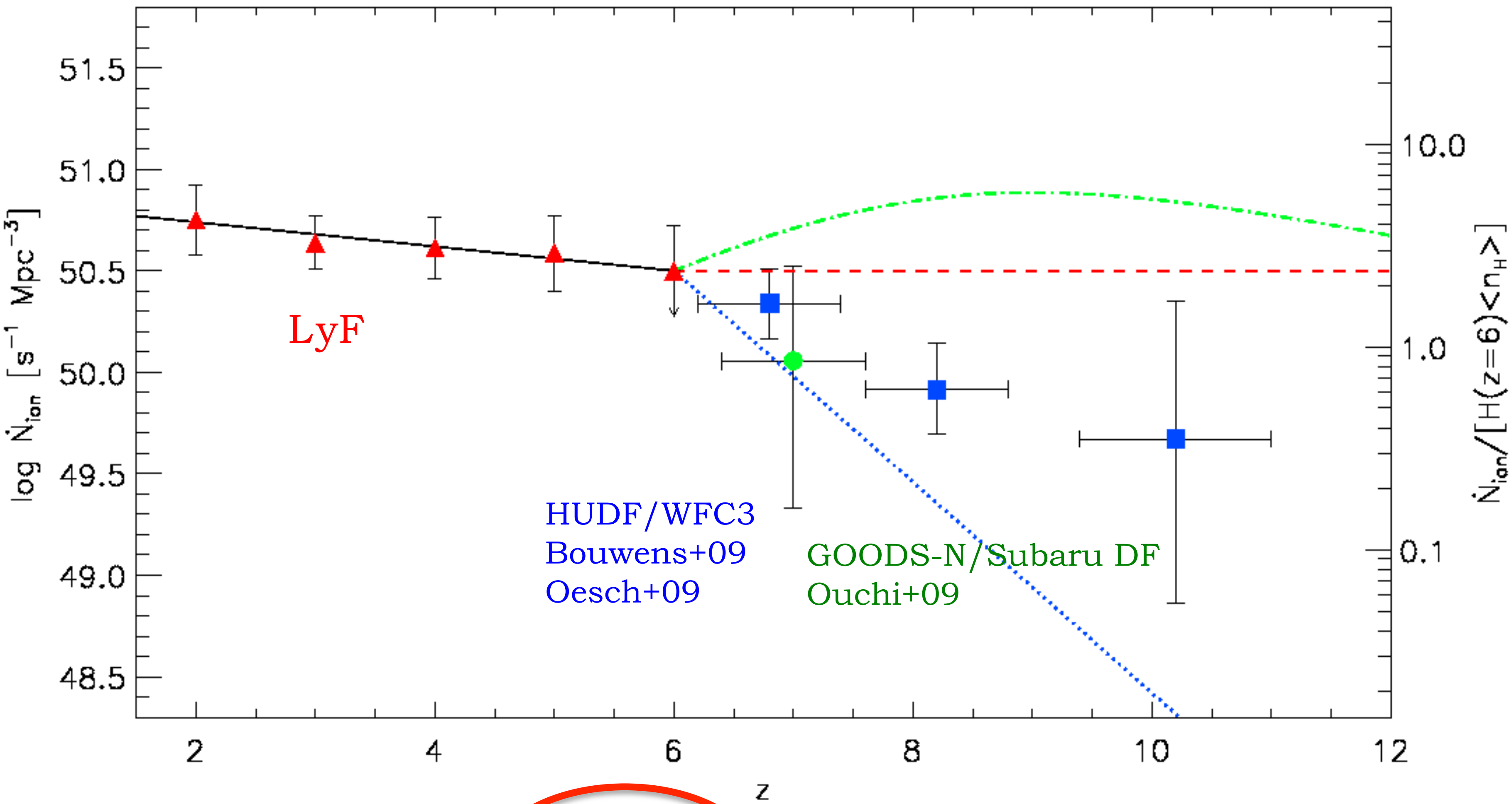
Constraints range from ~6 - 30% of required emissivity at *z*>6



$$f_{esc} = 0.2, \alpha_s = 3, M_{UV} = -18.3$$

Bolton & Haehnelt (2007)

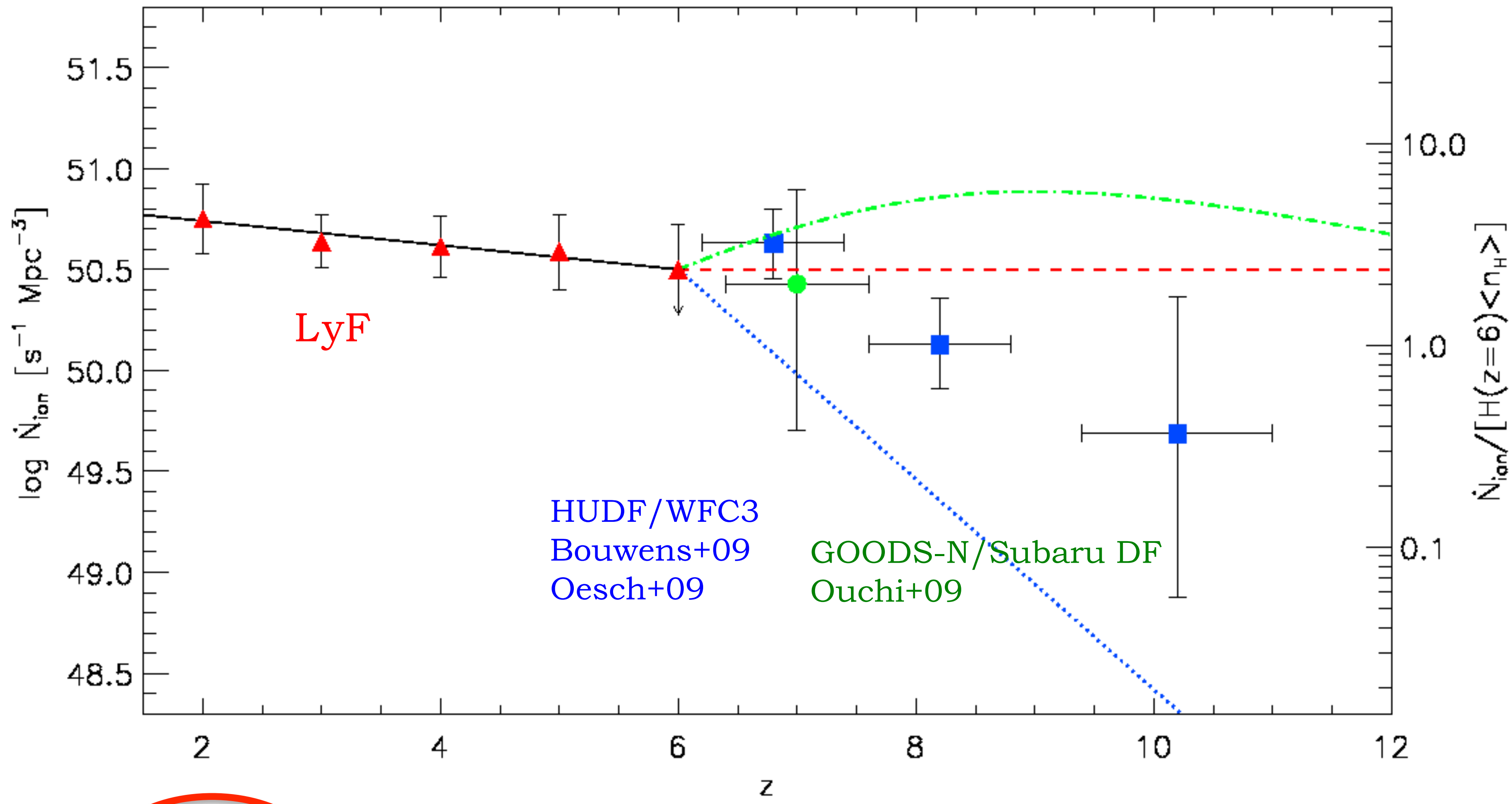
Missing faint sources?



$$f_{esc} = 0.2, \alpha_s = 3, M_{UV} = -15$$

Bolton & Haehnelt (2007)

Larger escape fraction?

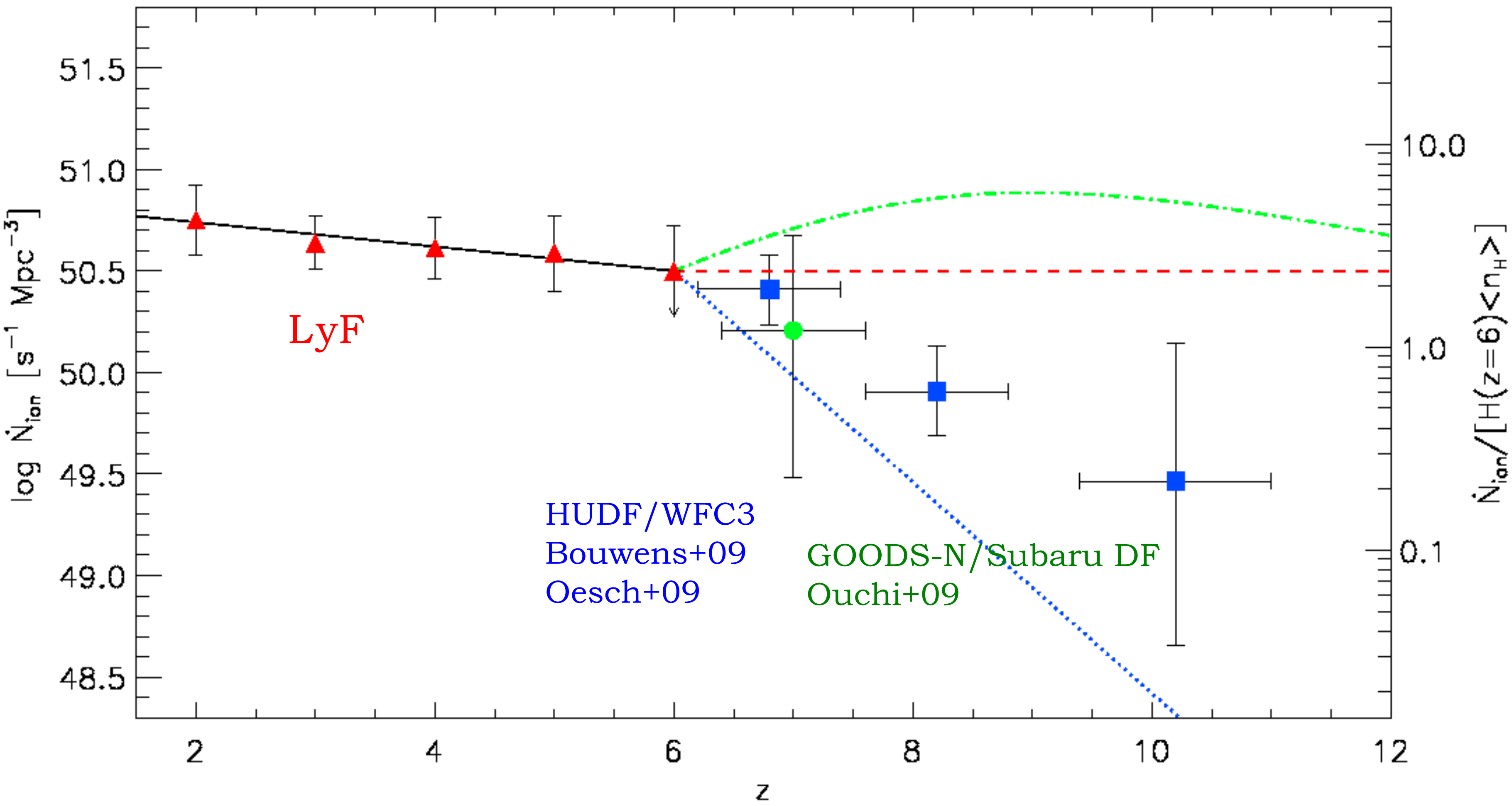


$f_{esc} = 1.0, \alpha_s = 3, M_{UV} = -18.3$

Bolton & Haehnelt (2007)

Harder spectra?

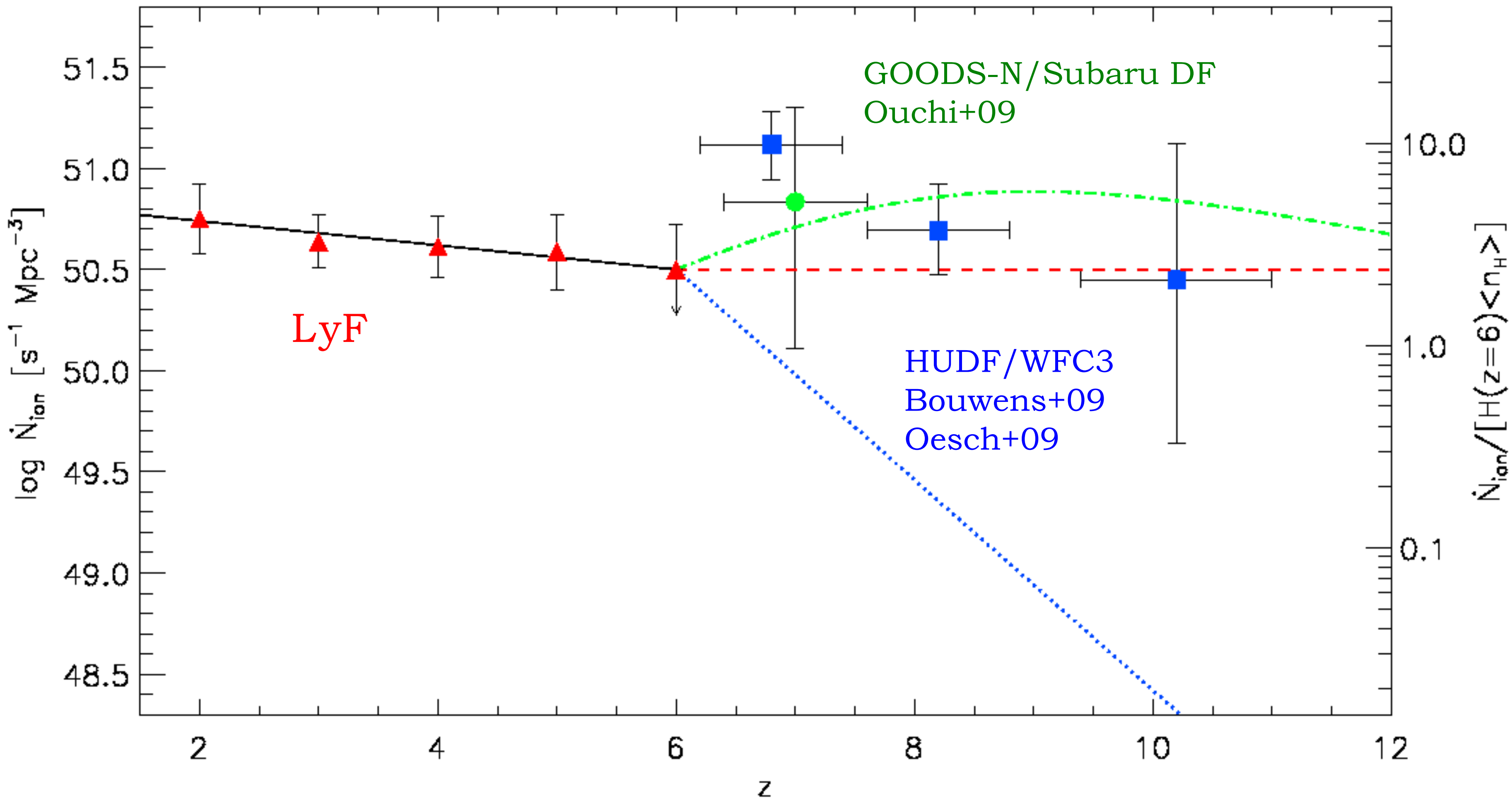
e.g. UV continuum slope β~3.0 at z~7 (Bouwens *et al.* 2010)



$$f_{esc} = 0.2, \alpha_s = 1, M_{UV} = -18.3$$

Bolton & Haehnelt (2007)

What do we *currently* need if C_{HII}=2?



$$f_{esc} = 0.4, \alpha_s = 1, M_{UV} = -15$$

1) High f_{esc} (unrealistic?)
2) Hard ionising spectra (metal free?)
3) Many faint (as yet undetected) sources

Reionisation and the Lyα forest

• The emissivity has to moderately increase at z>6 for reionisation to complete by z=6 for C_{HII}=2

• Unless the ionising emissivity rises very rapidly just above z=6, reionisation must be a rather photon starved and extended process – there are only 1-3 photons/hydrogen atom at z=6.

• It also suggests we are still missing most of the faint ionising sources at z>6 required to complete reionisation unless escape fraction is large and spectra are very hard.

(see also e.g. Miralda-Escude 2003, Meiksin 2005, Choudhury & Ferrara 2005, 2007).

[A brief aside: constraining $C_{HII} = \frac{\langle \rho_b{}^2 \rangle_{HII}}{\langle \rho_b \rangle_{HII}^2}$]

$$\dot{\rho}_{SFR}(z) \approx \frac{0.004\, M_{sol}\, yr^{-1} Mpc^{-3}}{f_{esc}} \left(\frac{C_{HII}}{5}\right)\left(\frac{1+z}{7}\right)^3$$

Madau *et al.* (1999)

Express in terms of ionising photons

$$\dot{N}_{rec}(z) = \frac{\bar{n}_H(z)}{\langle t_{rec}(z) \rangle} \approx 10^{50.7}\, s^{-1} Mpc^{-3} \left(\frac{C_{HII}}{5}\right)\left(\frac{1+z}{7}\right)^3$$

Photons required to keep IGM ionised

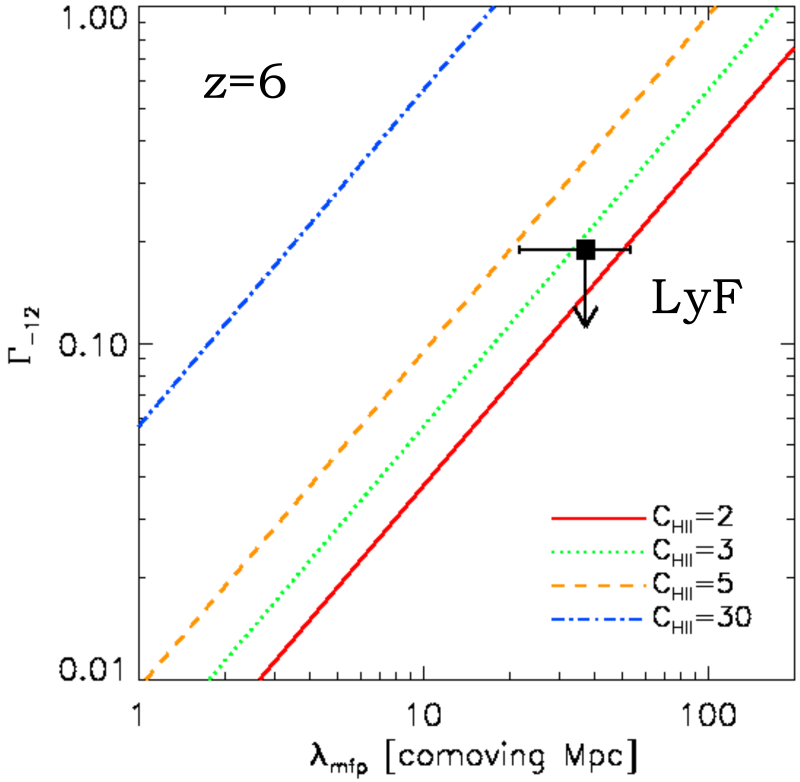
$$\dot{N}_{rec}(z) = \dot{N}_{ion}(z) \quad \Rightarrow \quad C_{HII} \approx 13.2 \left(\frac{\Gamma_{HI}}{10^{-12} s^{-1}}\right)\left(\frac{\lambda_{mfp}}{40\, Mpc}\right)^{-1}\left(\frac{1+z}{7}\right)^{-5}$$

Photons already present in ionised IGM

$$\dot{N}_{ion}(z) \approx 10^{51.2}\, s^{-1} Mpc^{-3} \left(\frac{\Gamma_{HI}}{10^{-12} s^{-1}}\right)\left(\frac{\lambda_{mfp}}{40\, Mpc}\right)^{-1}\left(\frac{1+z}{7}\right)^{-2}$$

[A brief aside: constraining $C_{HII} = \frac{\langle \rho_b{}^2 \rangle_{HII}}{\langle \rho_b \rangle_{HII}^2}$]

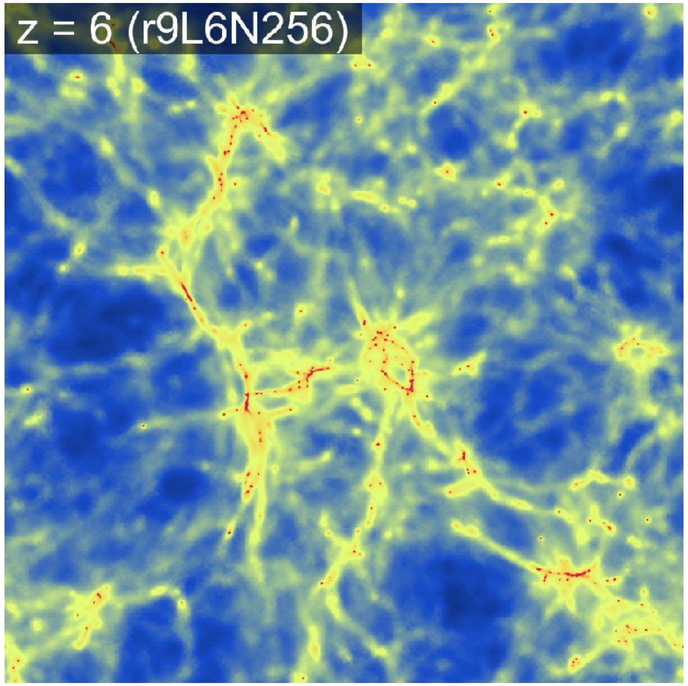
Observationally derived



$$C_{HII} \leq 2 - 5$$

Bolton & Haehnelt (2007)

Numerically derived



$$C_b \approx 5$$

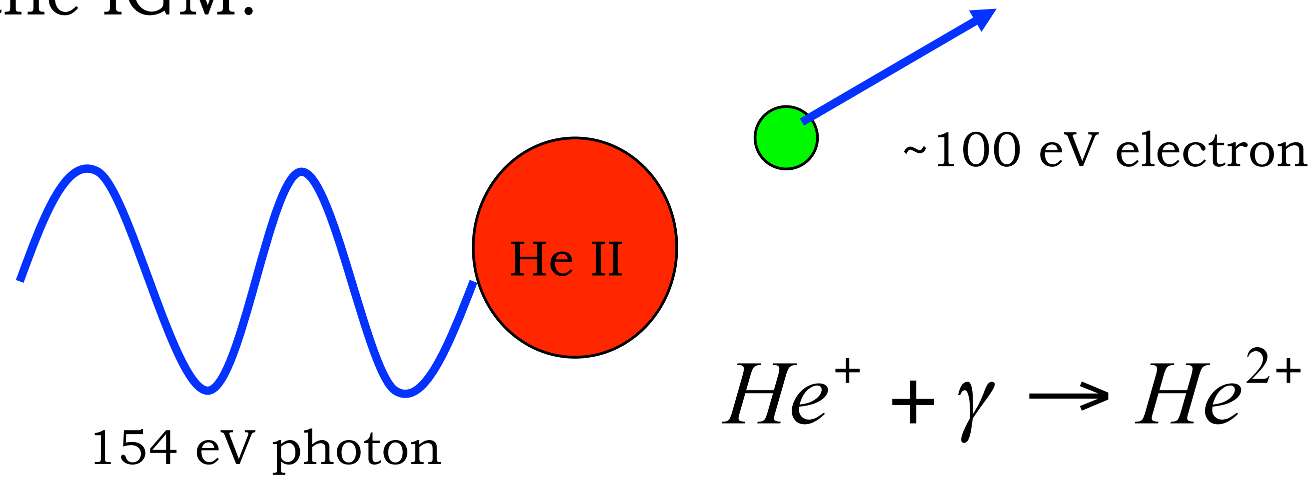
Pawlik et al. (2009)

II: The IGM temperature at z=6

with **George Becker (KICC, Cambridge)**
Stuart Wyithe (Melbourne)
Martin Haehnelt (IoA, Cambridge)
Wal Sargent (Caltech)

Photo-heating

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

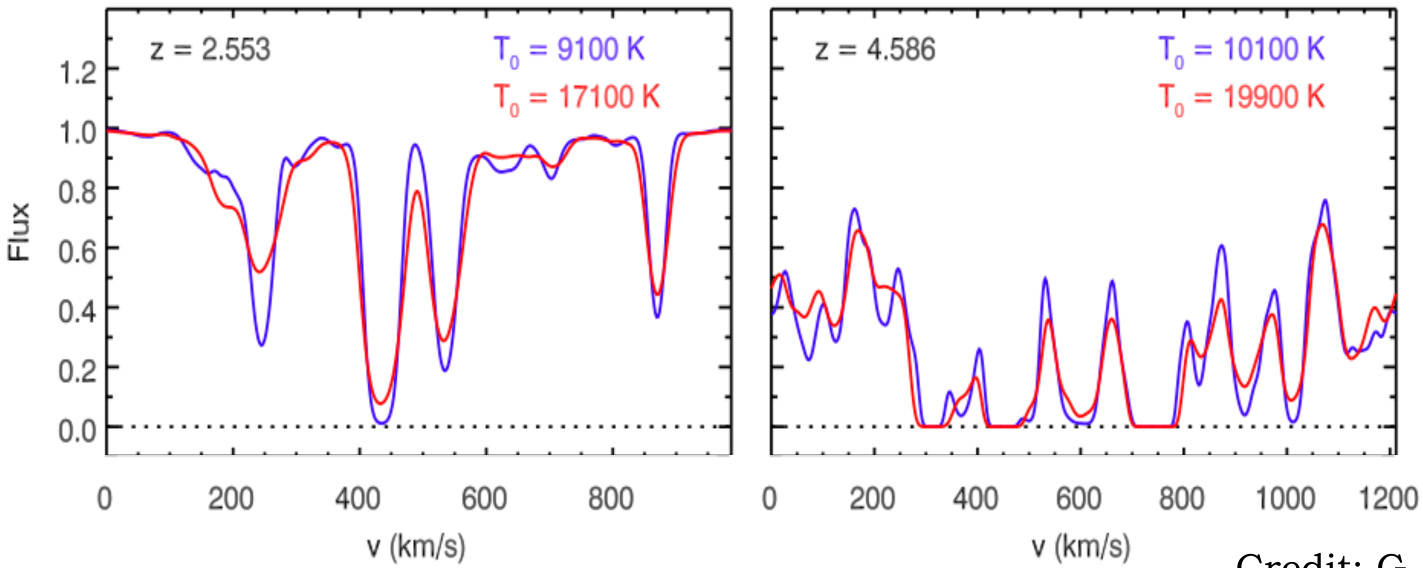


$$He^{+} + \gamma \rightarrow He^{2+} + e^{-}$$

Electrons share their energy with the baryons via Coulomb scattering.

The IGM temperature

- Higher temperatures broaden absorption features through thermal broadening and Jeans (pressure) smoothing.



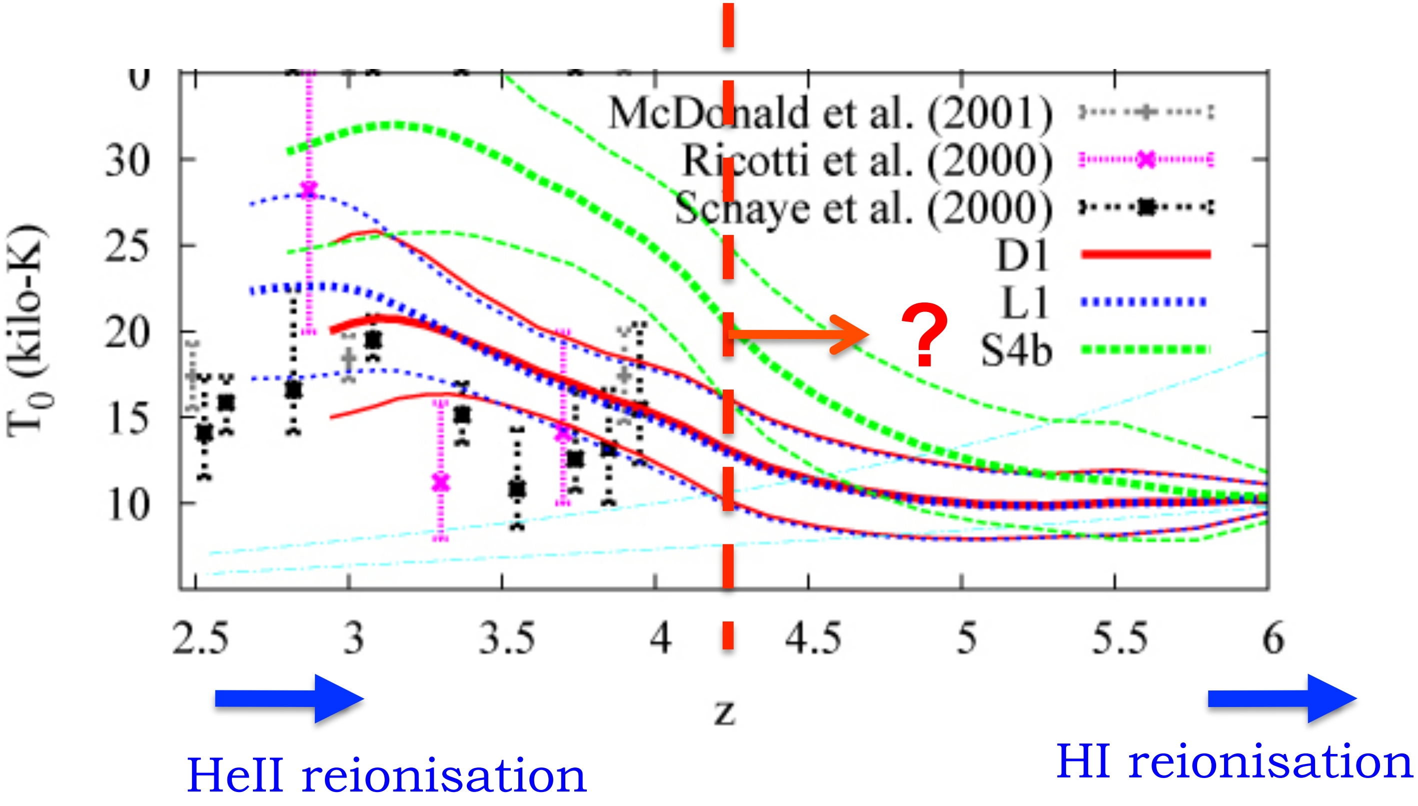
Credit: G. Becker

- Long cooling timescale enables use as an indirect probe of the H I and He II reionisation epochs (e.g. Theuns *et al.* 2002, Hui & Haiman 2003)

The high-z thermal history

- There are no constraints on the IGM temperature at z>4.5.

- In order to probe the thermal memory of HI reionisation,
we want to push to higher redshift (see also talk by G. Becker)

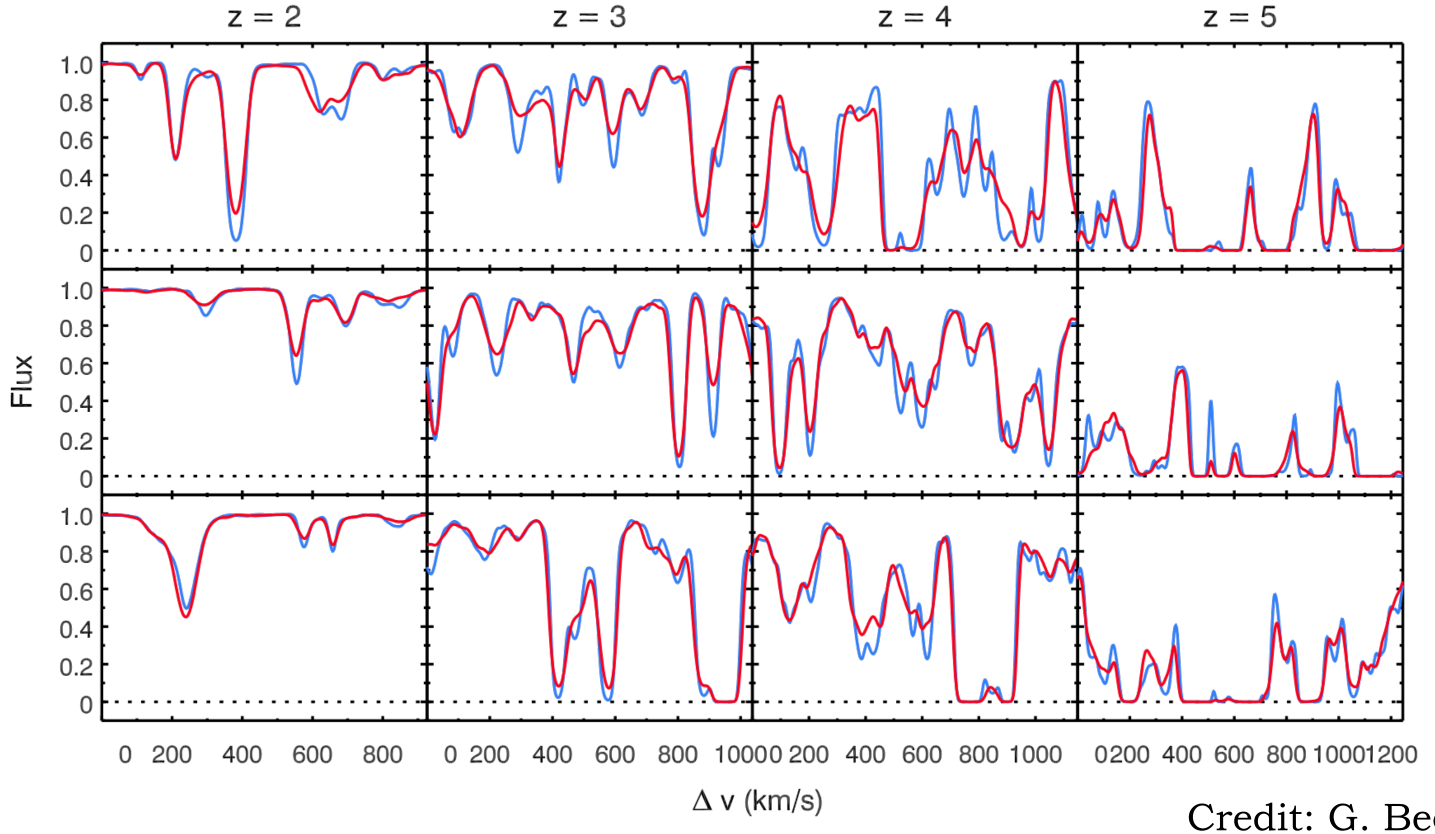


McQuinn *et al.* (2009)

Measuring T in the high-z forest

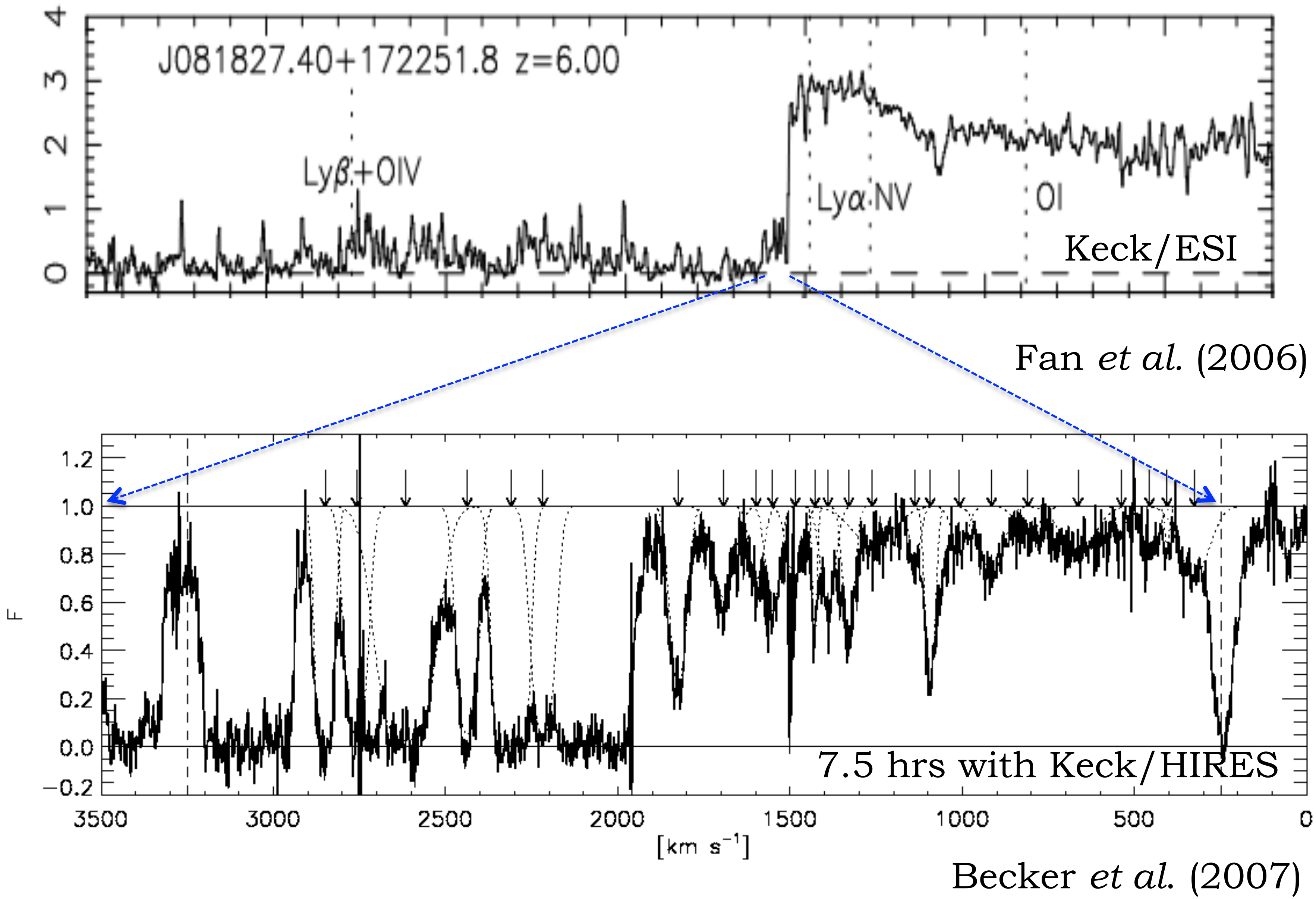
• Line fitting in the forest becomes very difficult at z>4 due to the disappearing transmission.

• High resolution spectra which resolve the thermal broadening kernel are required.



Credit: G. Becker

The temperature at z=6?



Simulating the IGM

- 18 GADGET-3 hydrodynamical simulations of the IGM,
- M_{gas} = 9×10^4 M_{sol}/h, 268 million particles each (2×512^3)
- Wide variety of thermal histories,
- Line-of-sight, multi-frequency radiative transfer to model QSO emission.

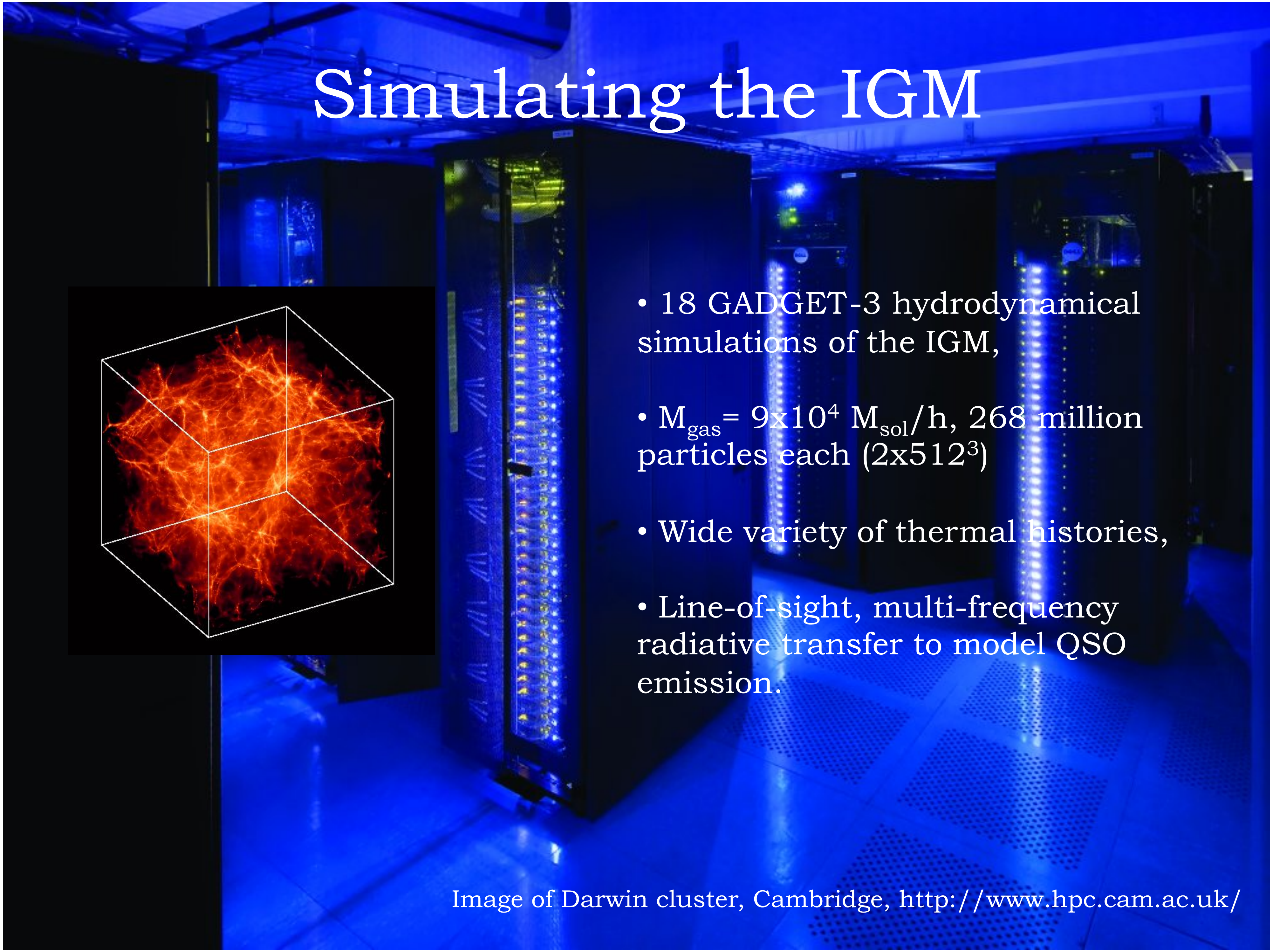
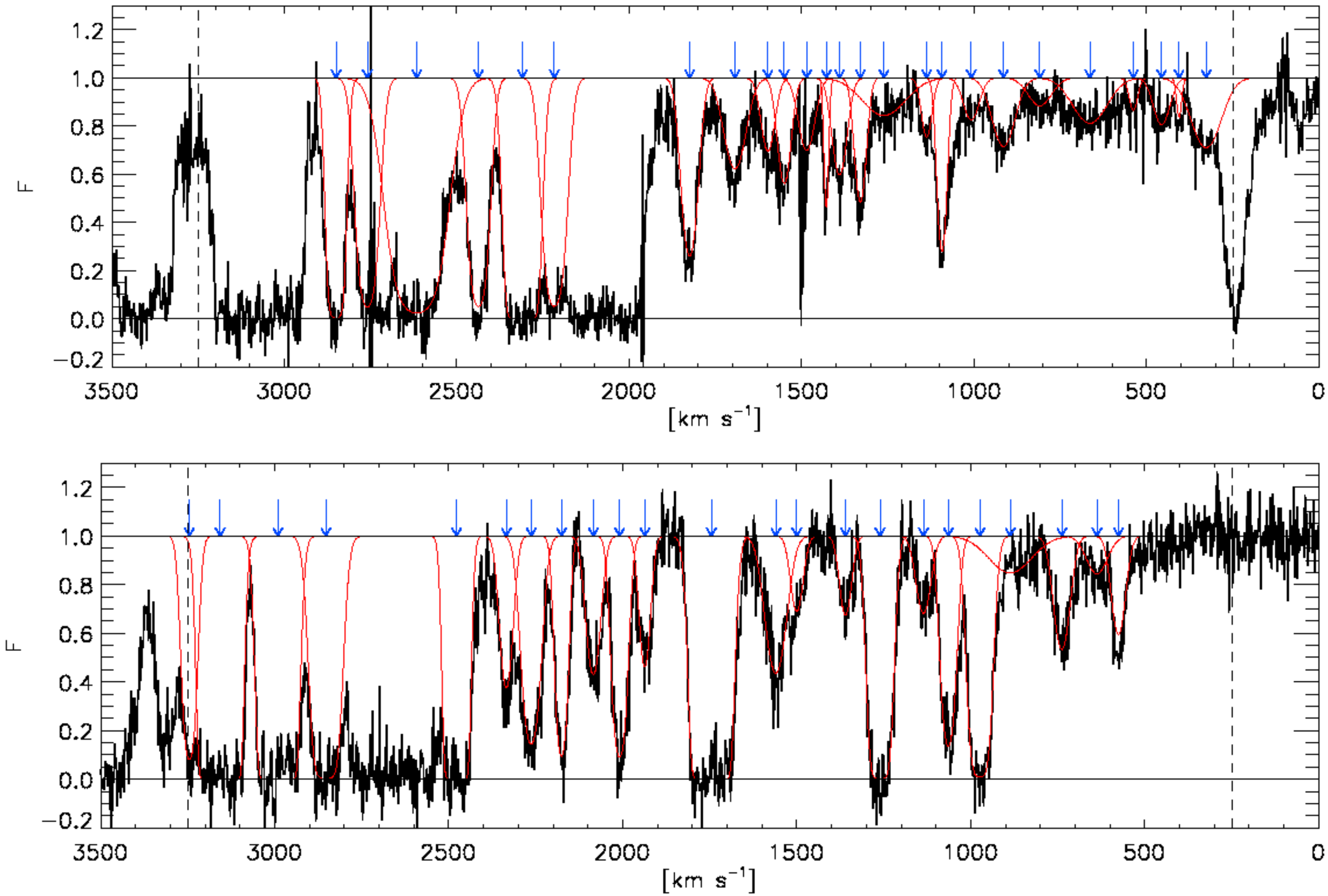


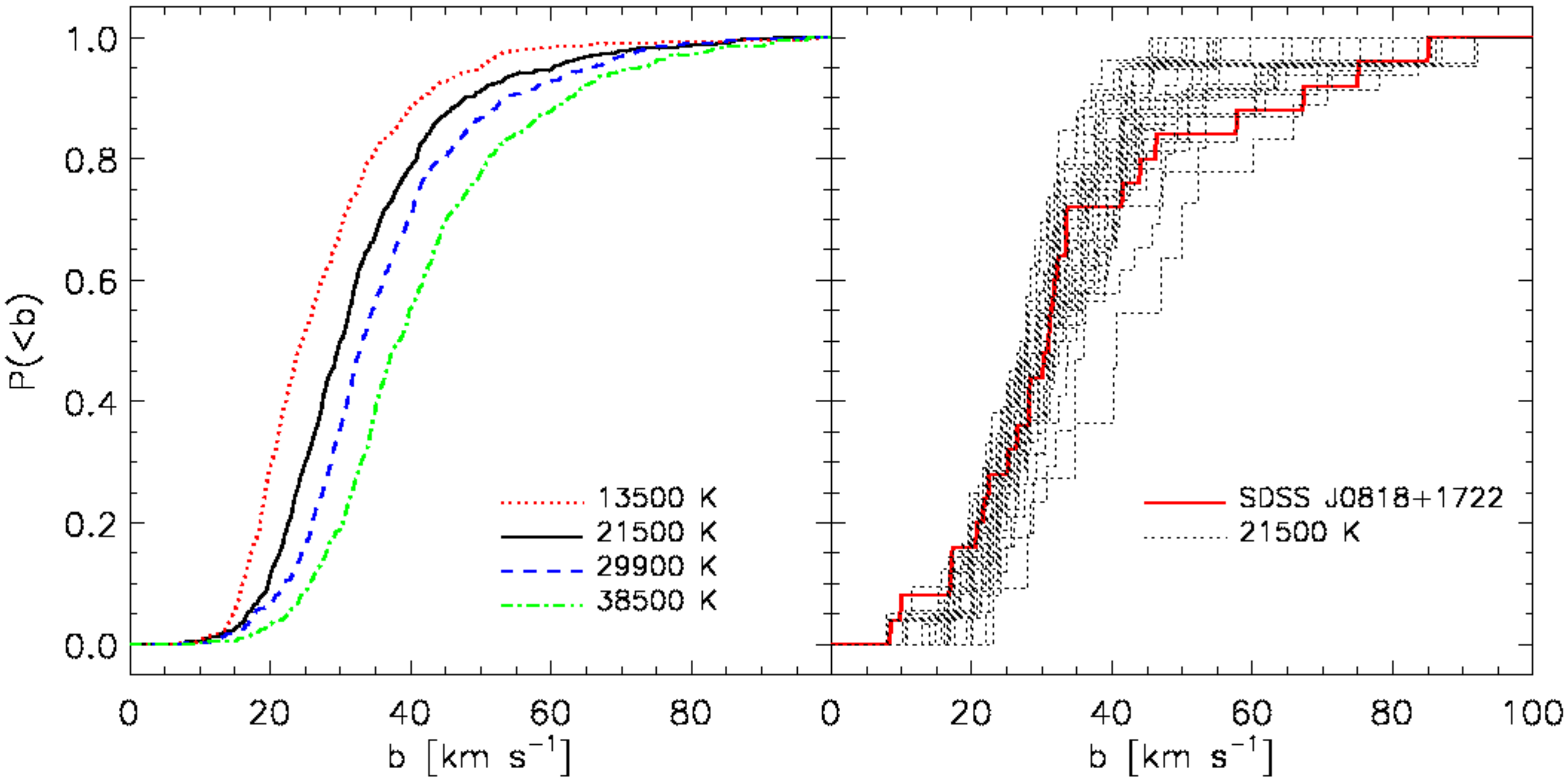
Image of Darwin cluster, Cambridge, http://www.hpc.cam.ac.uk/

Simulation vs Observation



Measuring the temperature

• Simulated Doppler parameter CPDF is sensitive to the temperature in the proximity zone



• Use detailed numerical simulations (mutiple hydro+RT sight-lines) to calibrate the CPDF and obtain constraints from data.

Bolton *et al.* (2010)

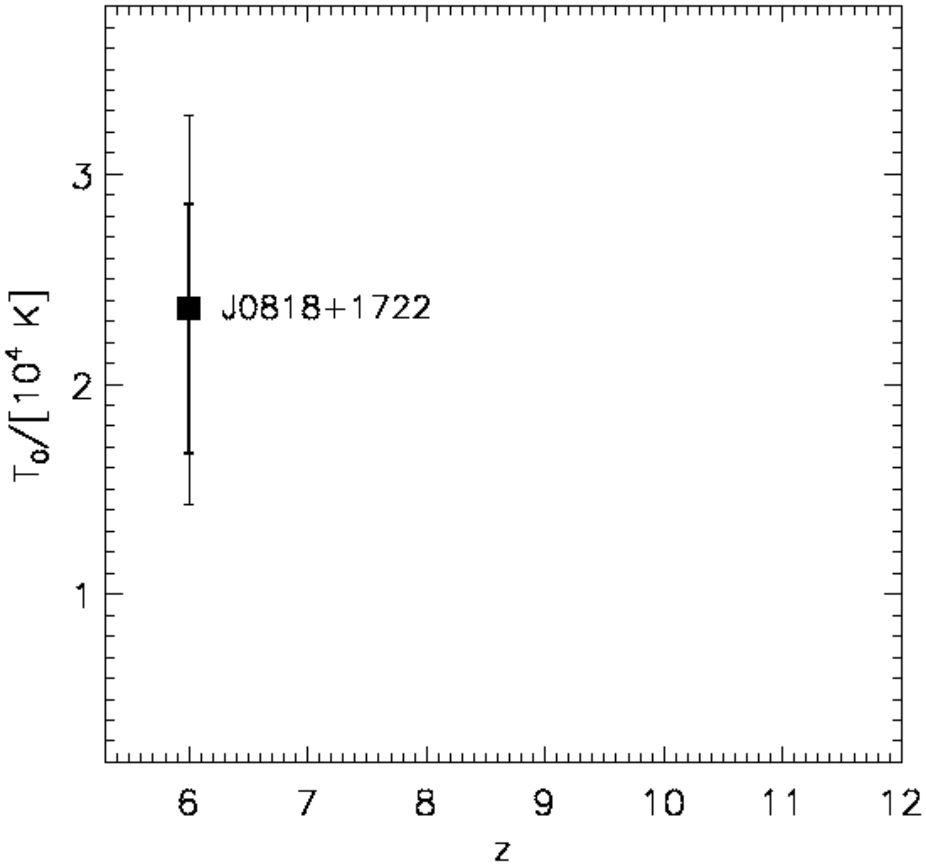
Constraint from J0818+1712

Temperature at mean density within 33 comoving Mpc
of SDSS J0818+1712 at z=6

$$T_0 = 23600 \pm^{5000}_{6900} K \, (\pm^{9200}_{9300} K)$$

at 68 % (95 %)

Thermal history at z>6



Bolton *et al.* (2010)

The temperature of the low density IGM provides an indirect probe of the reionisation history.

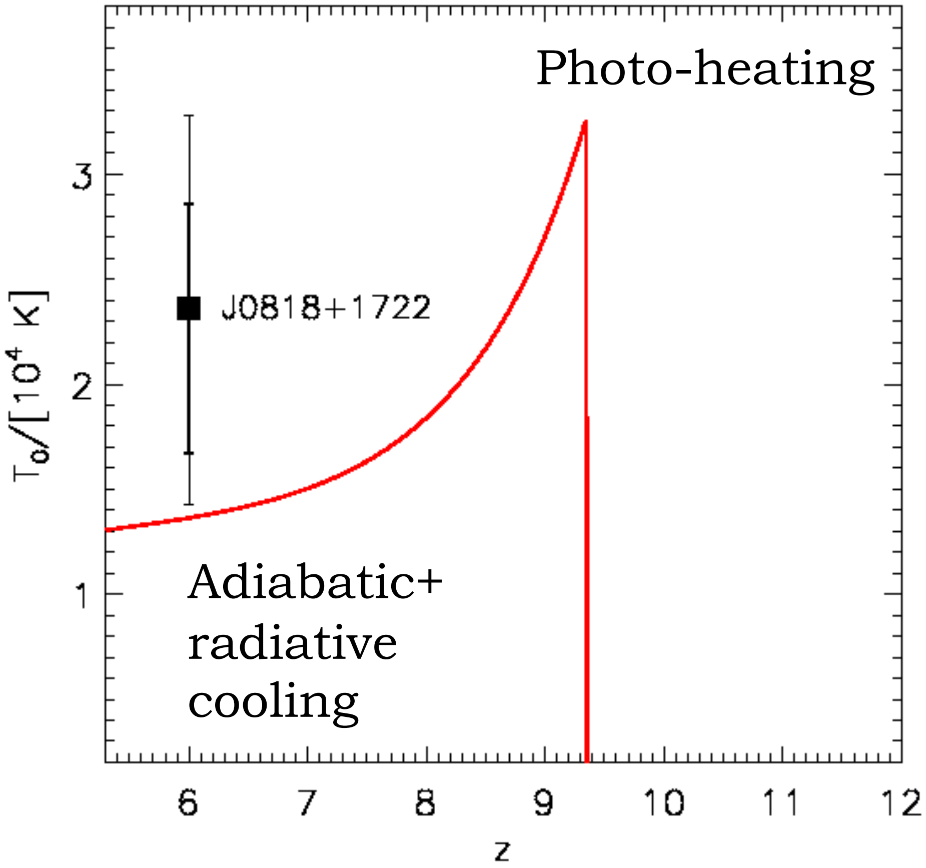
It retains a memory of the initial photo-heating during reionisation due to the long adiabatic cooling timescale (Theuns+02, Hui & Haiman 2003).

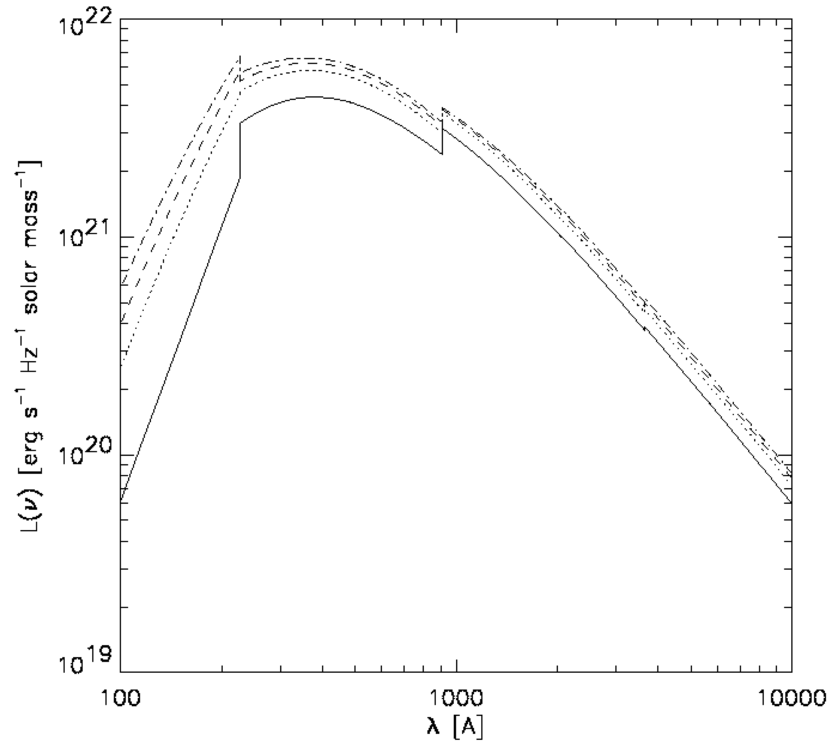
The temperature of the IGM thus depends on:

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

2) The spectra of the ionising sources responsible for reionisation (harder spectra = more heating).

Thermal history at z>6



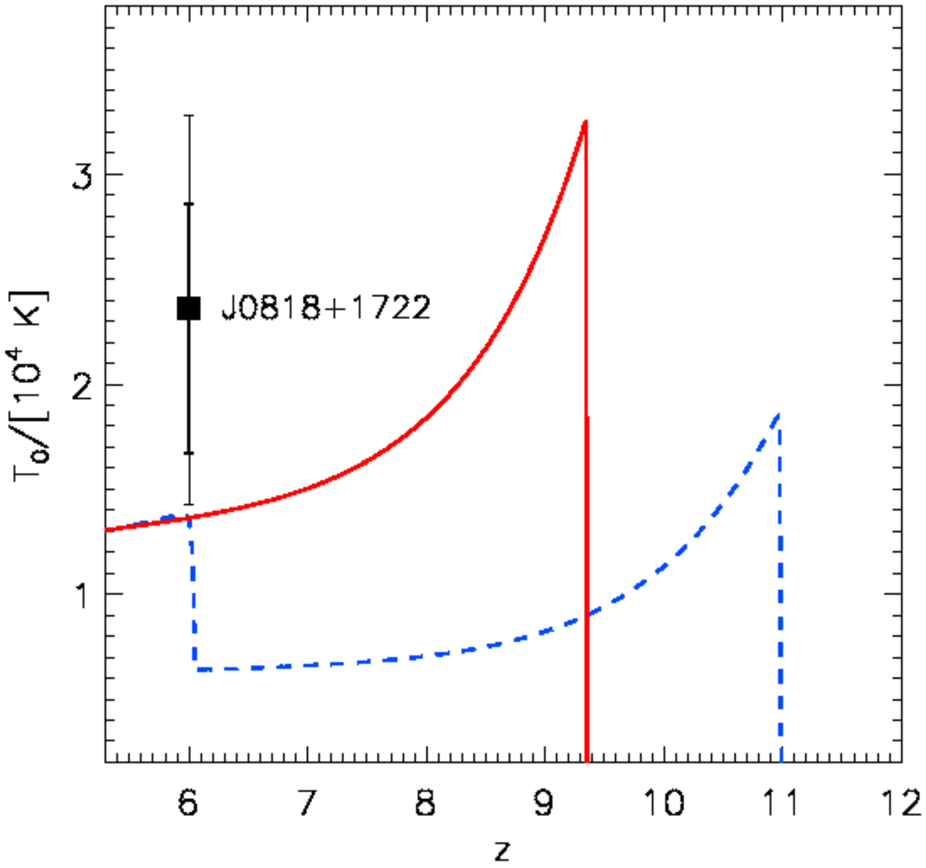


Spectrum 1: Pop. III (Bromm et al. 2001).

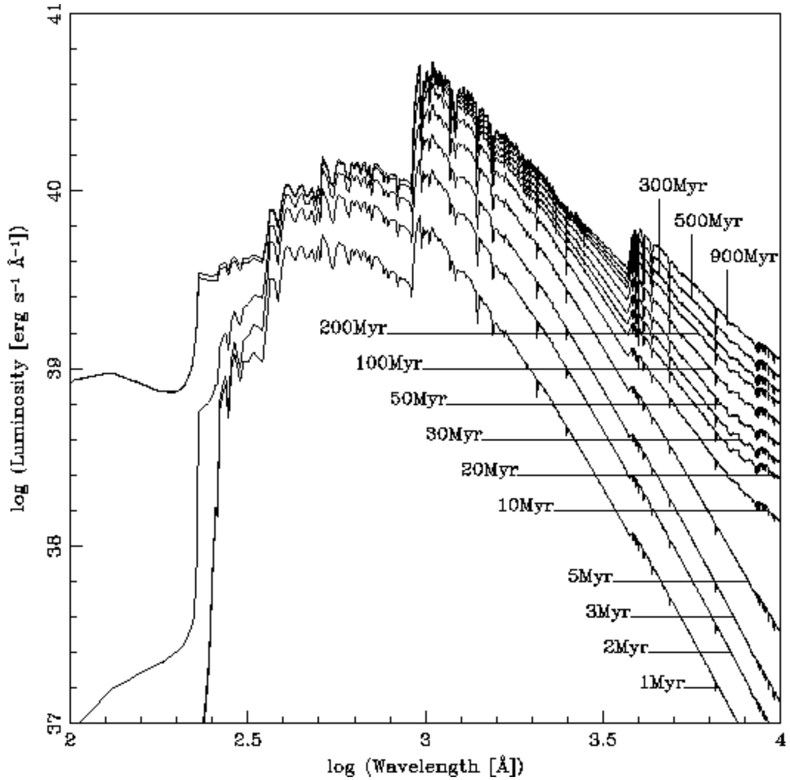
Bolton *et al.* (2010)

Very hard spectrum, reionises HI and HeII simultaneously

Thermal history at z>6



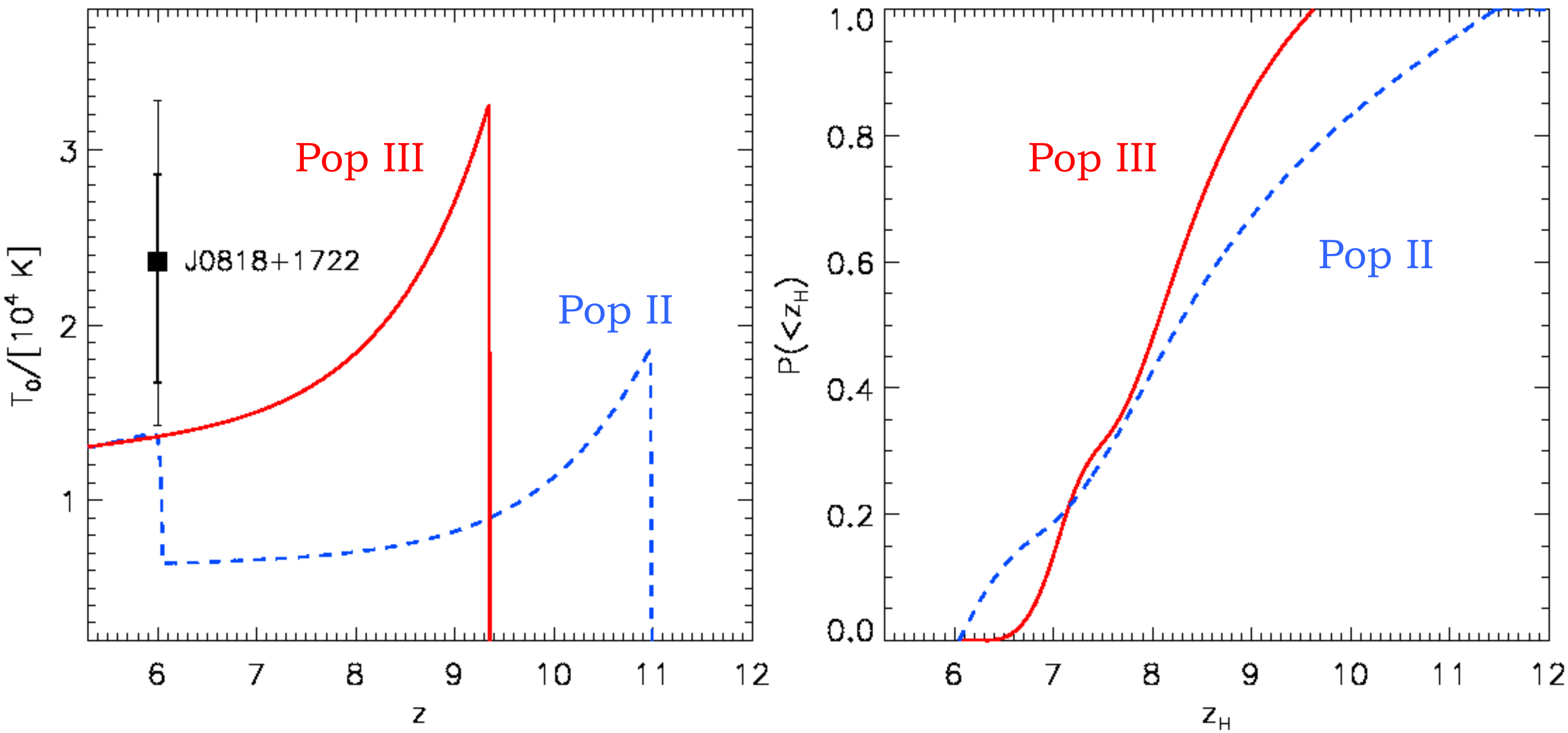
Bolton *et al.* (2010)



Spectrum 2: Pop. II (Leitherer *et al.* 1999)

Softer spectrum, reionises HI, HeII by the quasar itself.

Reionisation around J0818+1722



$$PopIII: \quad z_H < 8.4\,(<9.4) \quad 68\%\,(95\%)$$

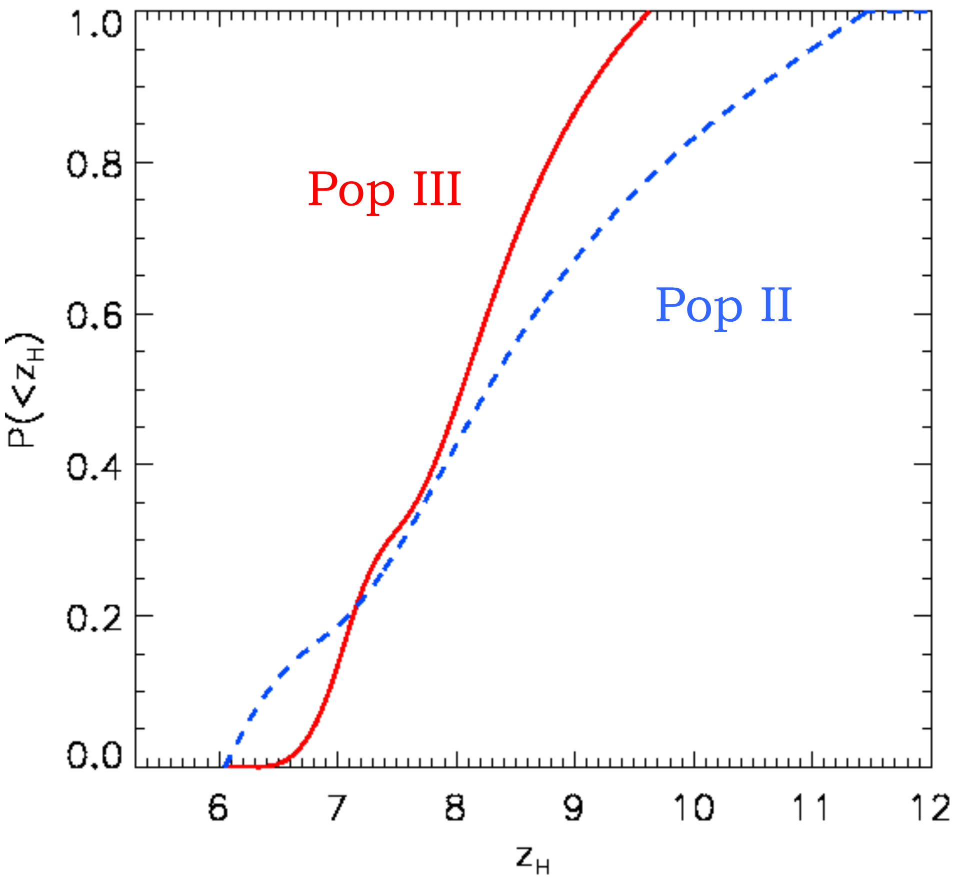
$$PopII: \quad z_H < 9.0\,(<11.0) \quad 68\%\,(95\%)$$

Caveats

• Source modelling uncertain: higher temperatures will weaken the upper limits.

• Assumes instantaneous, homogeneous reionisation. This is incorrect globally, but more reasonable (but not ideal) for a single quasar proximity zone.

• *Applies to reionisation around J0818+1722 only.* But the biased regions around quasars could be amongst the first patches of the IGM to be ionised.



Bolton *et al.* (2010)

Summary I

The Lyman-α forest provides an invaluable probe of the ionisation history of the IGM, beyond just the well known GP trough constraint.

- The metagalactic ionising emissivity at z=6 corresponds to ~1-3 ionising photons emitted per hydrogen atom over a time interval corresponding to the age of the Universe at z=6. The IGM at z=6 is photon-starved.

- The ionising emissivity must rise at z>6 for consistency with the observed Lyman-α forest opacity at z<6. Unless the emissivity rises (unusually) rapidly just above z=6, reionisation is likely to have been an extended process.

- The emissivity requirements imply significant star formation activity (many faint, as yet undetected galaxies) at z>6.

Summary II

- The clumping factor of baryons in the ionised IGM is $C_{HII}<5$. This is expected from the observed Lyα forest opacity as well as theoretical grounds;

- The thermal history of the IGM provides a valuable, indirect probe of the HI and HeII reionisation history of the IGM. We present the first direct IGM temperature measurements around a quasar at z=6;

- The data enables us to place constraints on the redshift of hydrogen reionisation ***around J0818+1722*** under the assumption of two different source spectra. We find $z_H<9.4$ for population III and $z_H<11.0$ for population II sources in the limit of instantaneous, homogeneous reionisation;

- These results are consistent with an epoch of HI reionisation extending from well above z=6.