Cosmological Structures from Reionisation to Galaxies, 12.05.15

Modelling the thermal state of the intergalactic medium

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with thanks to
Bradley Greig (SNS Pisa), Sudhir Raskutti (Princeton)

The University of Nottingham
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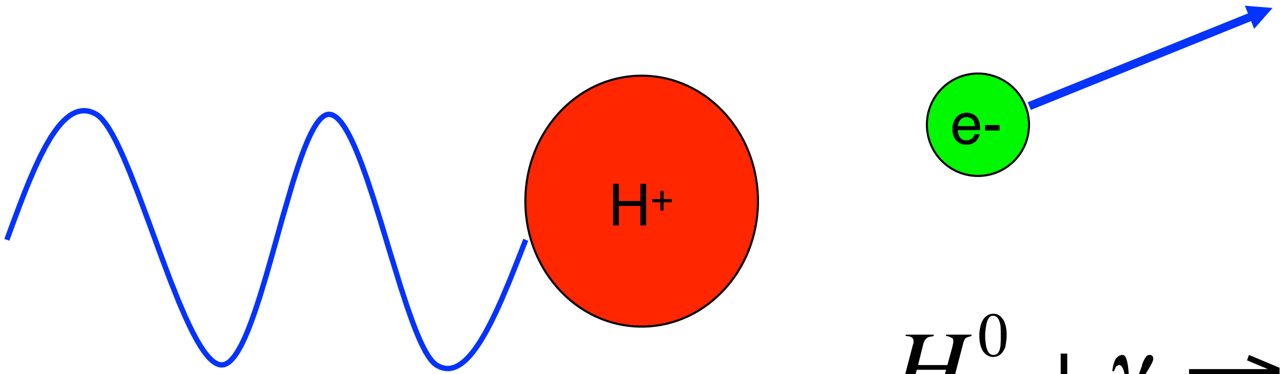
Motivation

- IGM contains majority of baryons in the Universe during reionisation and “galaxy formation” era;
- (Post-reionisation) thermal state of IGM is indirect probe of the timing of reionisation and properties of first sources;
- Important nuisance parameter when extracting cosmological parameters from the Ly-α forest.

Photo-ionisation heating

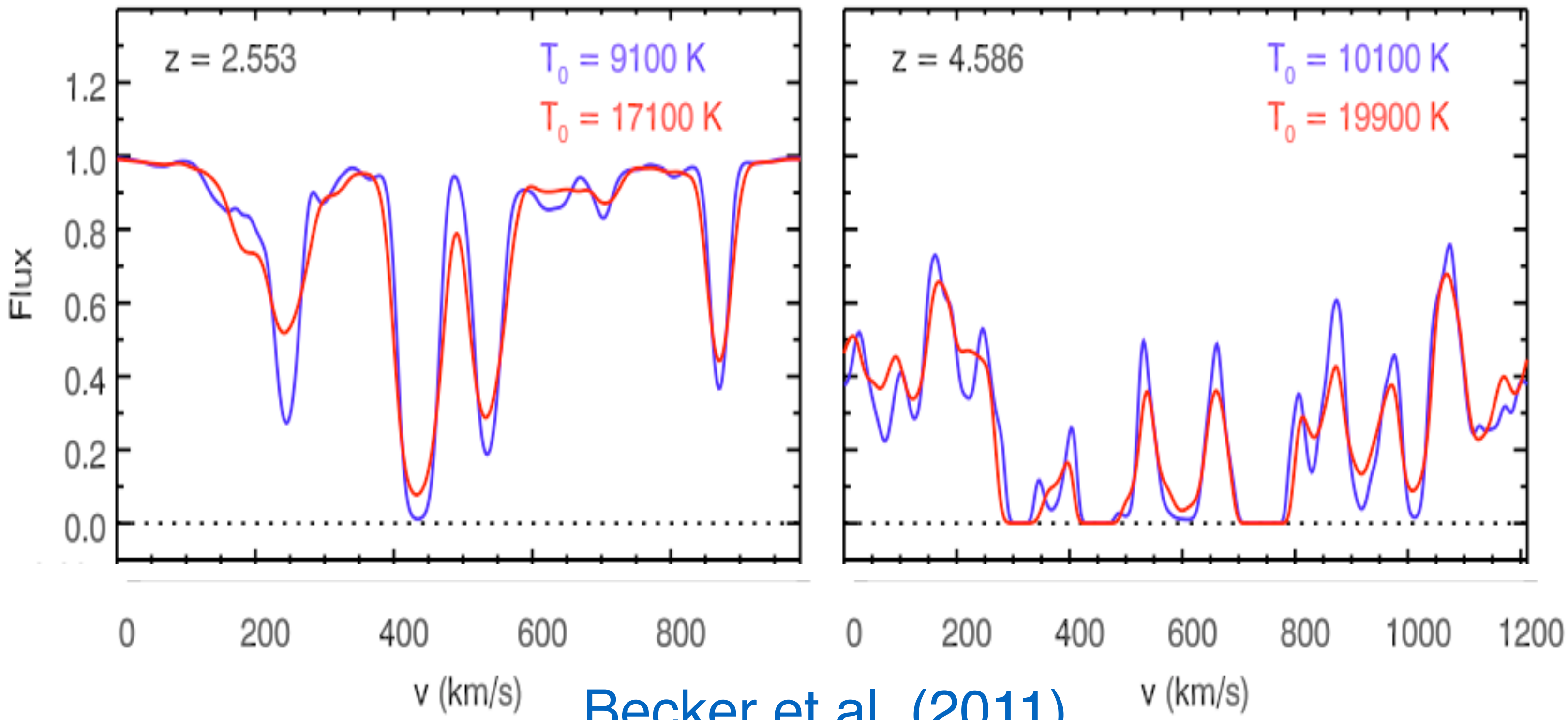


E > 13.6 eV photon

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

Ejected photo-electrons share their energy with neutrals via scattering and raise the temperature of the residual H-I.

The Ly-α forest as a thermometer



Becker et al. (2011)

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

Photo-ionisation heating

Low density (Δ<10), highly ionised IGM in photo-ionisation equilibrium

$$\frac{dT}{dt} = \frac{2}{3k_\mathrm{B}}\langle E\rangle\alpha(T)n - 2HT$$

Miralda-Escudé & Rees (1994)

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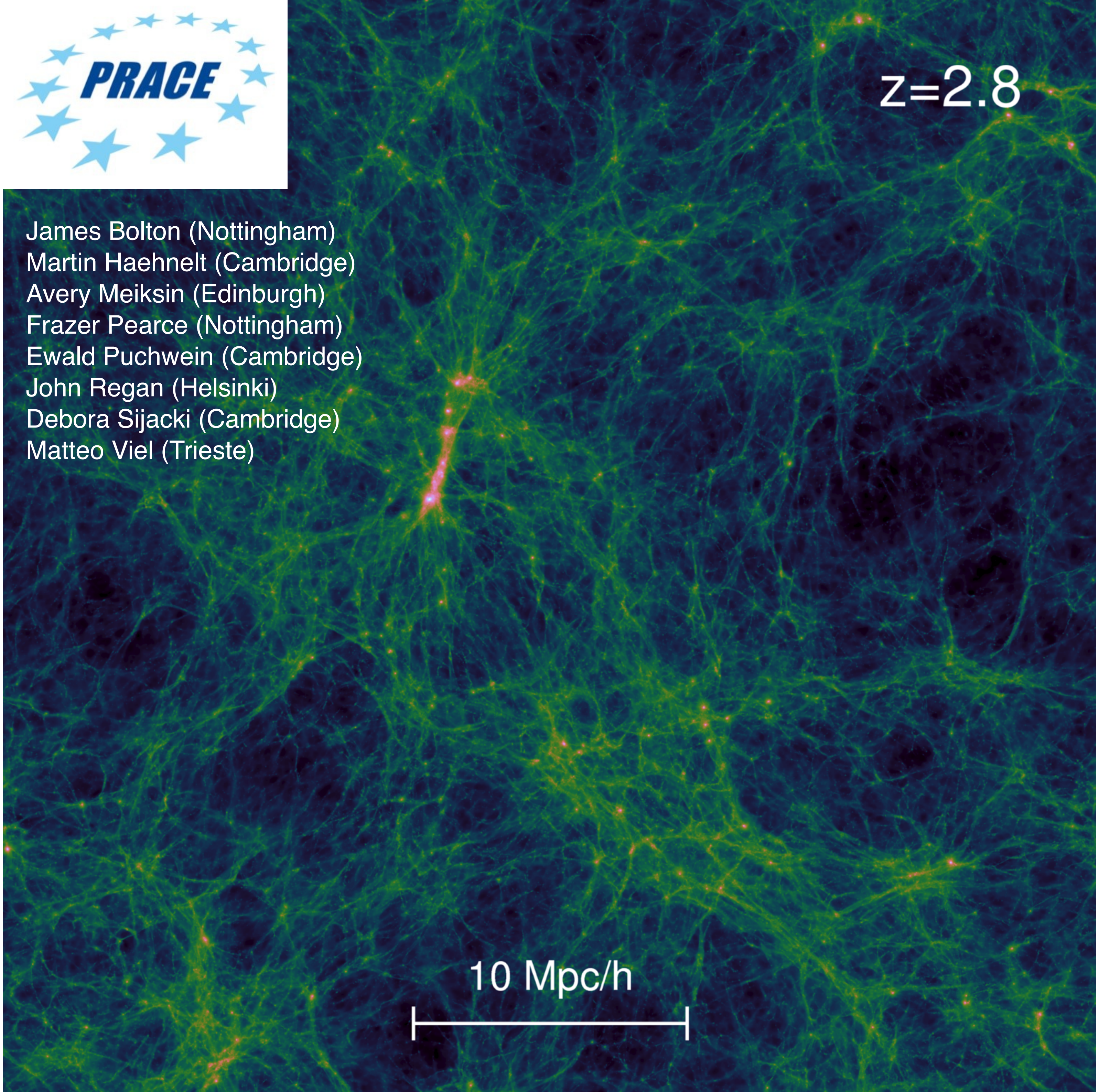
Miralda-Escudé & Rees (1994)

Optically thin IGM, power-law spectrum for UV background: $J_\nu \propto \nu^{-\beta}$

$$\langle E\rangle = \frac{h\nu_i}{\beta + 2}$$

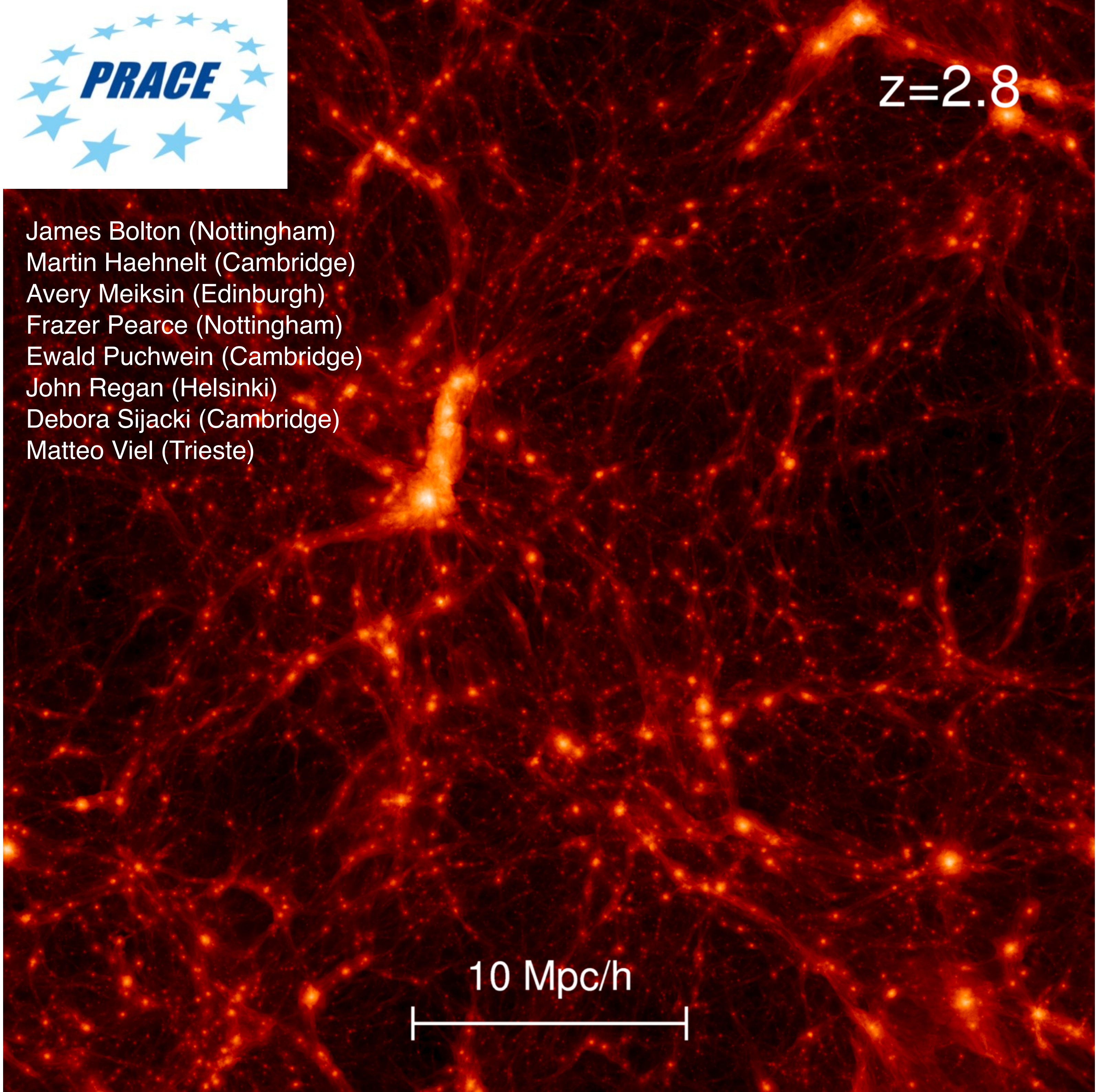
Abel & Haehnelt (1999)



- Hydrodynamical IGM simulations with P-Gadget-3;
- 15 million hours on Curie through PRACE;
- 40-160 Mpc/h boxes, 2×2048^3 particles;
- Planck-1 cosmology;
- Designed for studying the IGM approaching reionisation.

PRACE

James Bolton (Nottingham)
Martin Haehnelt (Cambridge)
Avery Meiksin (Edinburgh)
Frazer Pearce (Nottingham)
Ewald Puchwein (Cambridge)
John Regan (Helsinki)
Debora Sijacki (Cambridge)
Matteo Viel (Trieste)



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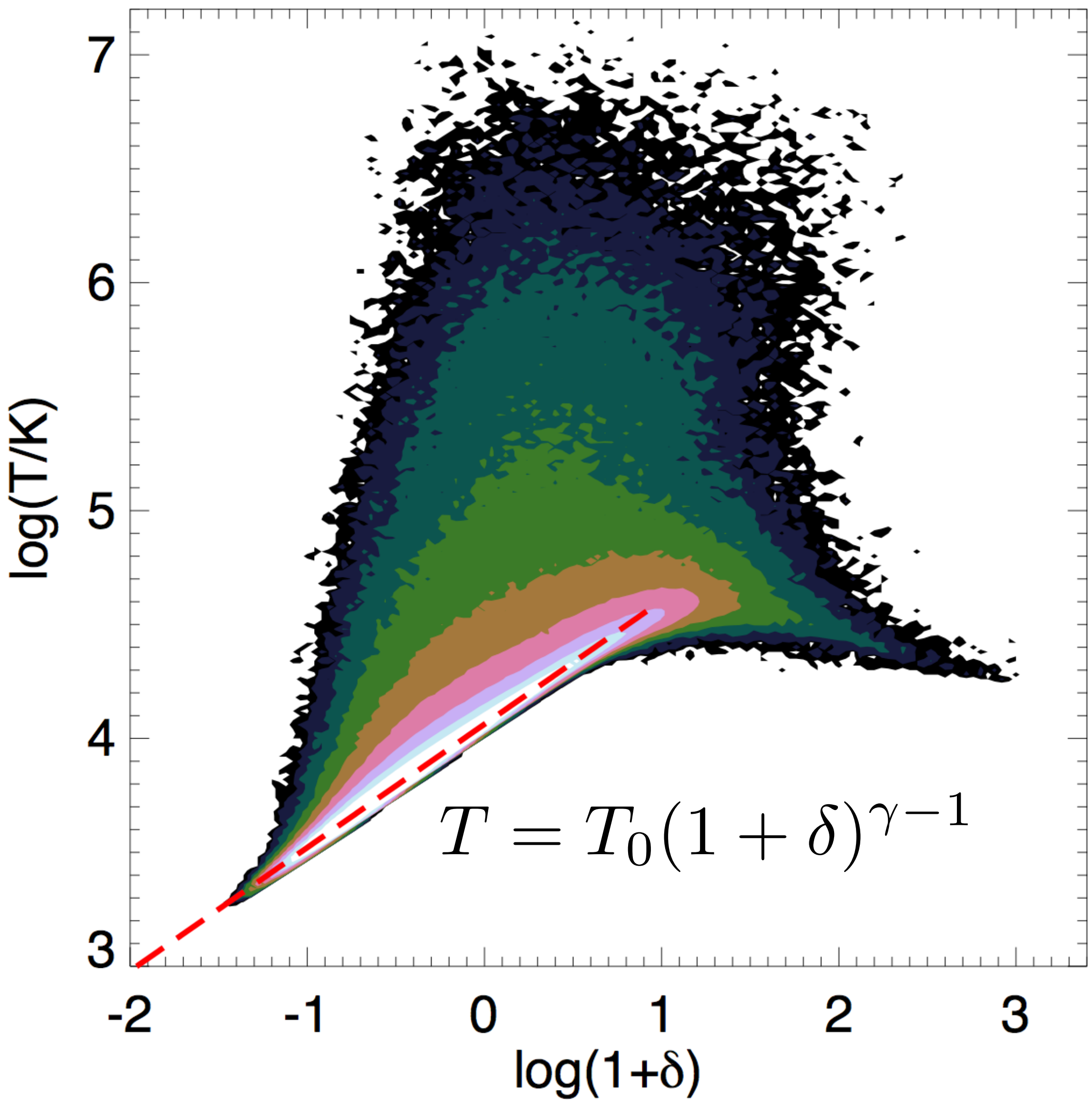
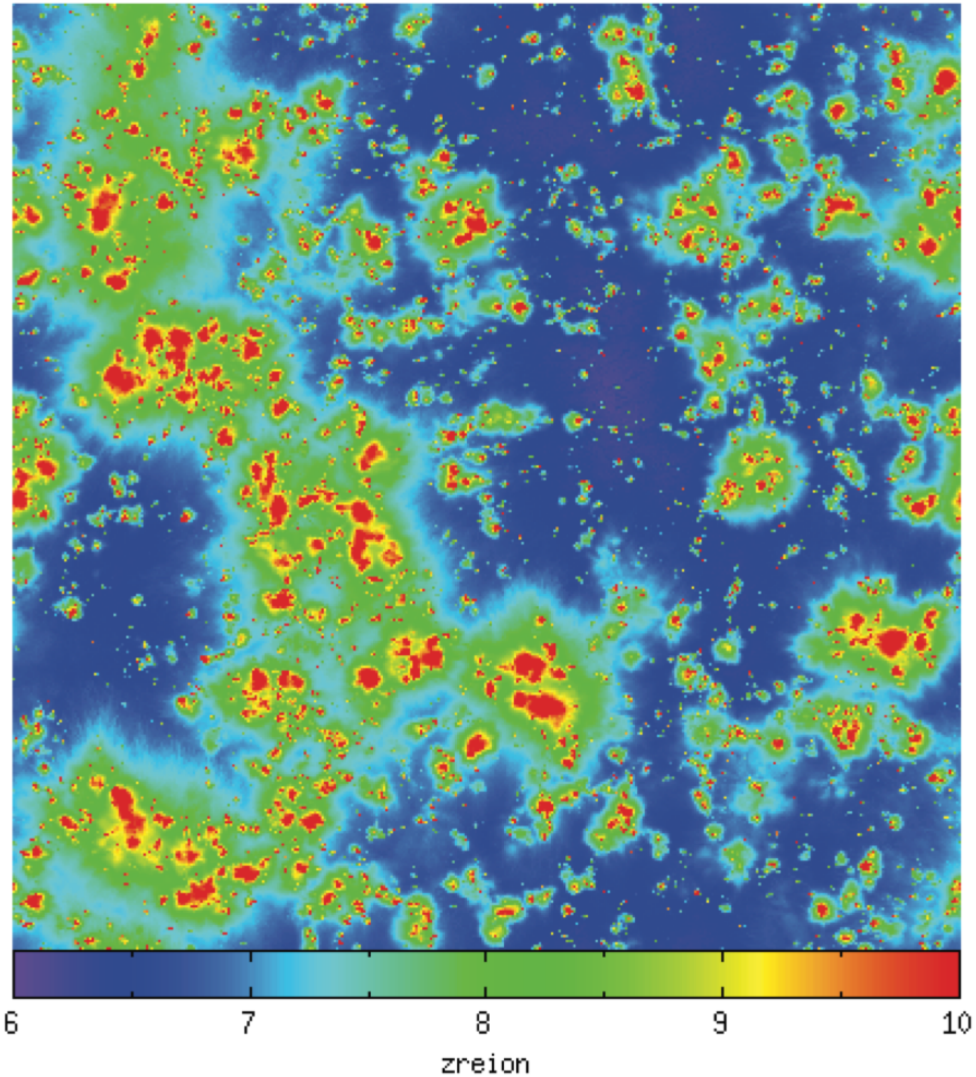
The temperature-density relation



Optically thin IGM, power-law relationship between temperature and density, γ~1.0-1.6

e.g. Hui & Gnedin (1997)

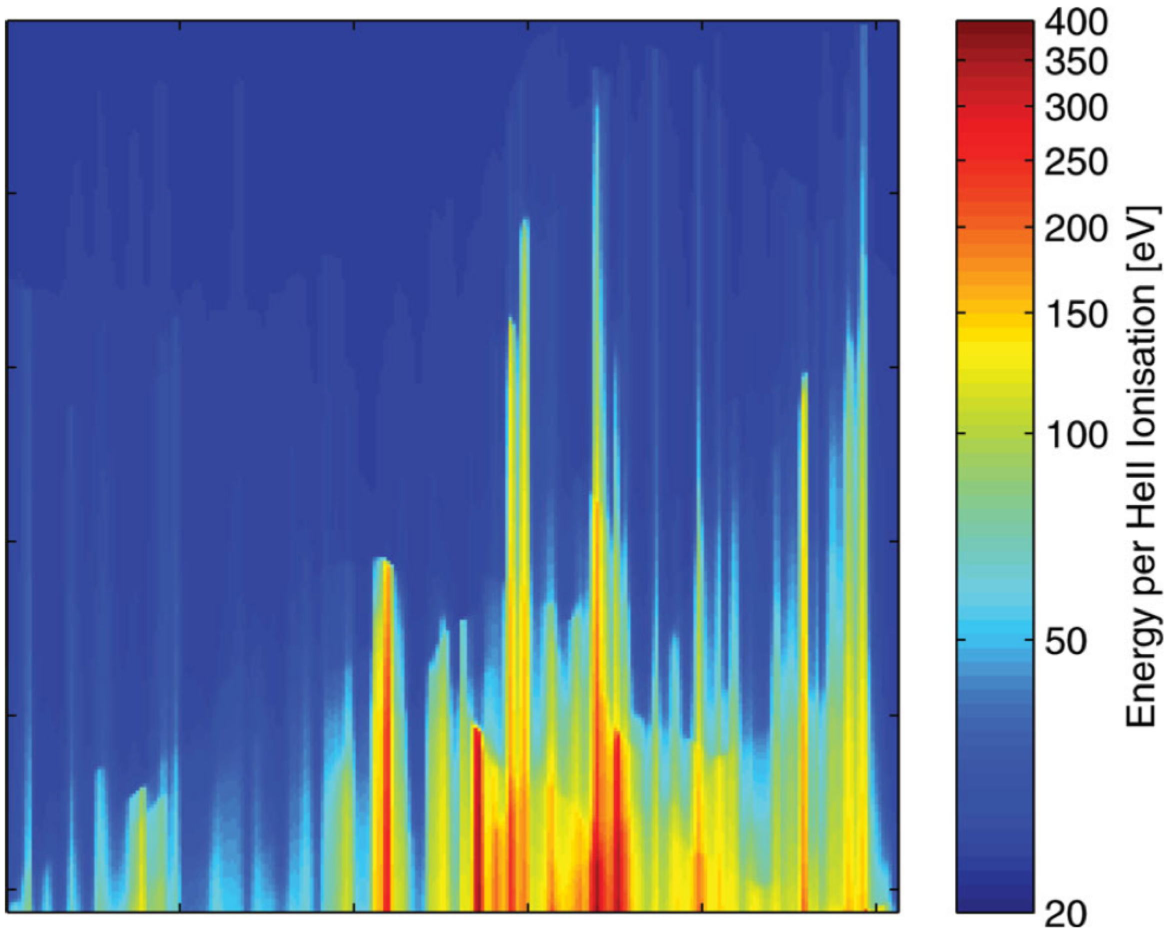
Additional effects during reionisation



Trac, Cen & Loeb (2008)

1) Patchy ionisation and heating: regions far from sources are heated last, have less time to cool.

Additional effects during reionisation

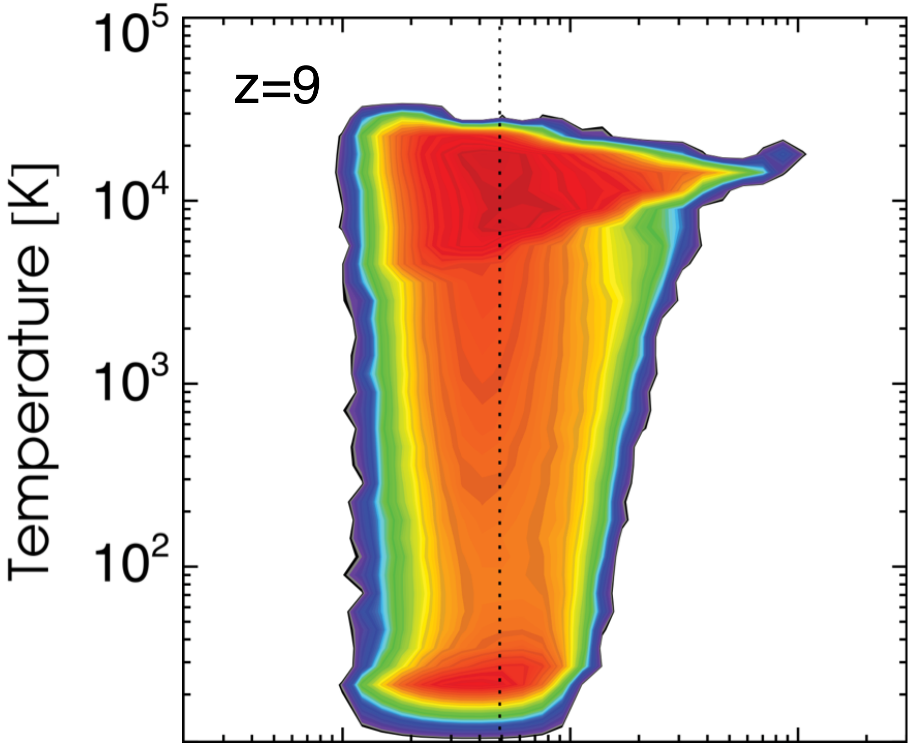


2) Spectral filtering: hard photons have longer mfp, average <E> larger ahead of ionisation front.

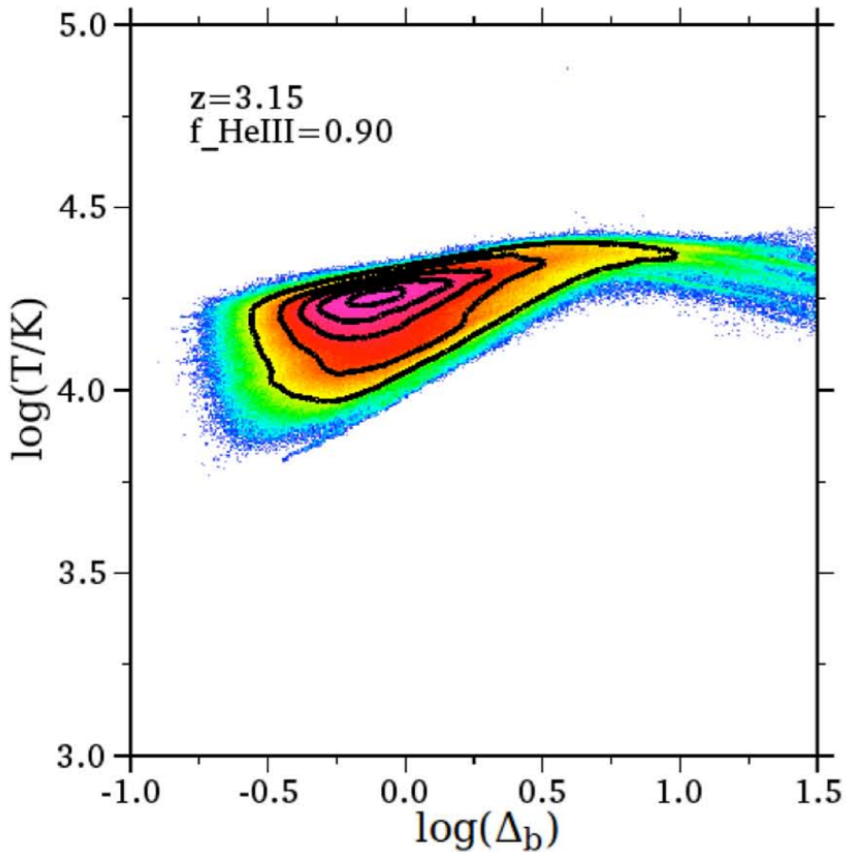
Meiksin & Tittley (2012)
see also Abel & Haehnelt (1999)

The temperature-density relation

Inhomogeneous heating and spectral filtering will induce scatter in the temperature-density relation (H-I *and* He-II reionisation)

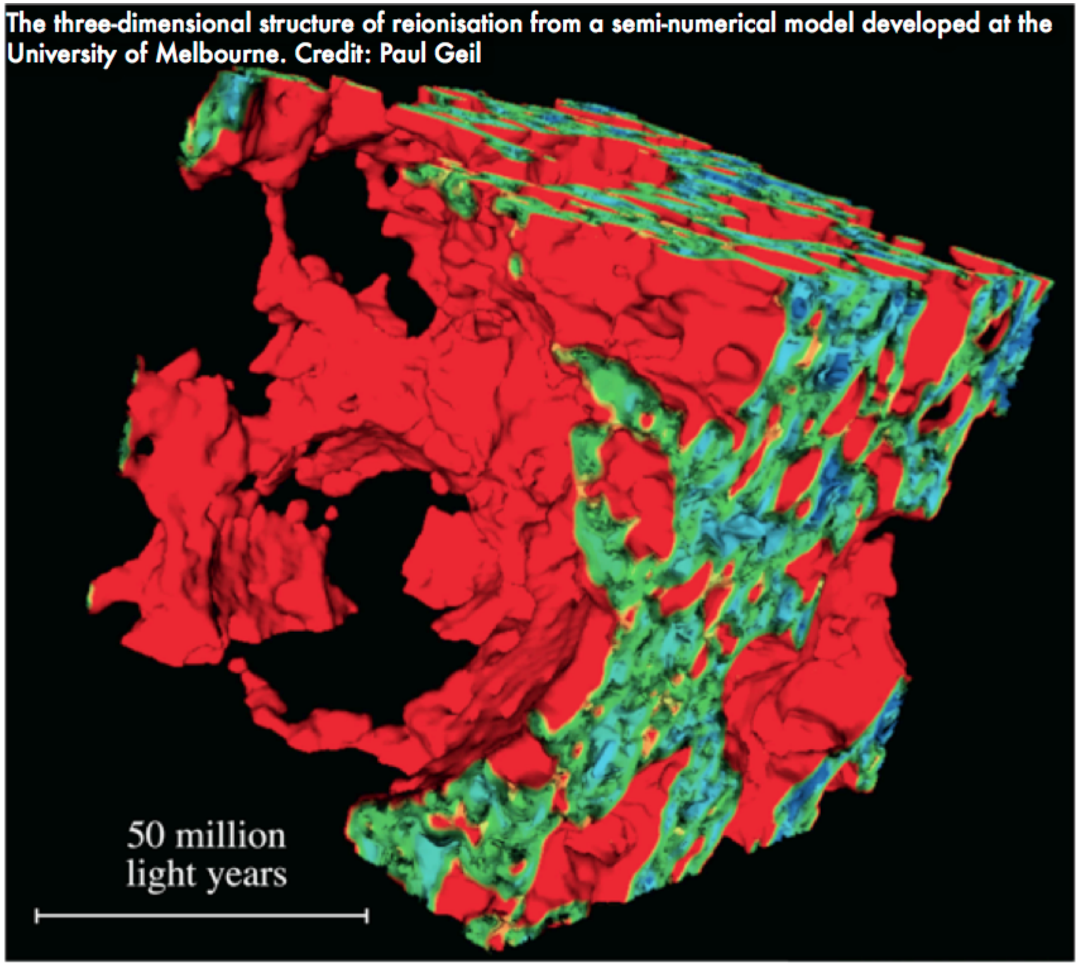


Ciardi et al. (2012)



Compostella et al. (2013)

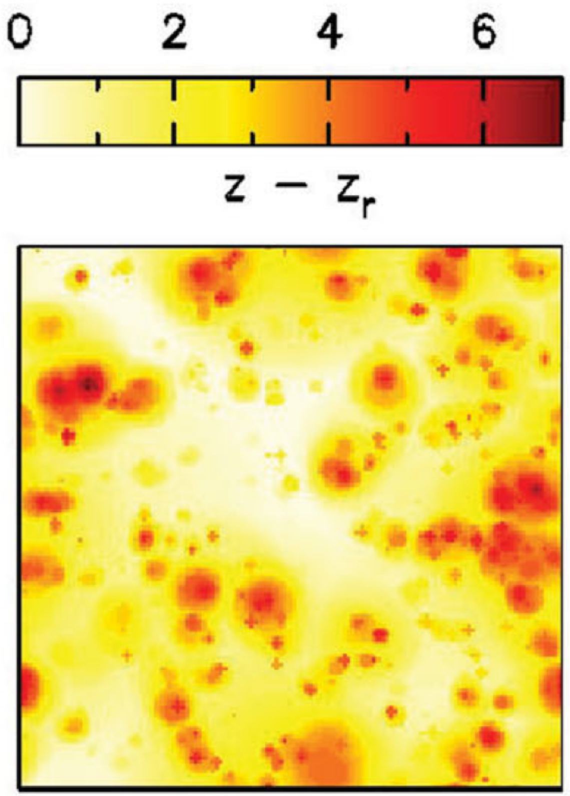
“Semi numerical” approach

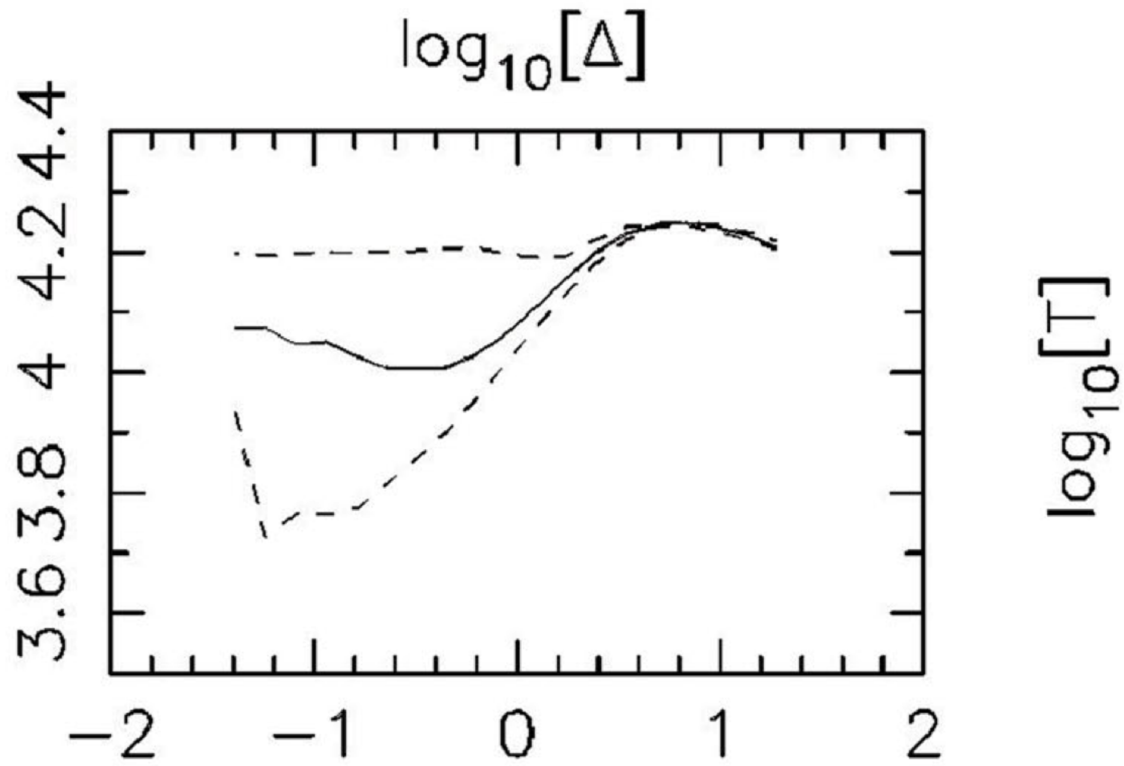


Geil & Wyithe (2007)

- Patchy reionisation on large scales L~100 Mpc/h, $f_{coll}(R)>\xi^{-1}$;
- Calibrate emissivity in ionised regions to match CMB and Ly-α forest data;
- Ionisation and heating from emissivity & mean free path.

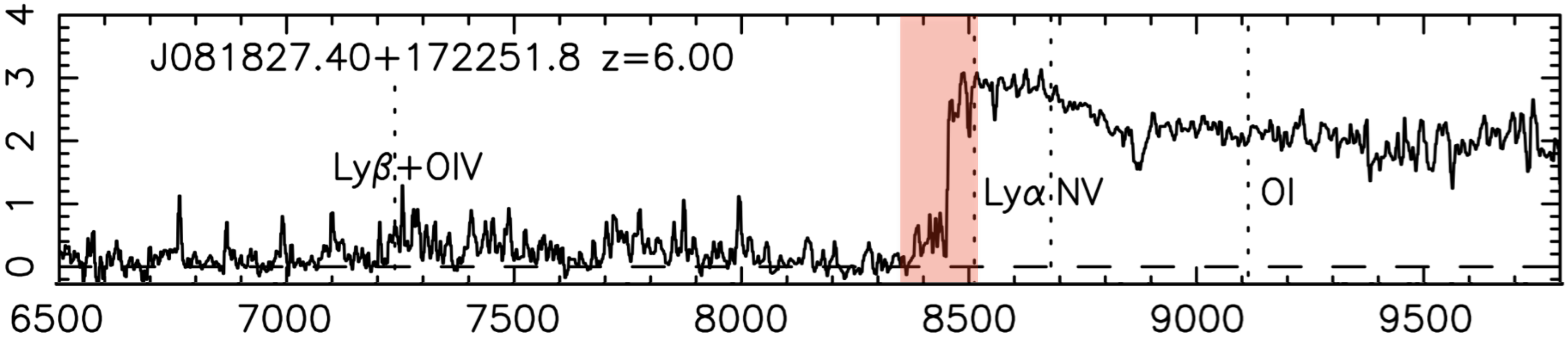
“Semi numerical” approach





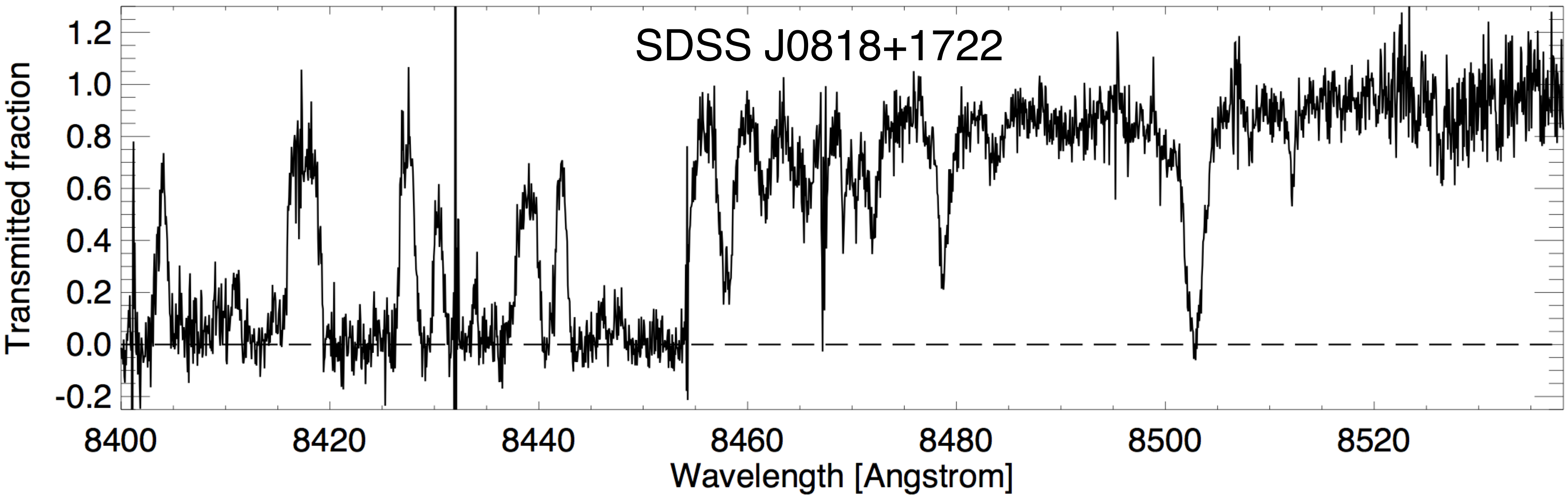
Raskutti et al. (2012)
see also Lidz & Malloy (2014)

Application: IGM temperature at z~6



Keck/ESI, shown at R~1800

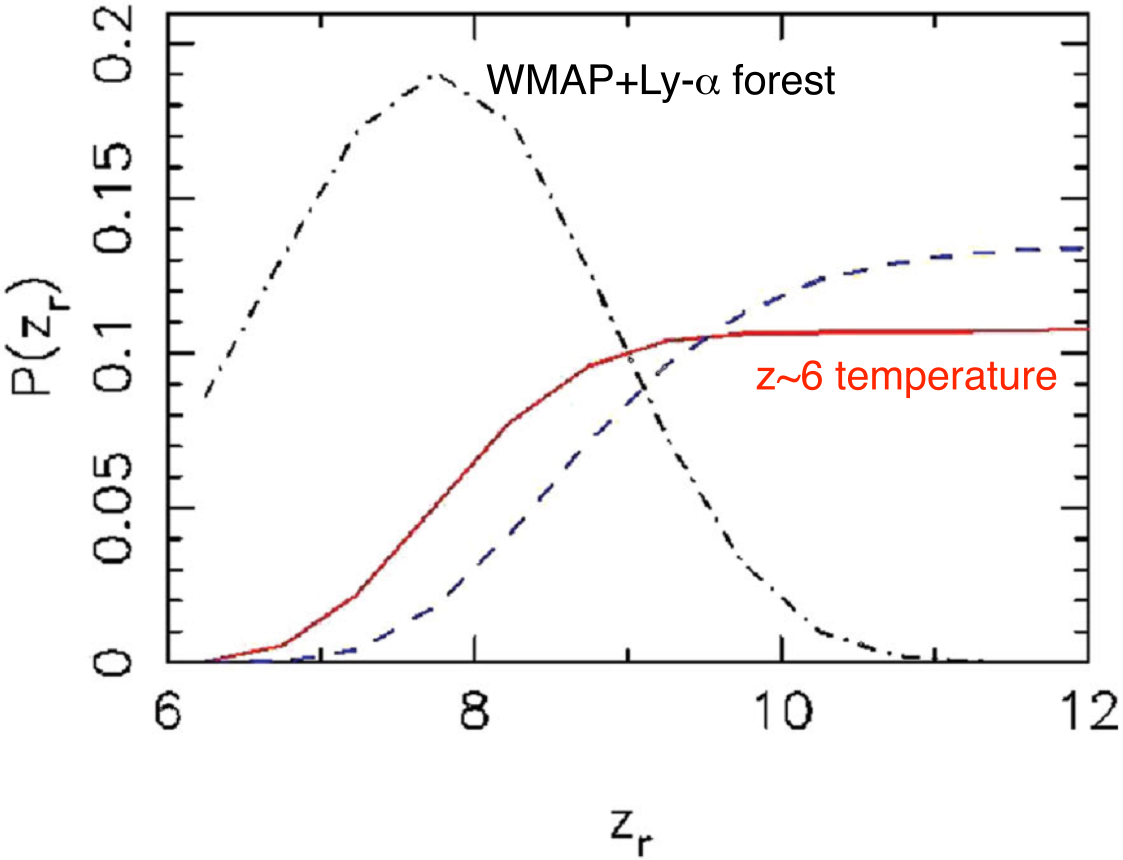
Fan et al. (2006)



Keck/HIRES, R~40,000

Becker et al. (2007)

Application: IGM temperature at z~6

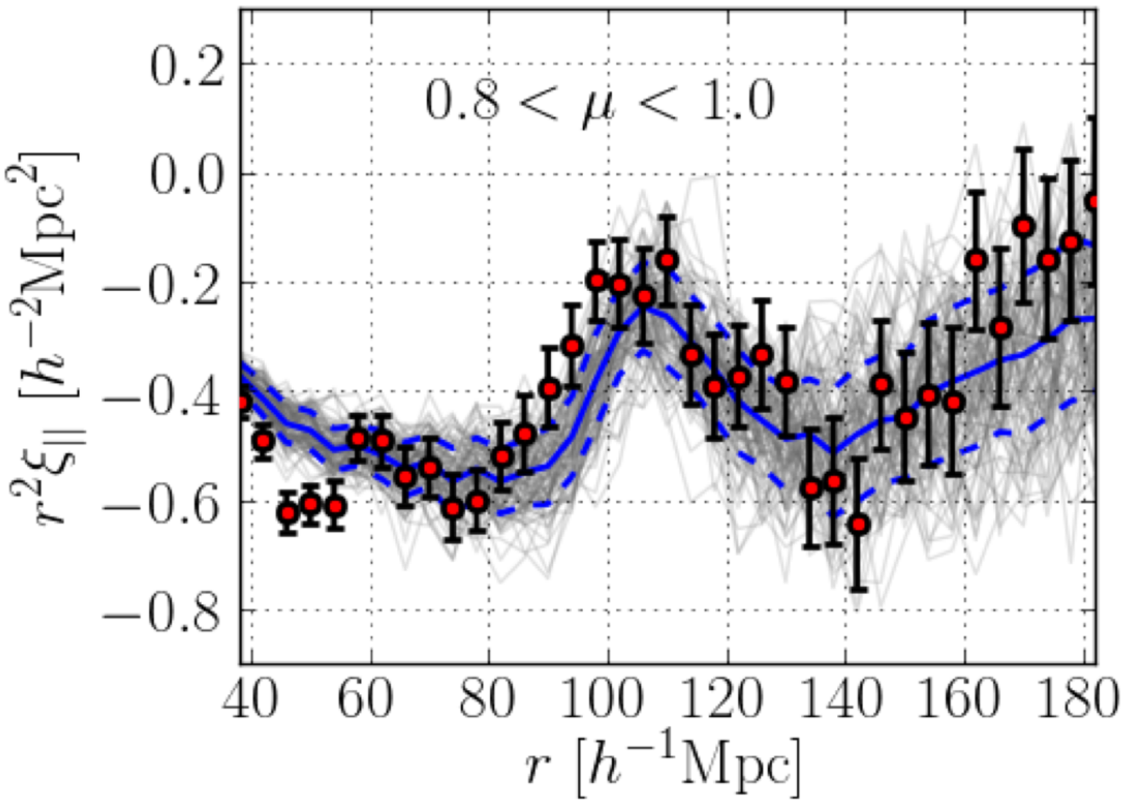


Raskutti et al. (2012)

- Temperature data inconsistent with very late end to reionisation, z<6.5;
- Limited constraining power at higher redshift due to thermal asymptote;
- Model dependent: harder sources favour earlier end to reionisation.

see also Miralda-Escudé & Rees (1994), Theuns et al. (2002), Hui & Haiman (2003)

Application: 3D Lyα−F clustering



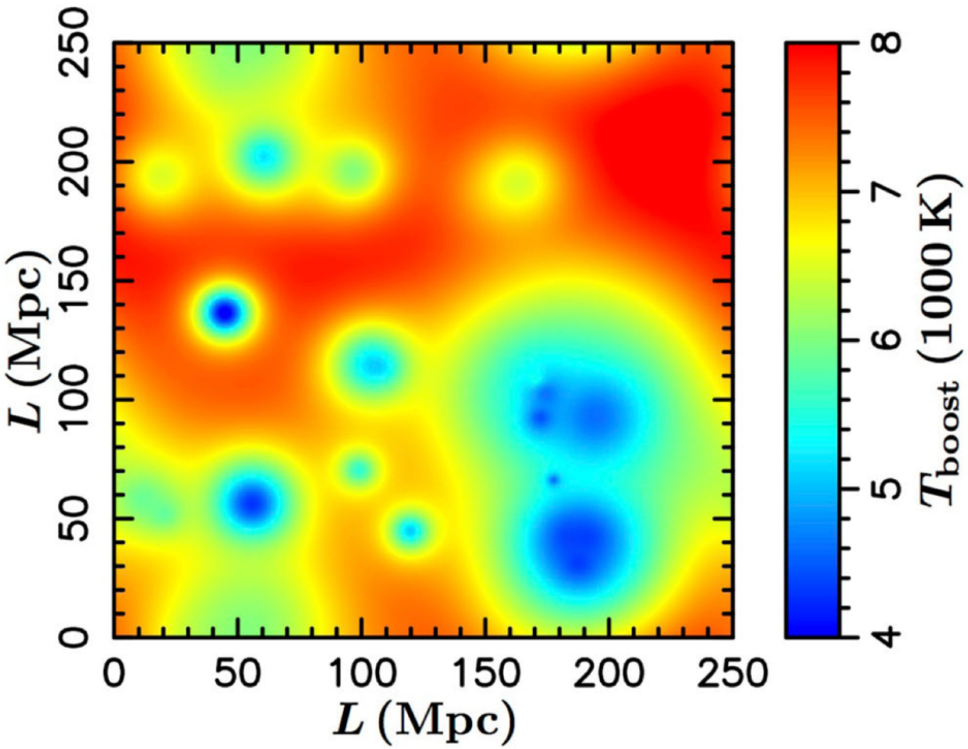
Debulac et al. (2015)

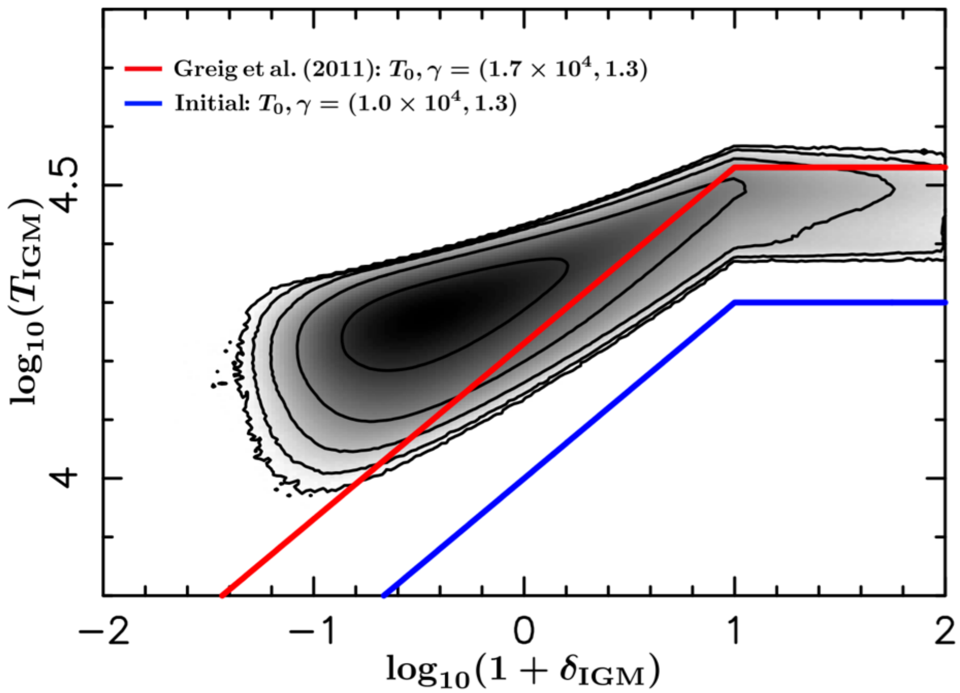
- Measurement of BAO scale from 3D Lya forest clustering with BOSS;
- Broadband term which accounts for non-BAO cosmology and systematics.

$$\xi(r_{||}, r_{\perp}, \alpha_{||}, \alpha_{\perp}) = \xi_{\mathrm{cosmo}}(r_{||}, r_{\perp}, \alpha_{||}, \alpha_{\perp}) + \xi_{\mathrm{bb}}(r_{||}, r_{\perp}).$$

Application: 3D Lyα–F clustering

He-II reionisation by quasars will induce large scale (>30 cMpc) spatial fluctuations in the IGM temperature.

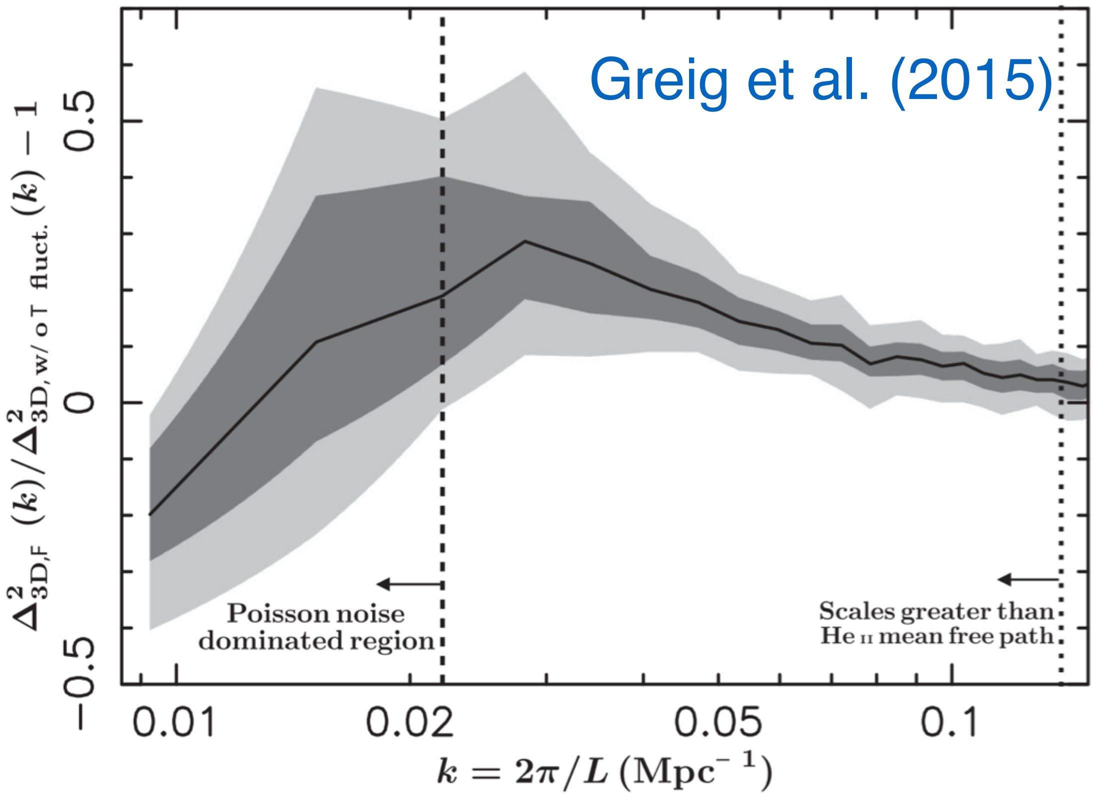




Greig et al. (2015)

Application: 3D Lyα–F clustering

BOSS-like 3D P(k), S/N=5, 15 deg^{-2}



Temperature fluctuations impact on 3D Ly-α forest power spectrum; relevant for forward modelling of broadband term

see also McQuinn+11, Pontzen+14, Gontcho+14

Summary

- Fast, approximate approaches to modelling IGM thermal state, useful for exploring parameter space/dealing with large dynamic range;

- Temperatures around quasars at z~6 disfavour a very late end to reionisation at z<6.5;

- Spatial fluctuations in gas temperature during He-II reionisation impact on broadband power in 3D P(k) at k~0.02 Mpc^{-1}