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The Lyman-α forest and the IGM thermal state

Jamie Bolton

With thanks to:
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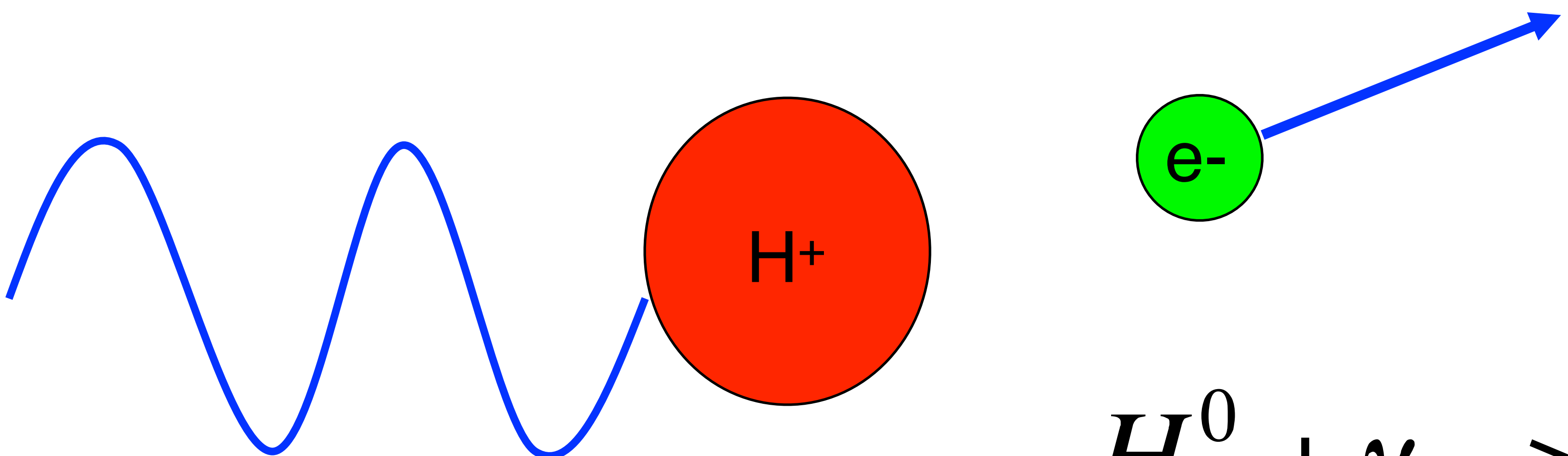
Talk overview

- Brief outline of the basic physics (mostly closed);
- Current measurements: agreements and apparent discrepancies (which issues are closed/open?);
- (Biased selection of) open issues.

Motivation

- Indirect probe of (H-I and He-II) reionisation timing;
- Sensitive to spectral shape of UVB (AGN vs stars as sources);
- Important “nuisance parameter” for dark matter coldness and/or cosmology constraints from forest.

Photo-ionisation heating by UVB



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

E > 13.6 eV photon

(E > 54.4 eV photon for $\mathrm{He}^+ + \gamma \rightarrow \mathrm{He}^{2+} + \mathrm{e}^-$)

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

Photo-ionisation heating by UVB

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)

Photo-ionisation heating by UVB

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

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

Miralda-Escudé & Rees (1994)

For a power-law spectrum for UV background: $J_\nu \propto \nu^{-\beta}$

$$\langle E\rangle = \frac{h\nu_i}{\beta+2}$$ (Optically thin limit)

Abel & Haehnelt (1999)

Photo-ionisation heating by UVB

Net temperature change is approximately

$$k_{\mathrm{B}}T = \frac{\langle E \rangle}{3}$$

Miralda-Escudé & Rees (1994)

Photo-ionisation heating by UVB

Net temperature change is approximately

$$k_{\rm B}T = \frac{\langle E \rangle}{3}$$

Miralda-Escudé & Rees (1994)

For a UVB power-law spectral index $\beta = 2$

$$\langle E \rangle = 3.4\,{\rm eV} \;\Rightarrow\quad T \simeq 13\,000\,{\rm K}$$

So we expect $T \simeq 10^4\,{\rm K}$ from hydrogen photo-ionisation

The temperature-density relation

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

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

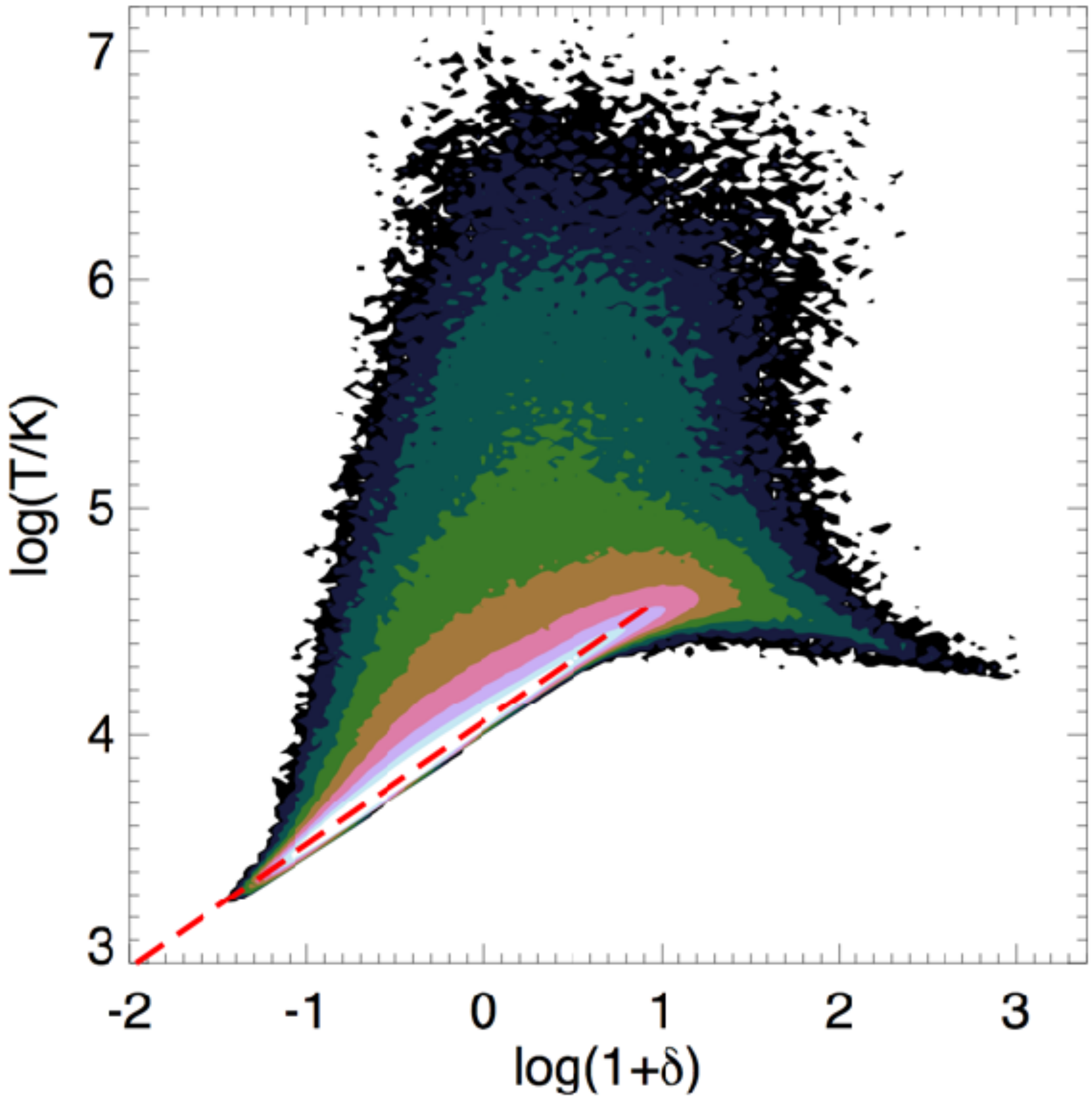
Miralda-Escudé & Rees (1994)

Solve ignoring adiabatic cooling, and assuming $\alpha(T) \propto T^{-0.7}$

$$T \propto n^{1/1.7} \sim n^{0.6}$$

See McQuinn & Upton Sanderbeck (2016) for a detailed treatment.

The temperature-density relation

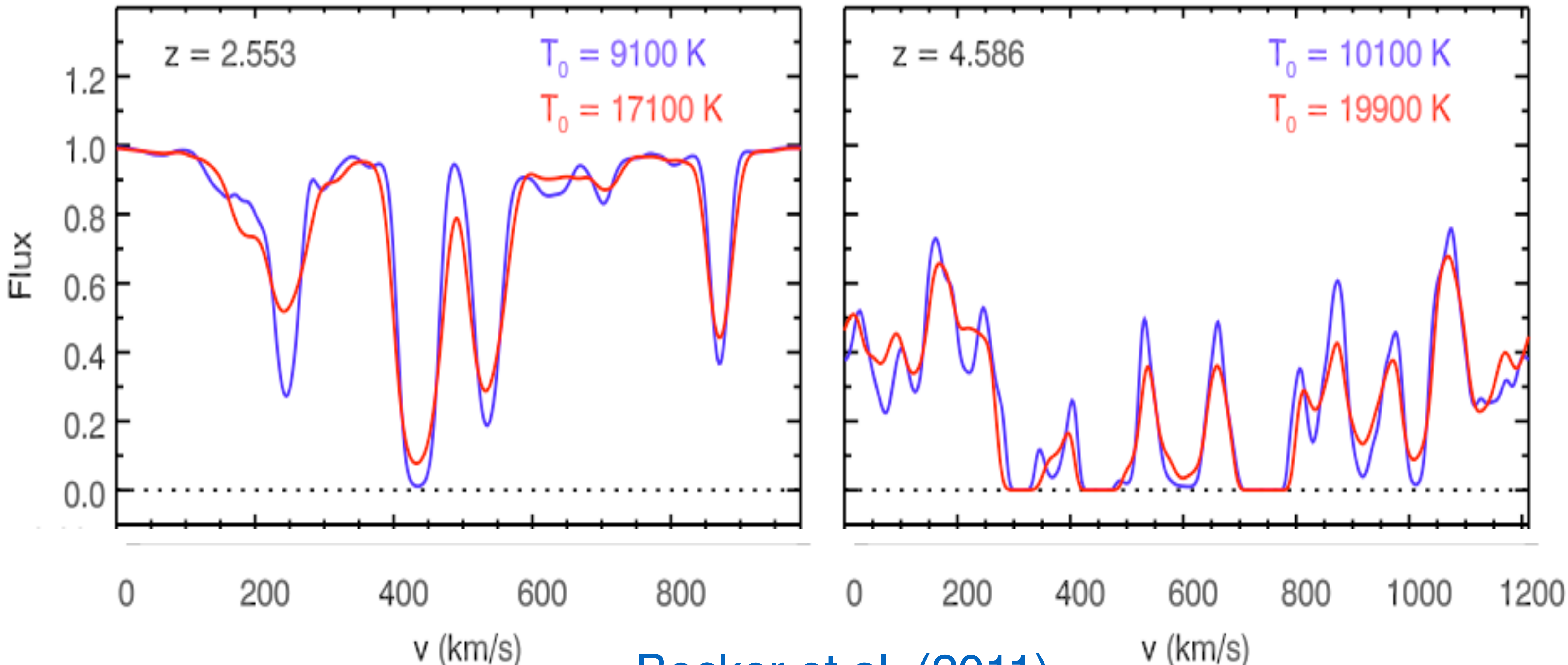


Power-law relationship between temperature and density, $\gamma \sim 1.0\text{-}1.6$

$$T = T_0(1+\delta)^{\gamma-1}$$

Hui & Gnedin (1997), McQuinn & Upton Sanderbeck (2016)

The Ly-α forest as a thermometer



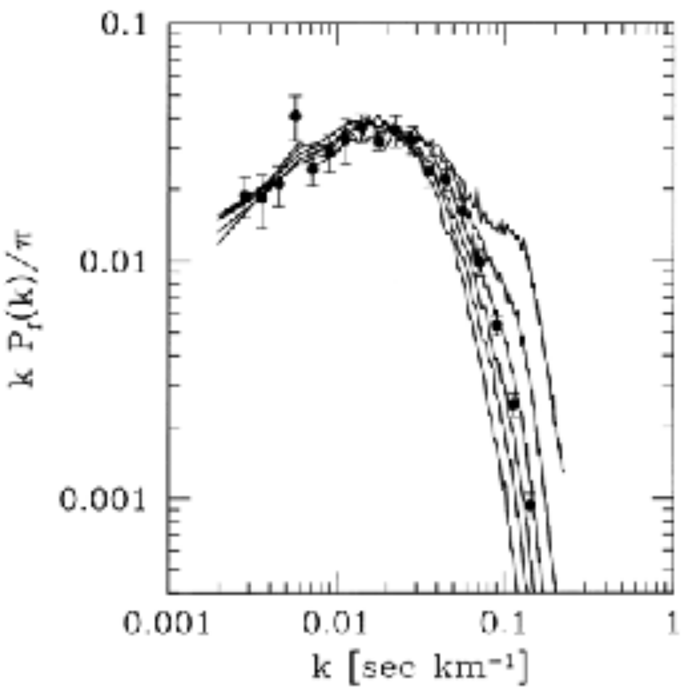
Becker et al. (2011)

1) Thermal broadening by instantaneous temperature (along the line of sight only);

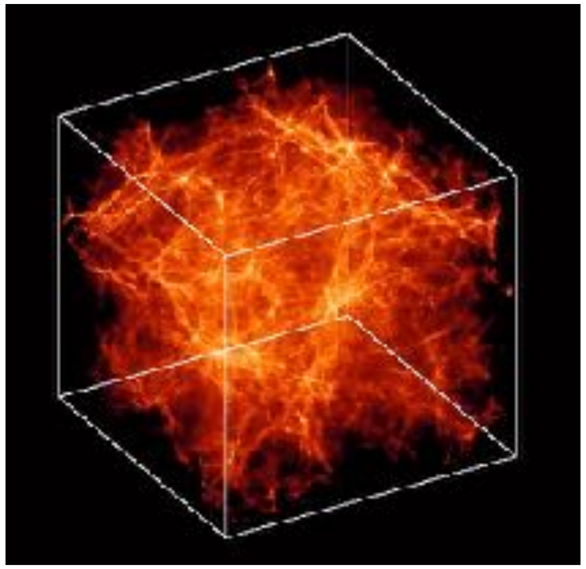
2) Jeans smoothing via integrated heating history (in three dimensions).

Measuring the temperature

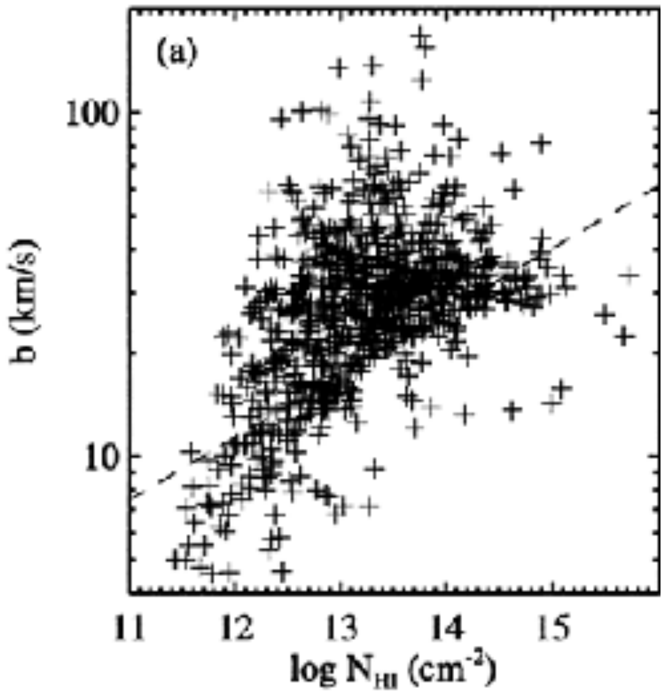
Transmitted flux statistics



IGM model



Line decomposition



$$T_0, \gamma$$
$$(\sigma_J)$$

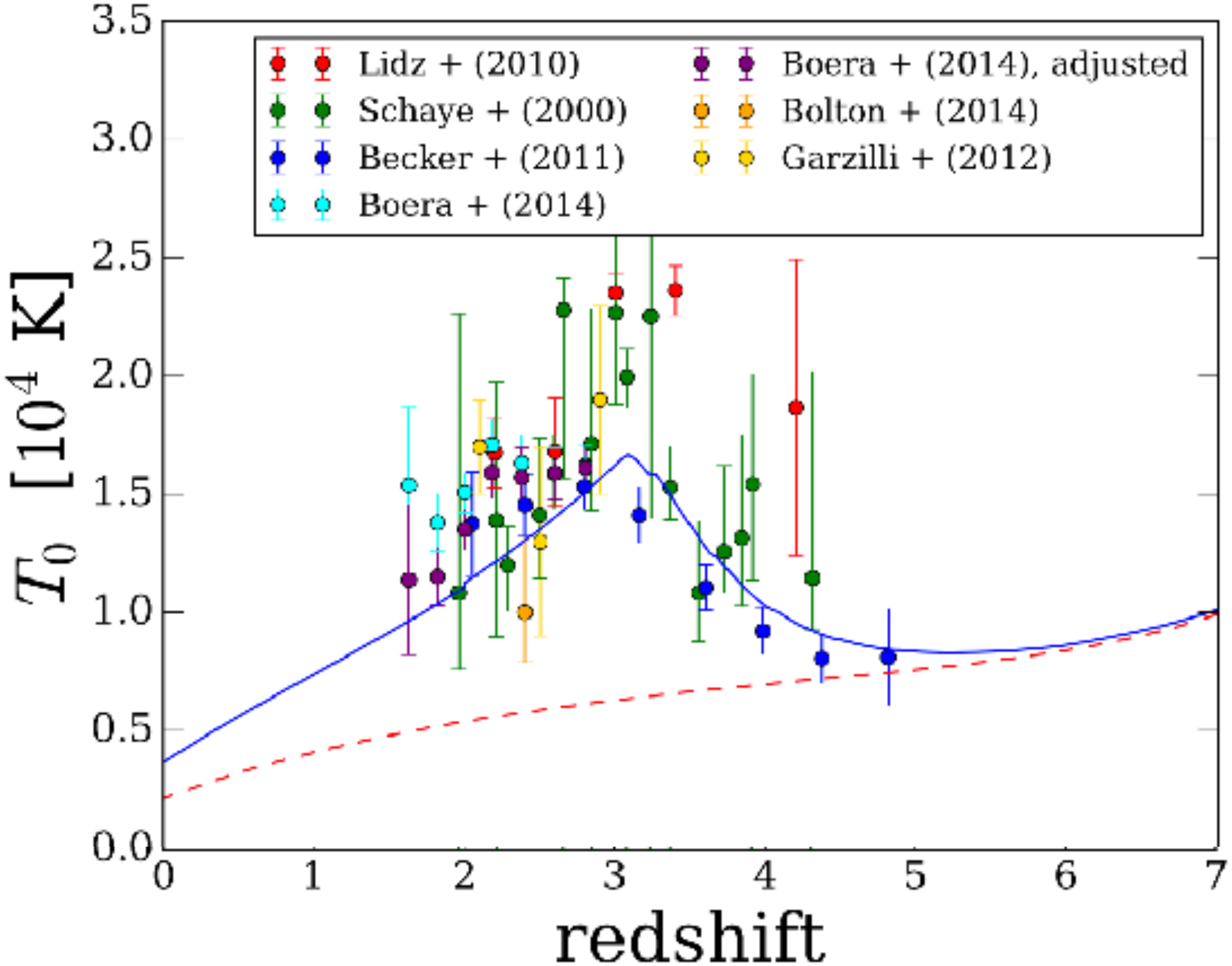
Zaldarriaga et al. (2001) [P(k)]
Theuns et al. (2002) [wavelets]
Bolton et al. (2008) [PDF]
Viel et al. (2009) [P(k)+PDF]
Lidz et al. (2010) [wavelets]
Becker et al. (2011) [curvature]
Garzilli et al. (2012) [wavelets]
Calura et al. (2012) [PDF]
Boera et al. (2014, 2016) [curvature]
Lee et al. (2015) [PDF]
Rorai et al. (2017) [PDF]

Schaye et al. (2000)
Ricotti et al. (2000)
Bryan & Machacek (2000)
McDonald et al. (2001)
Bolton et al. (2012, 2014)
Rudie et al. (2012)
Rorai et al. (2018)
Hiss et al. (2018)
Telikova et al. (2018)

Nearly always uses spectra with R~40000

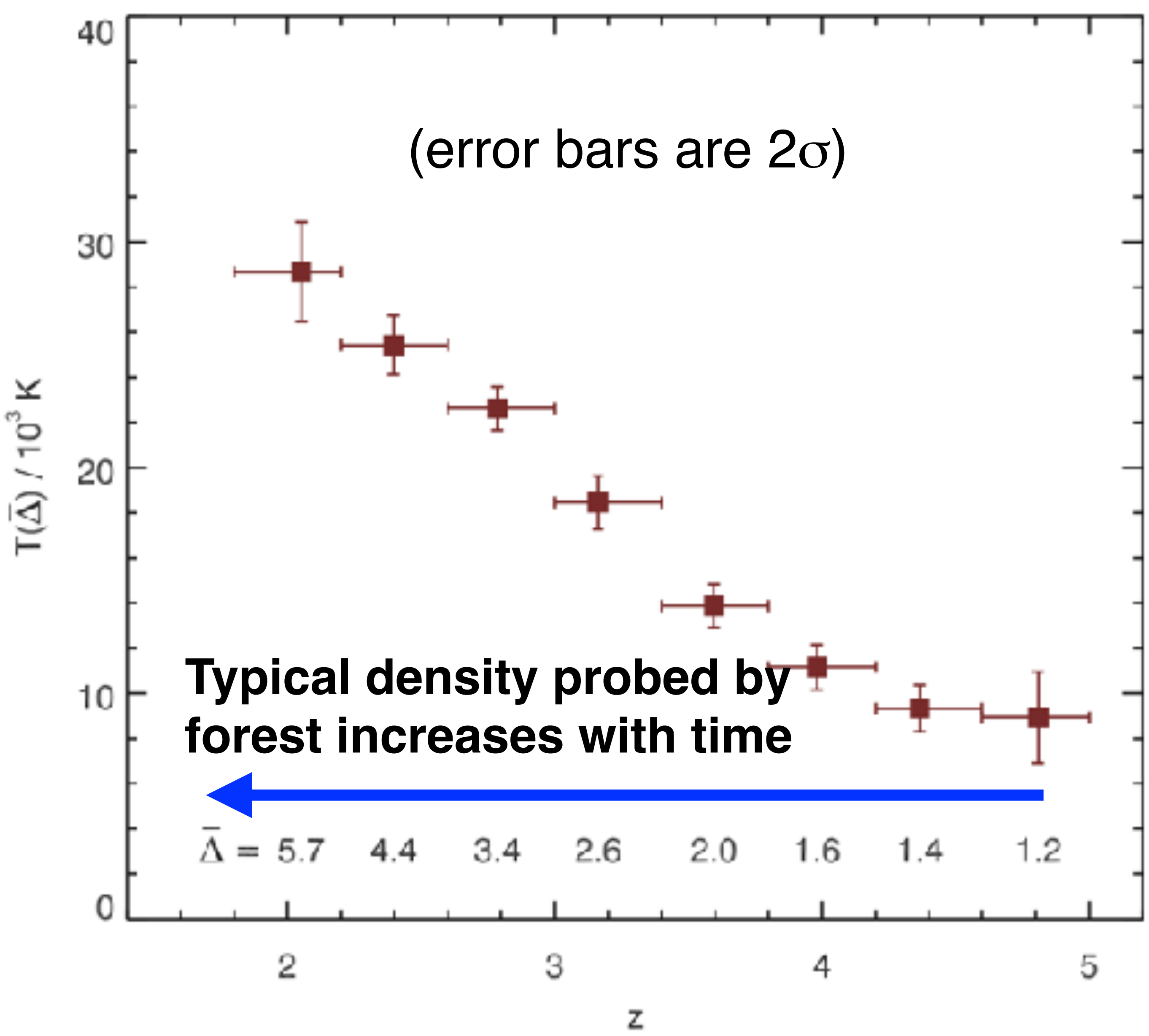
The temperature evolution (δ=0)

Data mainly at 2<z<4. Overall picture is where He-II reionisation heats IGM by ~7000K at z<4.5.



Upton Sanderbeck et al. (2016), see also Puchwein+18, D'Aloisio+18 for discussion in context of AGN reionisation models

The temperature evolution ($\delta = \delta_{char}$)

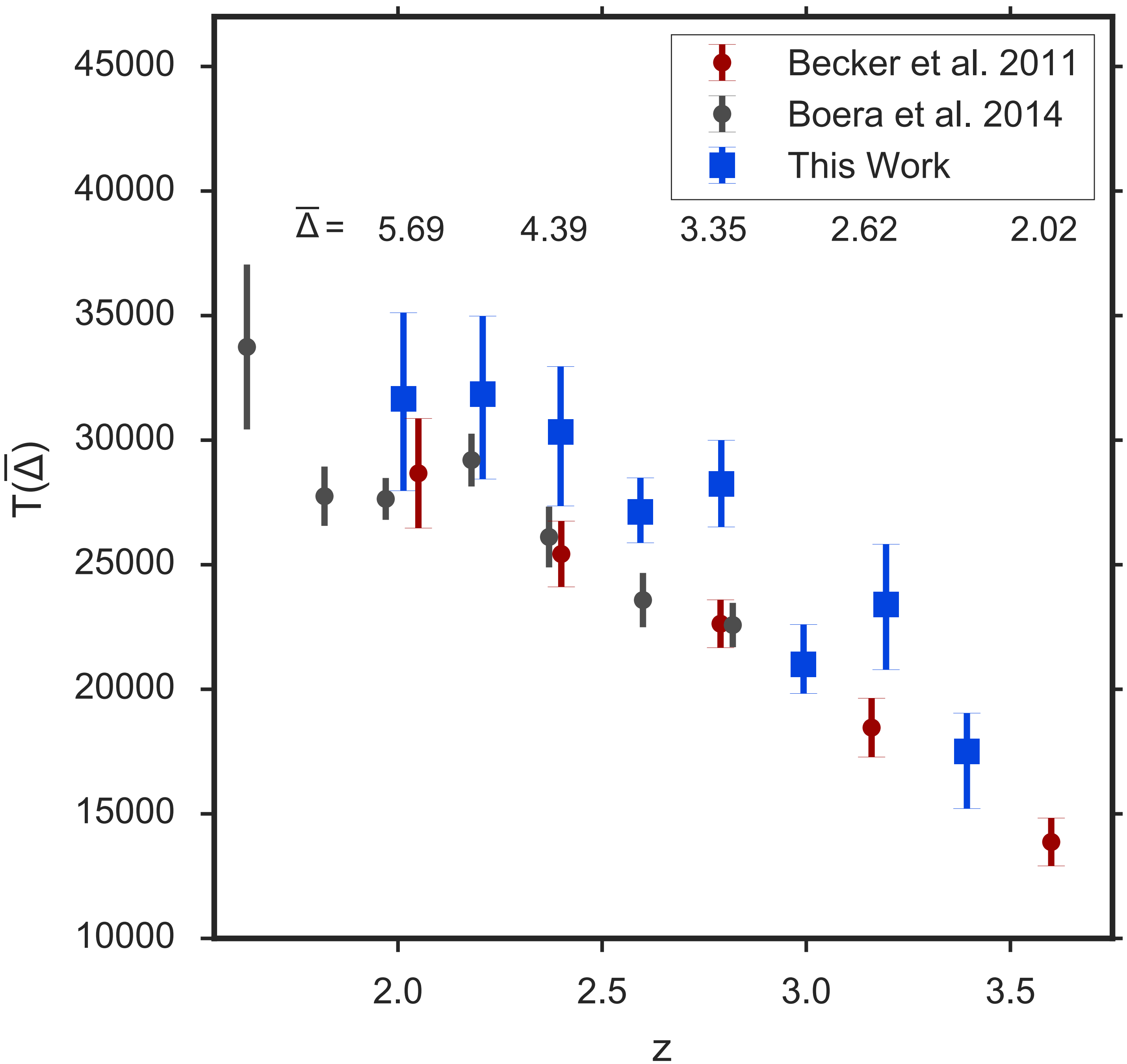


T(Δ) probed by forest precisely measured from Ly-α forest **curvature** at 2<z<5 in 61 HIRES and MIKE spectra

$$\kappa \equiv \frac{d^2F}{dv^2}\left[1 + \left(\frac{dF}{dv}\right)^2\right]^{-3/2}$$

Becker et al. (2011)
see also Boera et al. (2014, 2016)

The temperature evolution ($\delta=\delta_{char}$)



Hiss et al. (2018), see also Rorai+18

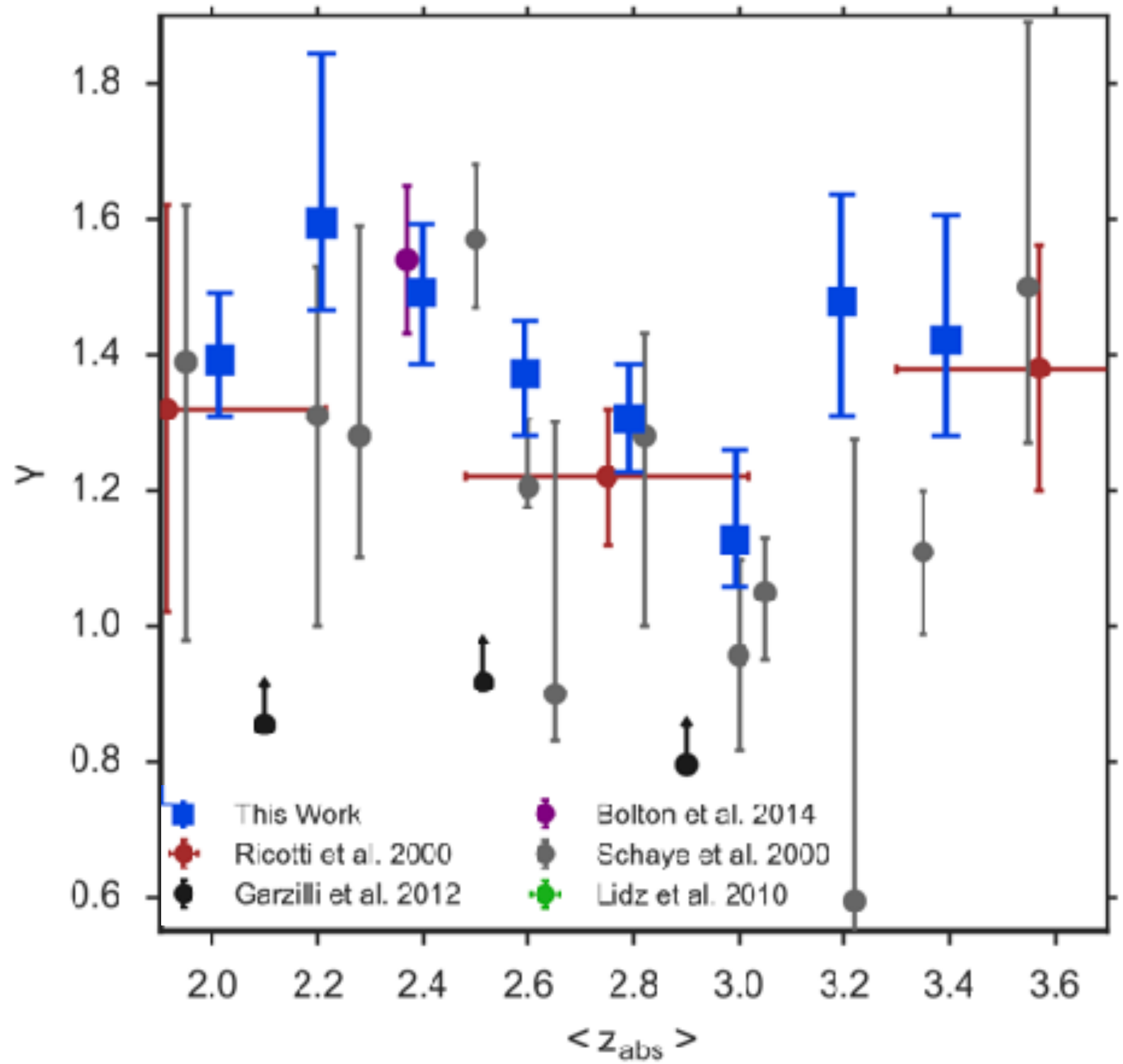
Discrepancy at z>2.6?

Possible systematics:

- Differences in calibration simulations and b-N fitting algorithms;
- Identifying the "characteristic density" is key. Depends on UVB and "characteristic density" definition.

The temperature-density relation

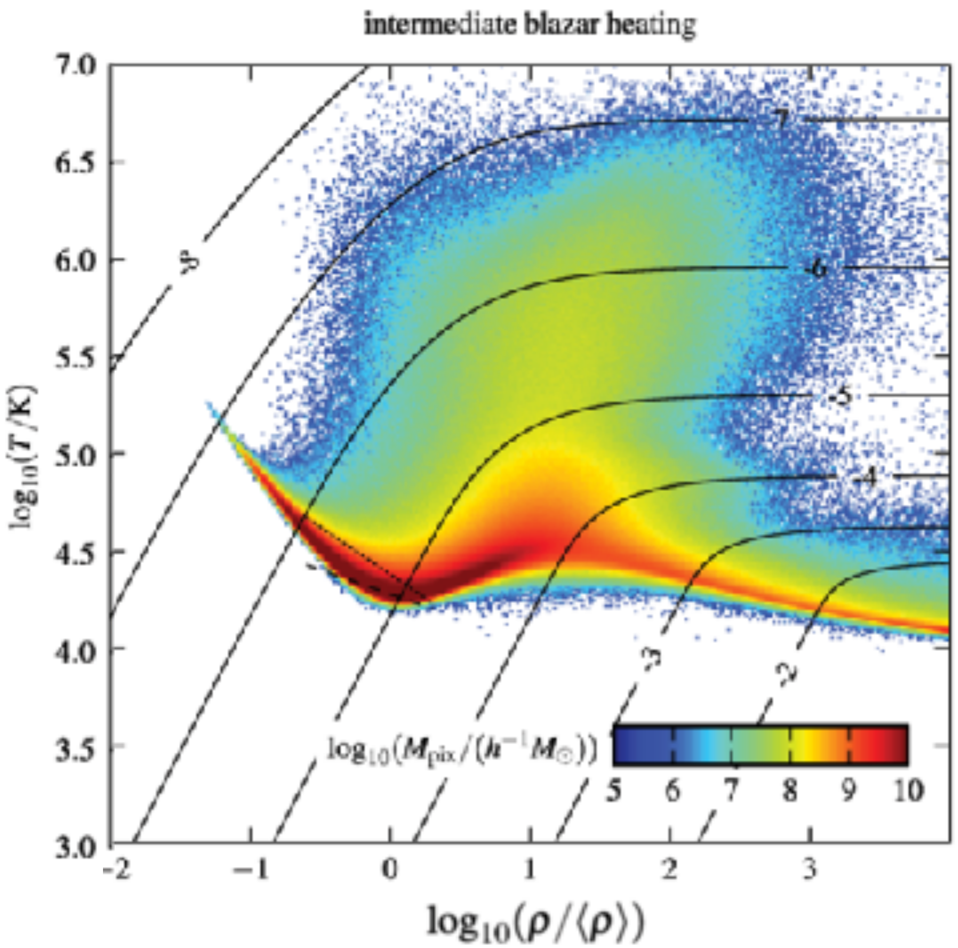
Constraints on T-δ slope are weaker, coming almost exclusively from fitting the b-N cut-off. Generally 1.0<γ<1.6 with hint of flattening at z=3 from He-II reionisation.



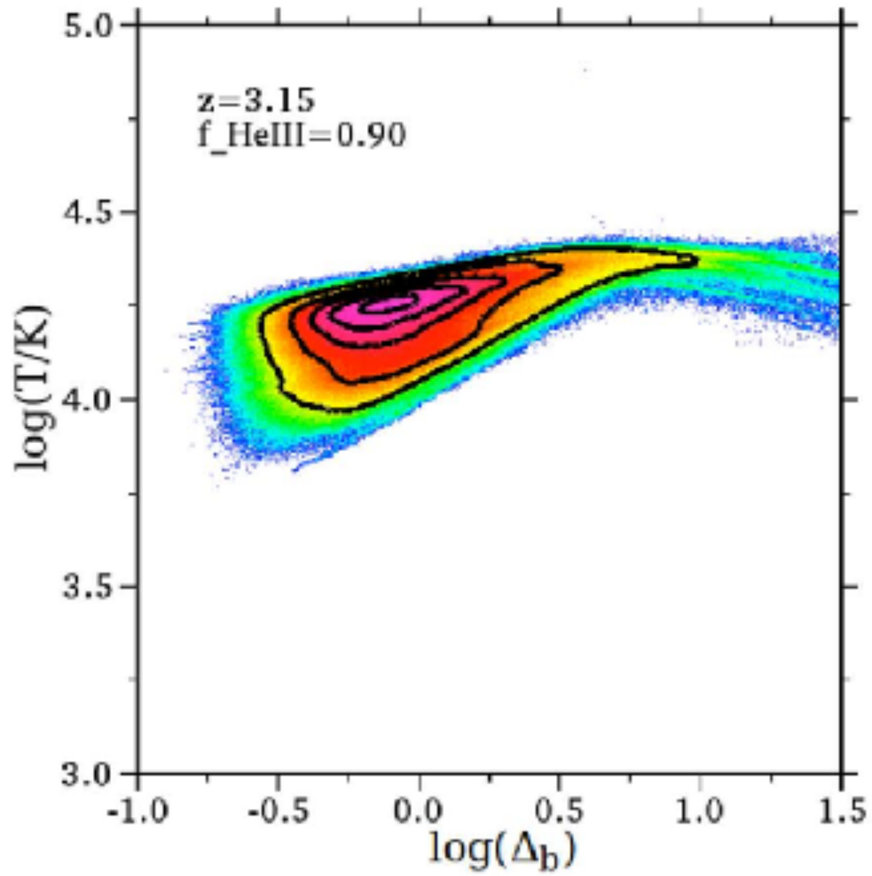
Hiss et al. (2018), see also Rorai+18, Telikova+18

The inverted T-δ relation at z~3

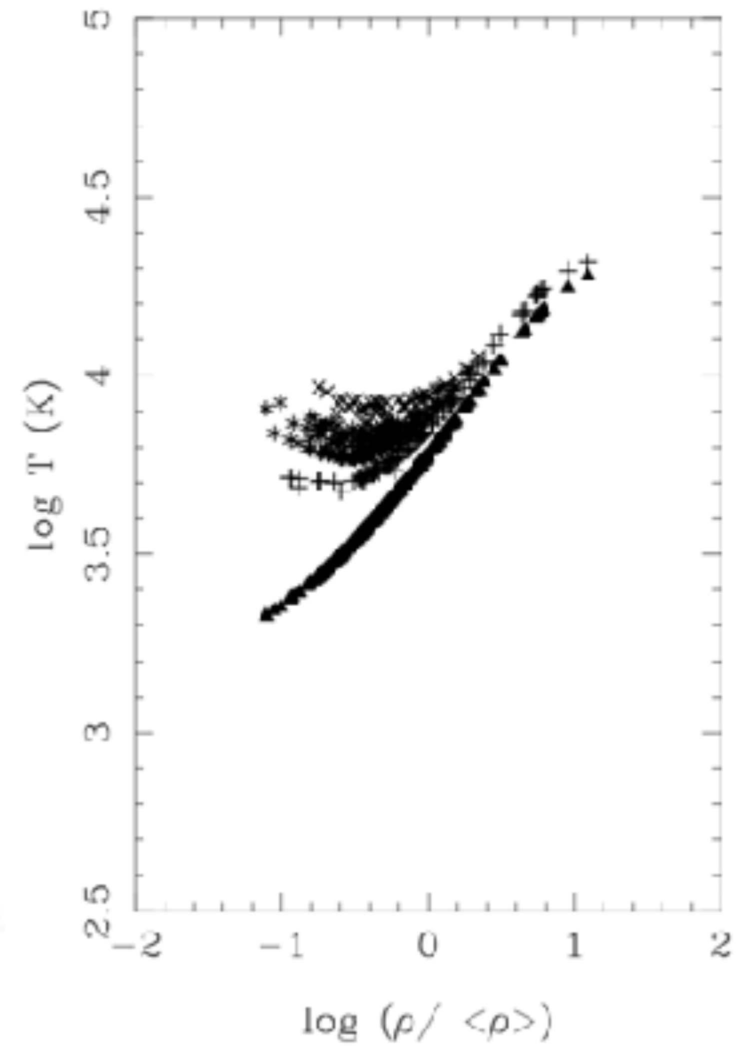
Motivations



Puchwein+12



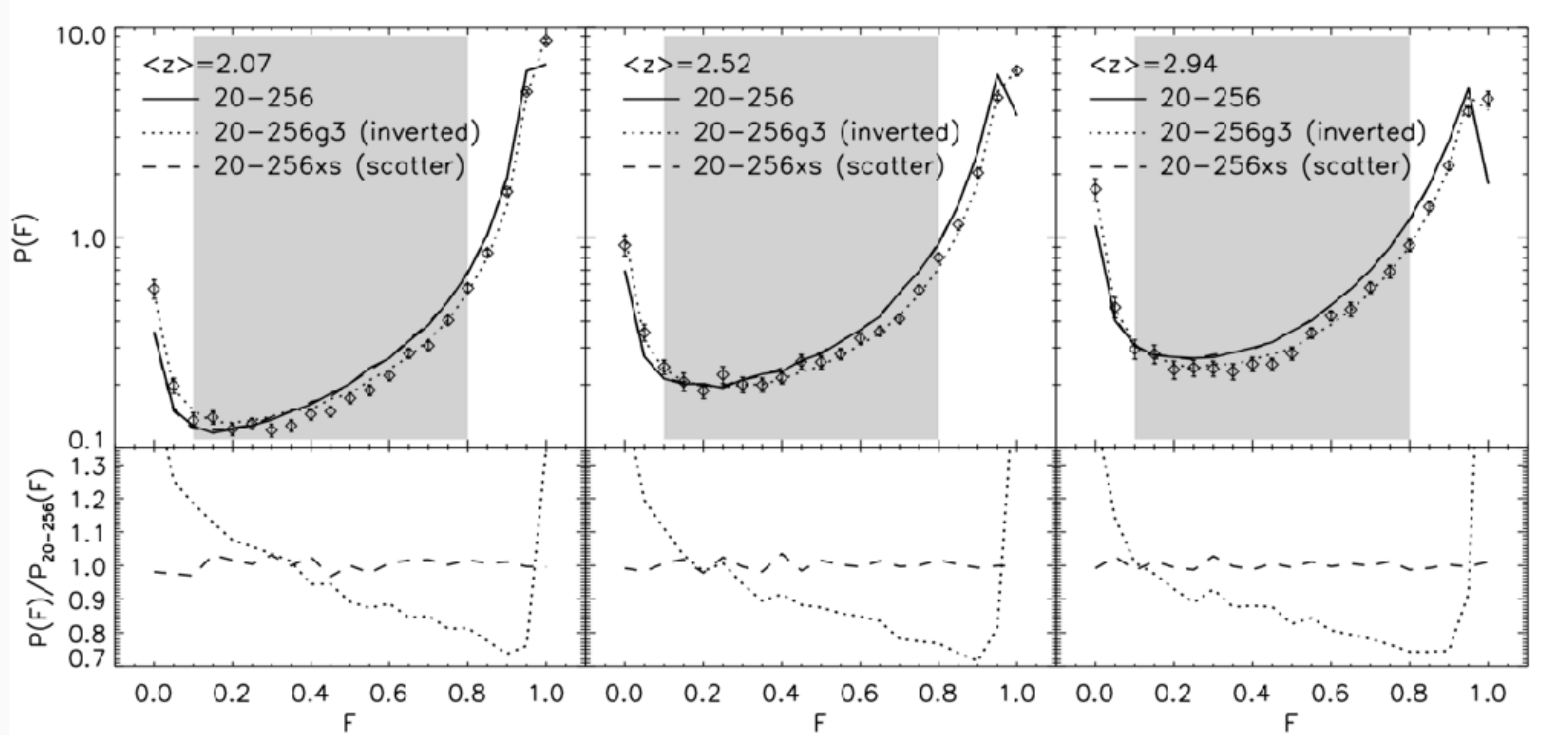
Compostella+13



Bolton+04

- Volumetric heating from blazar TeV emission heats under-dense gas (but see Miniati & Elyiv 2013)
- Patchy heating and spectral filtering induces scatter (H-I *and* He-II reionisation)

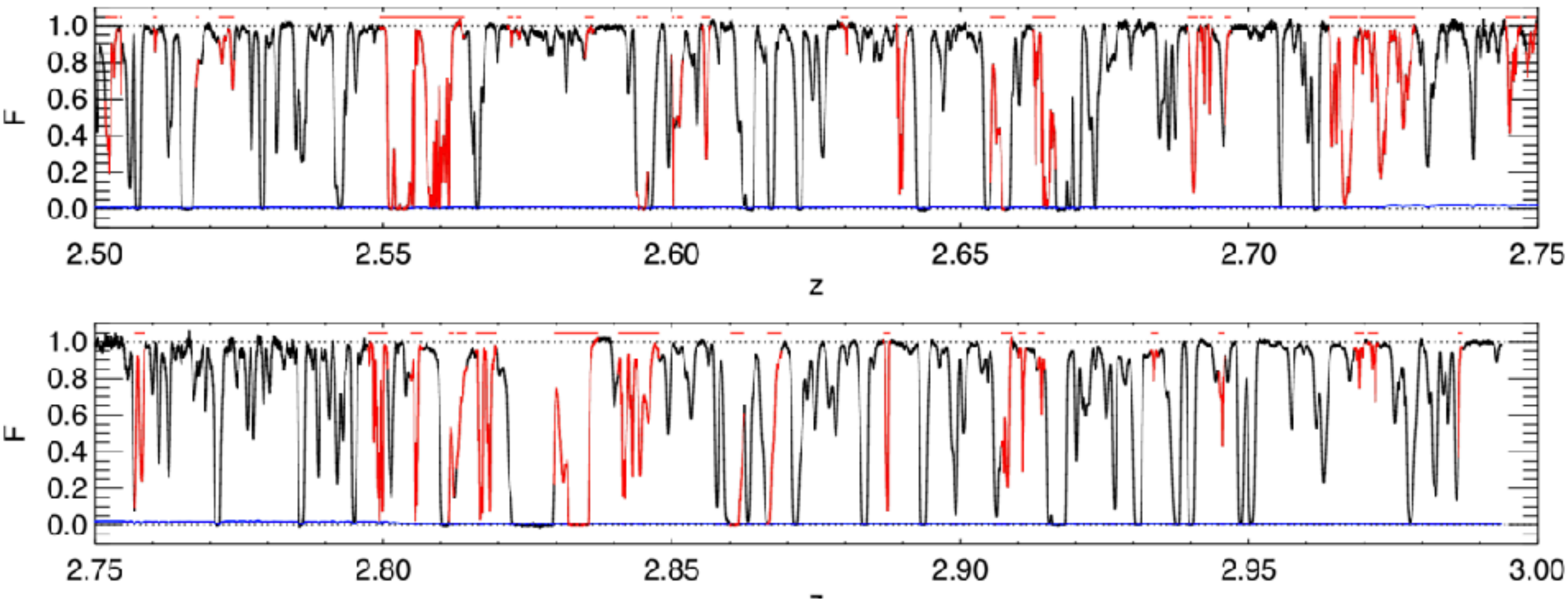
The inverted T-δ relation at z~3



- Transmitted flux PDF from Kim+07
- 18 VLT/UVES spectra at 1.7<z<3.2

Bolton et al. (2008)
But see also Lee+12, Rollinde+13

DEEP spectrum

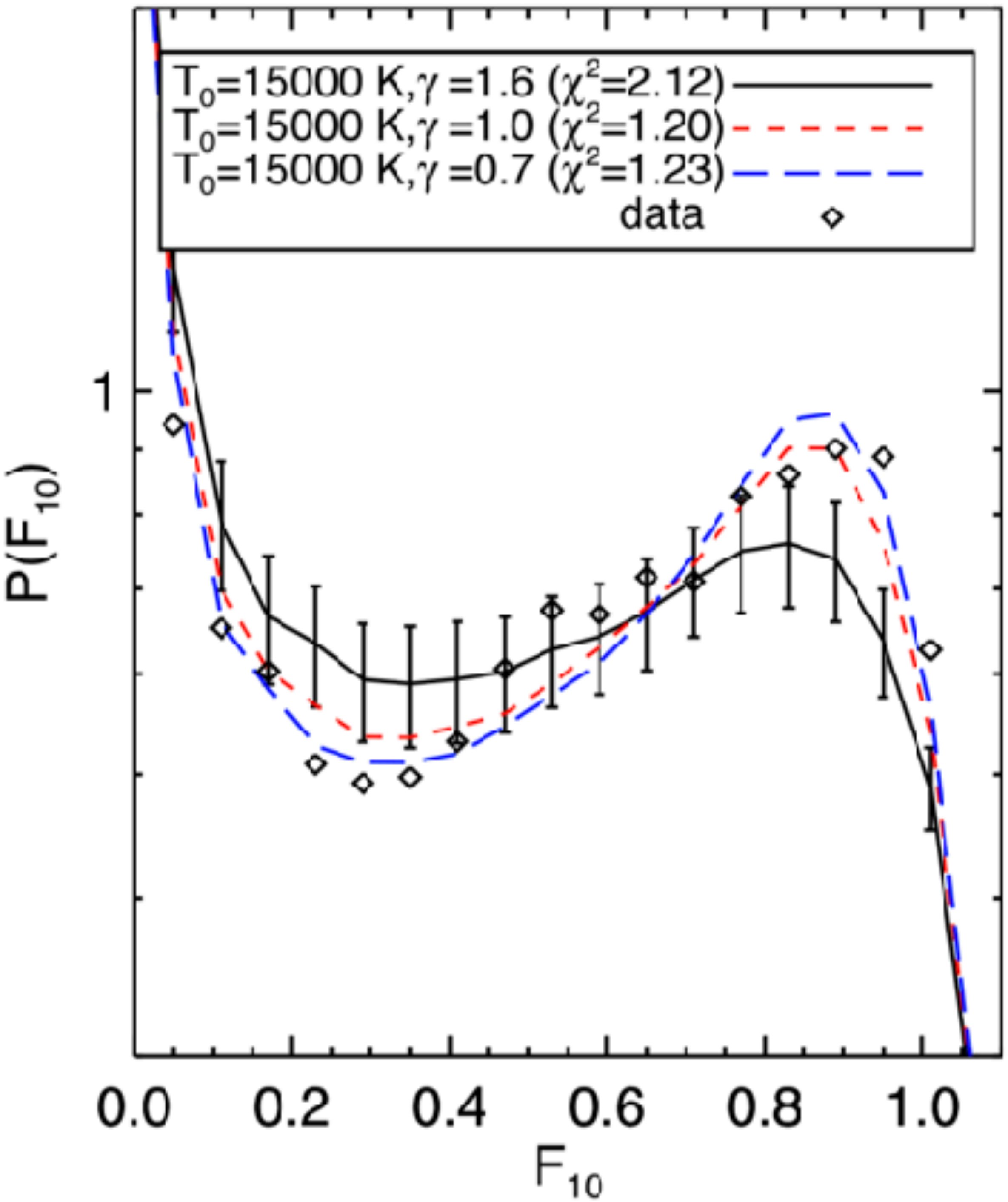


Rorai et al. (2017)

HE0940-1050 (z=3.09)

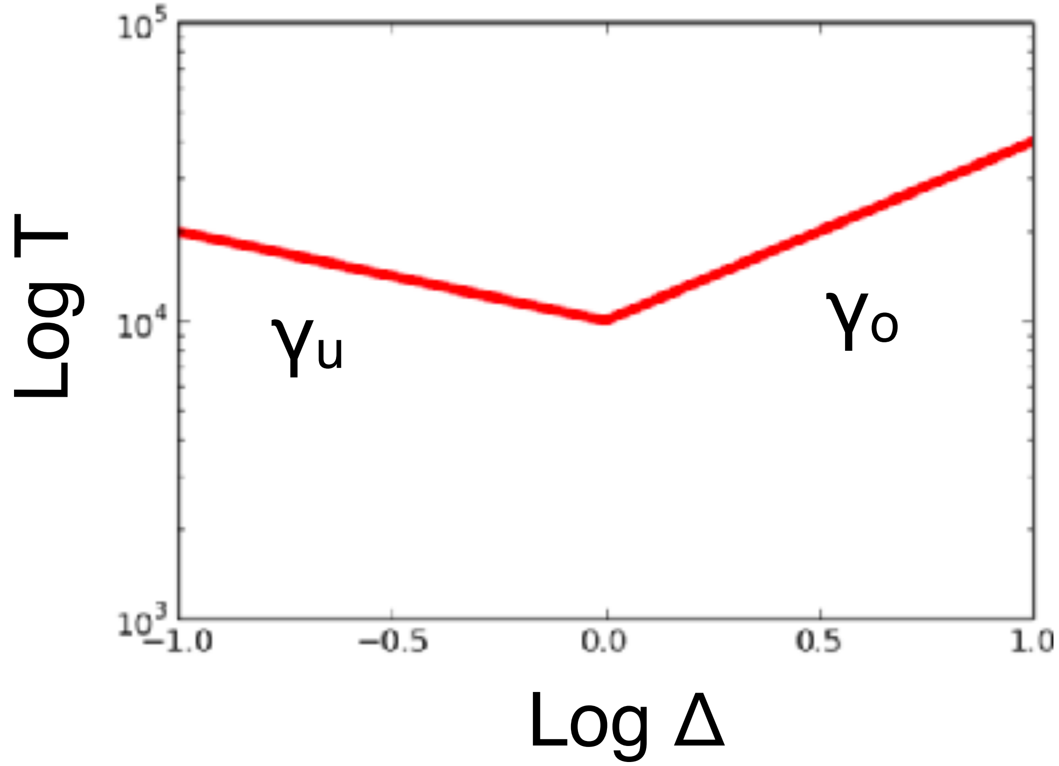
- 64.4 hrs on UVES (PI S. Cristiani)
- R~45000
- S/N=280 per resolution element

DEEP spectrum PDF



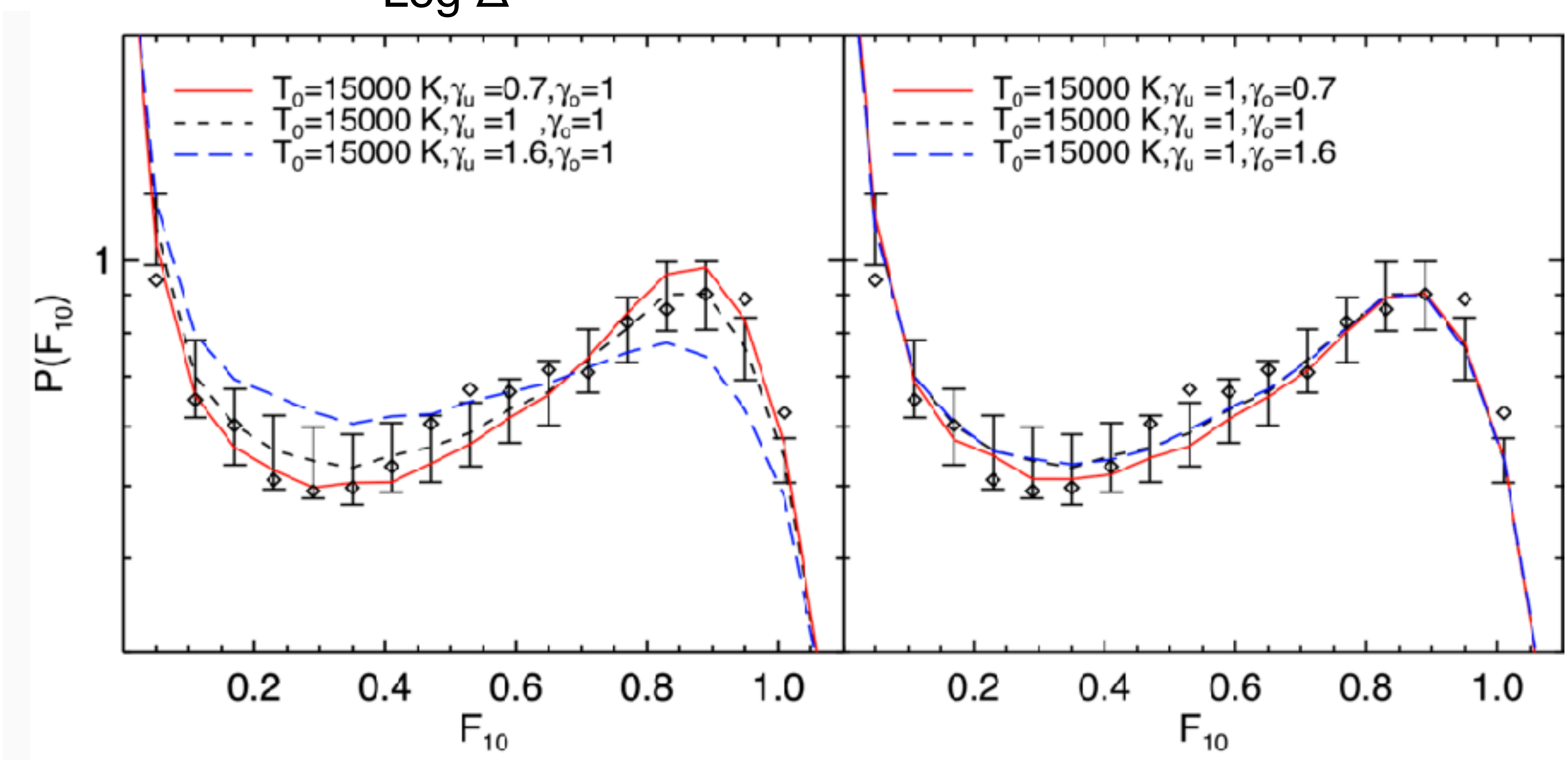
Rorai et al. (2017)

- Continuum regulation + optical depth scaling minimises continuum systematics and enhances sensitivity to pixels with high transmission;
- γ>1 excluded at 90% confidence

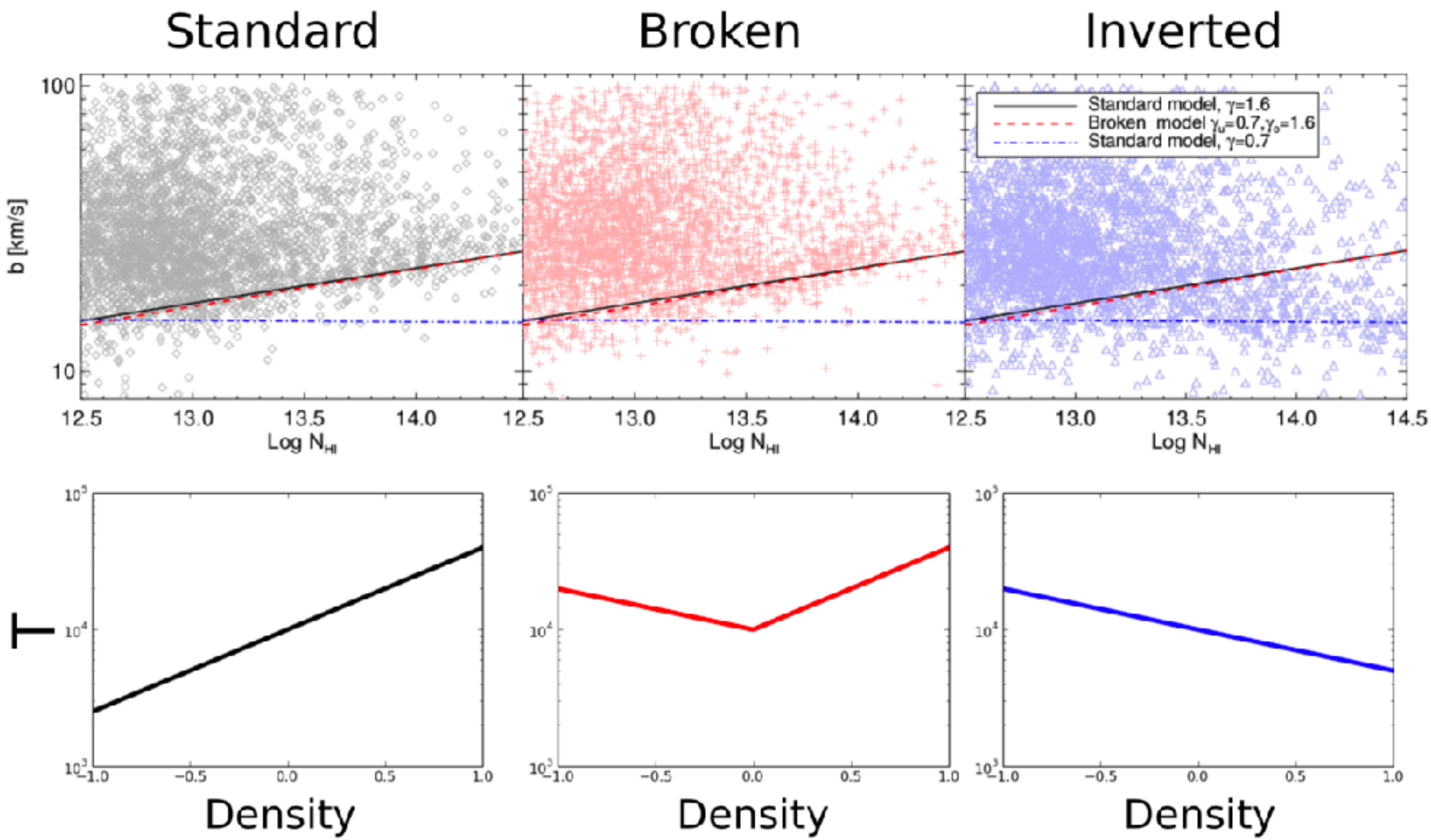


- Temperature-density relation only needs to be isothermal/inverted for underdense gas

Rorai et al. (2017)



Thermal state of under-dense gas



Rorai et al. (2017)

Summary (= matter density matters)

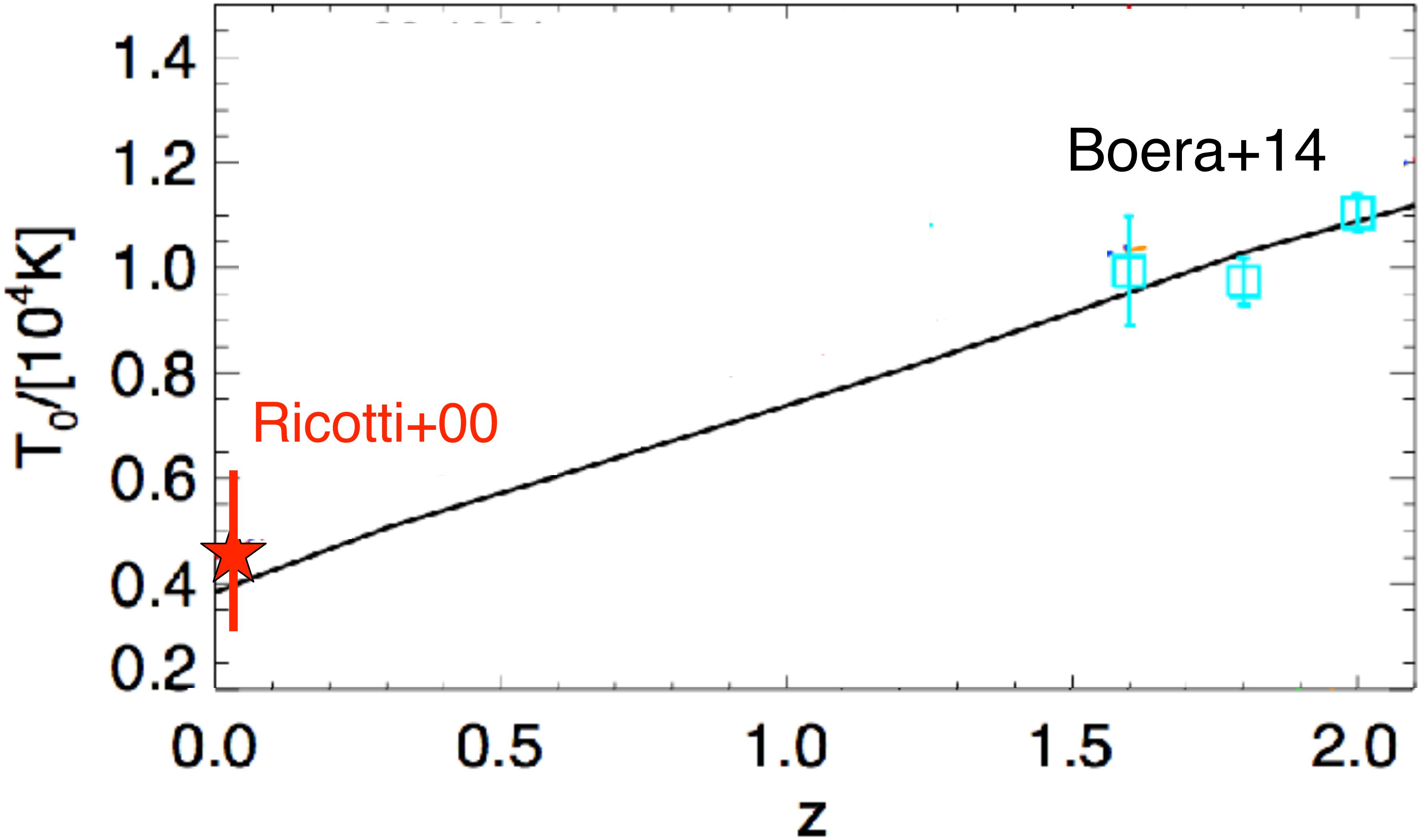
- Long-standing evidence for late He-II reionisation has not gone away — implications for AGN driven H-I reionisation; 😃

- b-N cut-off still clearly favours "standard" T-δ slope, $\gamma>1$, but note this probe is sensitive to overdense gas. 😃

- Possible discrepancies in temperature at fixed density at $z>3$. Depends on identifying the density probed by the forest/corresponding to mean density; 😐

- Measuring the slope of the T-δ relation is tricky. Should not necessarily expect a single power-law; evidence for hot underdense gas from PDF ($R\sim40000$ data) persists; 😐

T_0 evolution to z=0

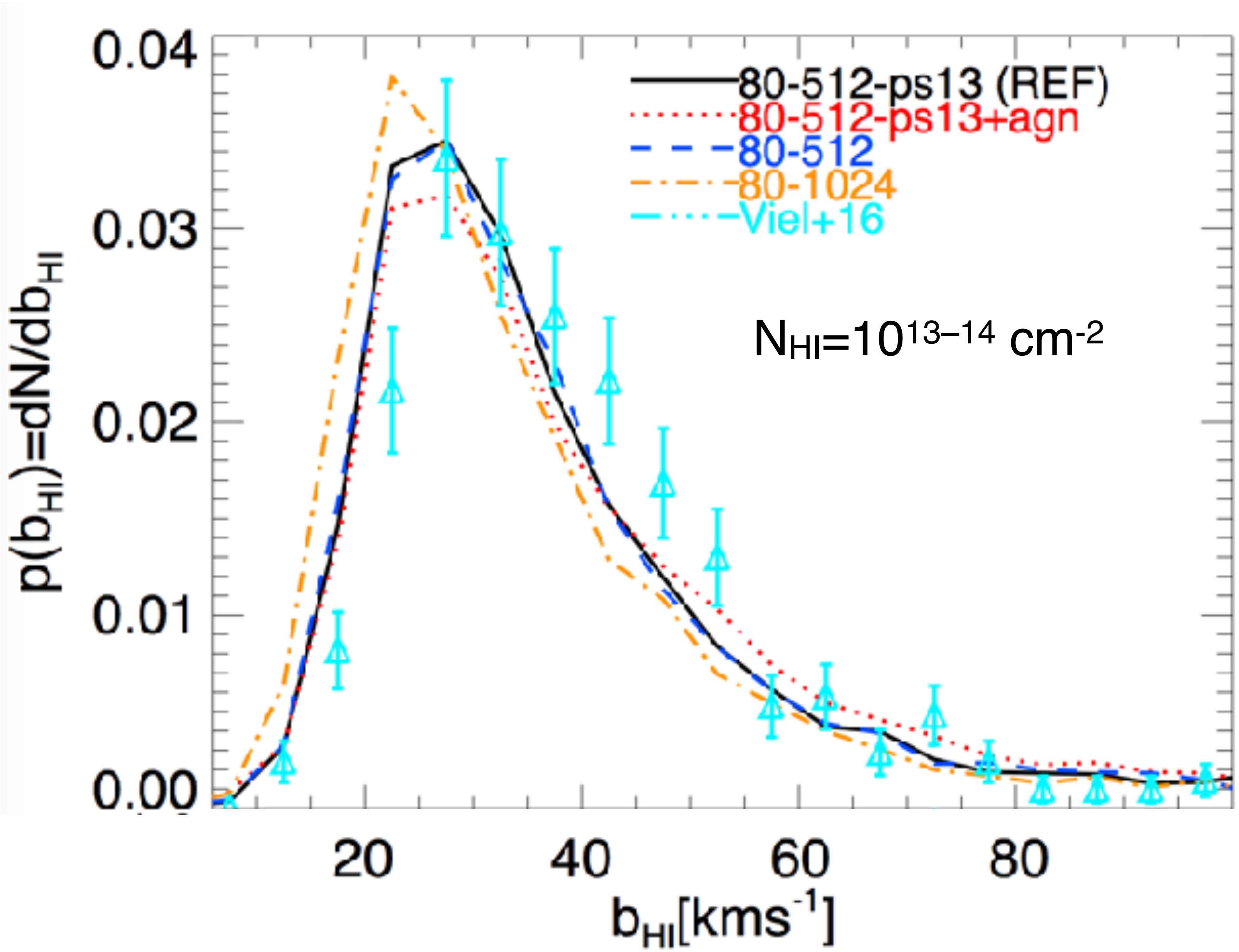


Nasir et al. (2017)

HI and He-II reionisation done. Expect well understood cooling to z=0 due to adiabatic expansion.

- Data point at z=0 from HST/GHRS b-N cut-off.

Line widths at z=0.1

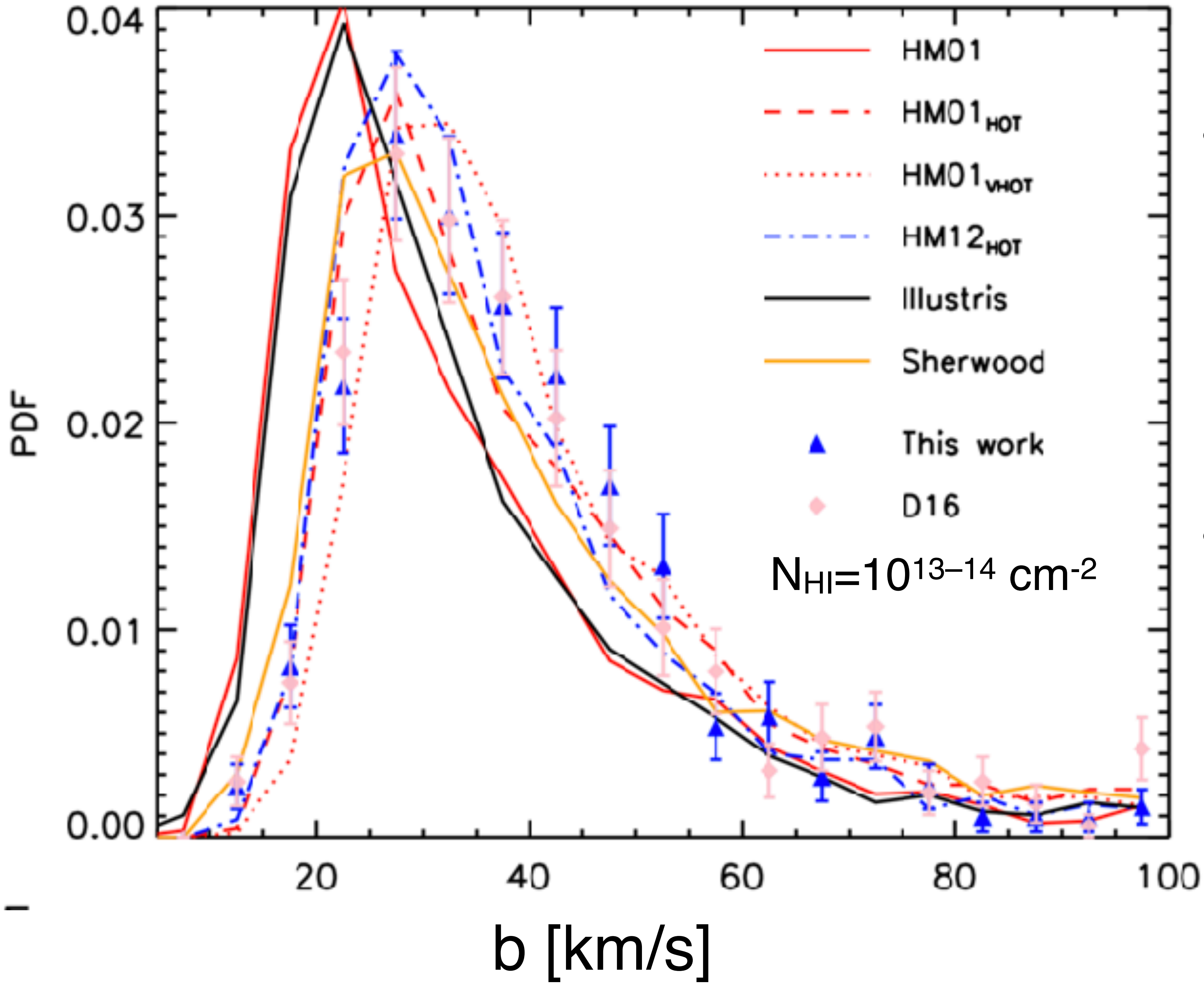


- Unsaturated line widths tend to be too narrow at z=0.1 compared to COS;

Viel et al. (2017);
Nasir et al. (2017)

see also Gaikwad+17

Line width distribution

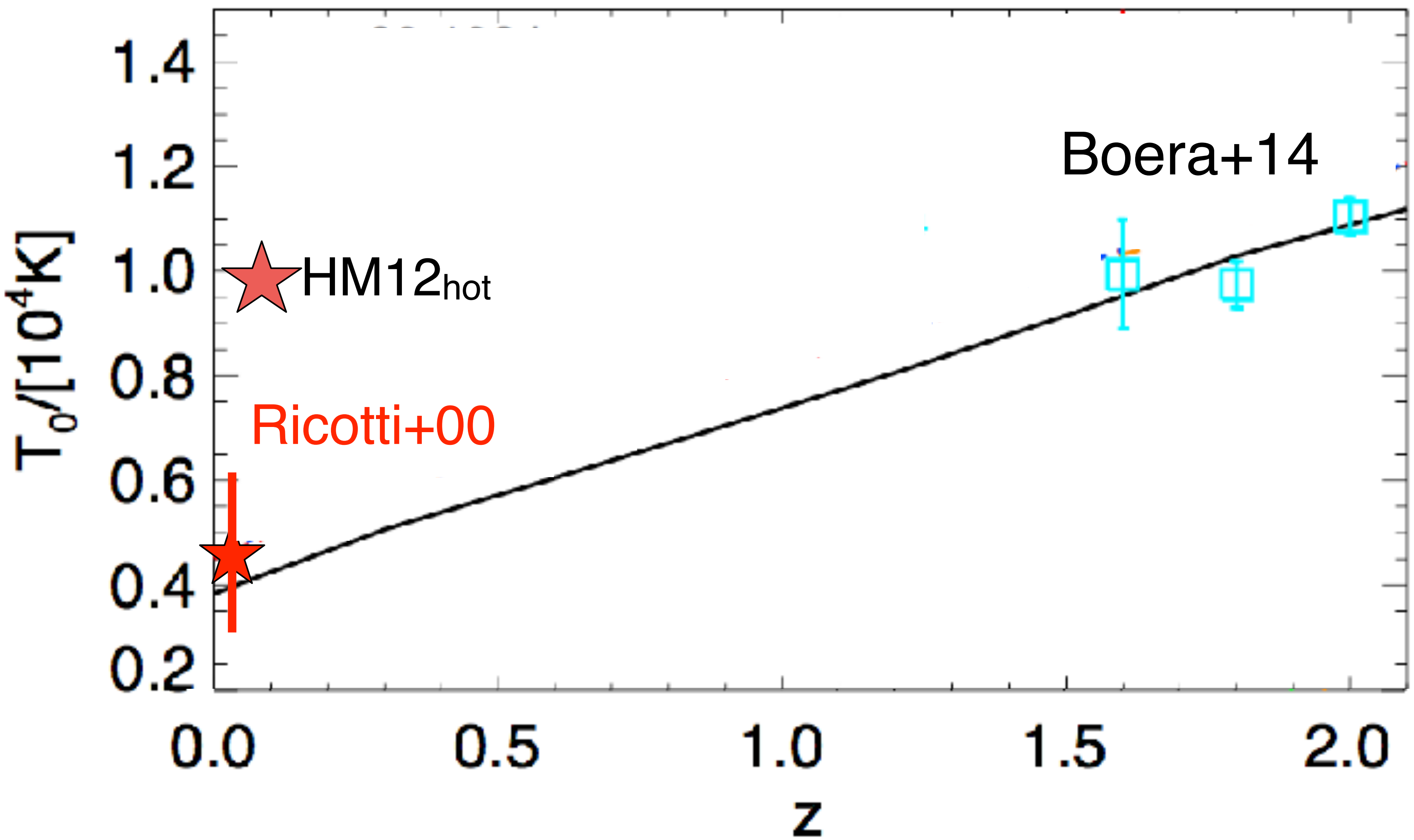


- Can improve agreement by boosting diffuse IGM temperature, but must also pay attention to constraints at z~2;
- Additional Jeans smoothing, unresolved turbulence?

Viel et al. (2017);
Nasir et al. (2017)

see also Gaikwad+17

T_0 evolution to z=0

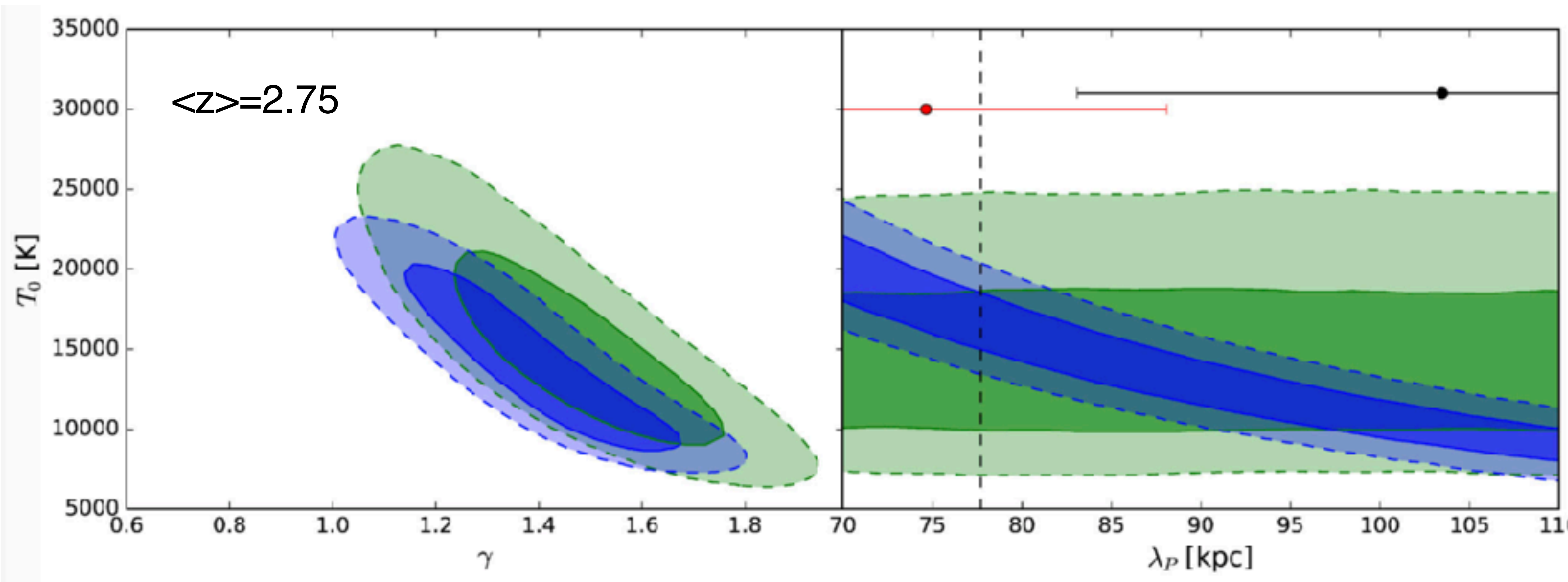


Nasir et al. (2017)

Boosting IGM temperature at z~0.1 implies additional heating from higher redshift. Additional Jeans smoothing, or unresolved turbulence?

How to measure temperature?

- There is more information in the data than just the b-N cut-off!

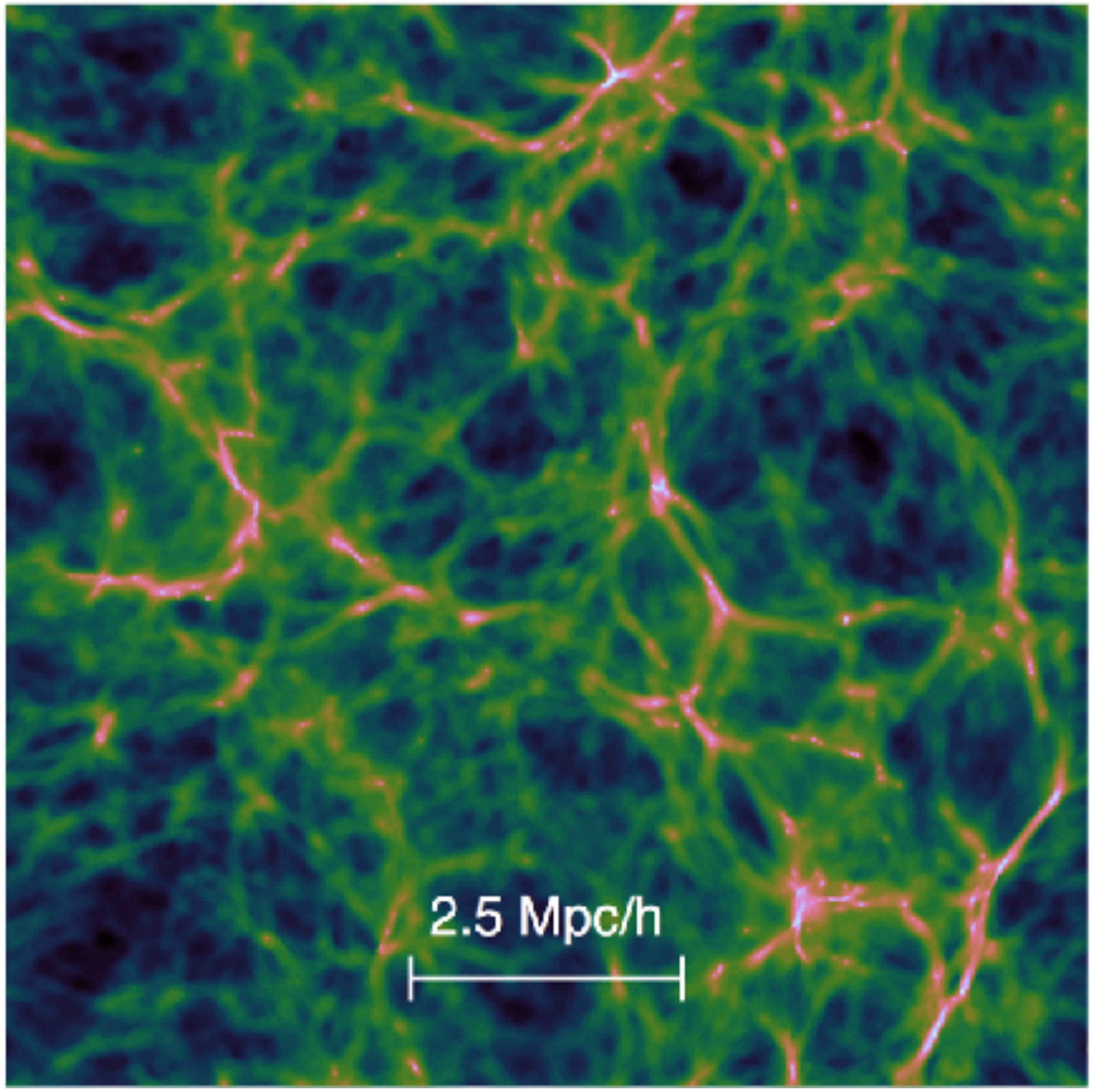


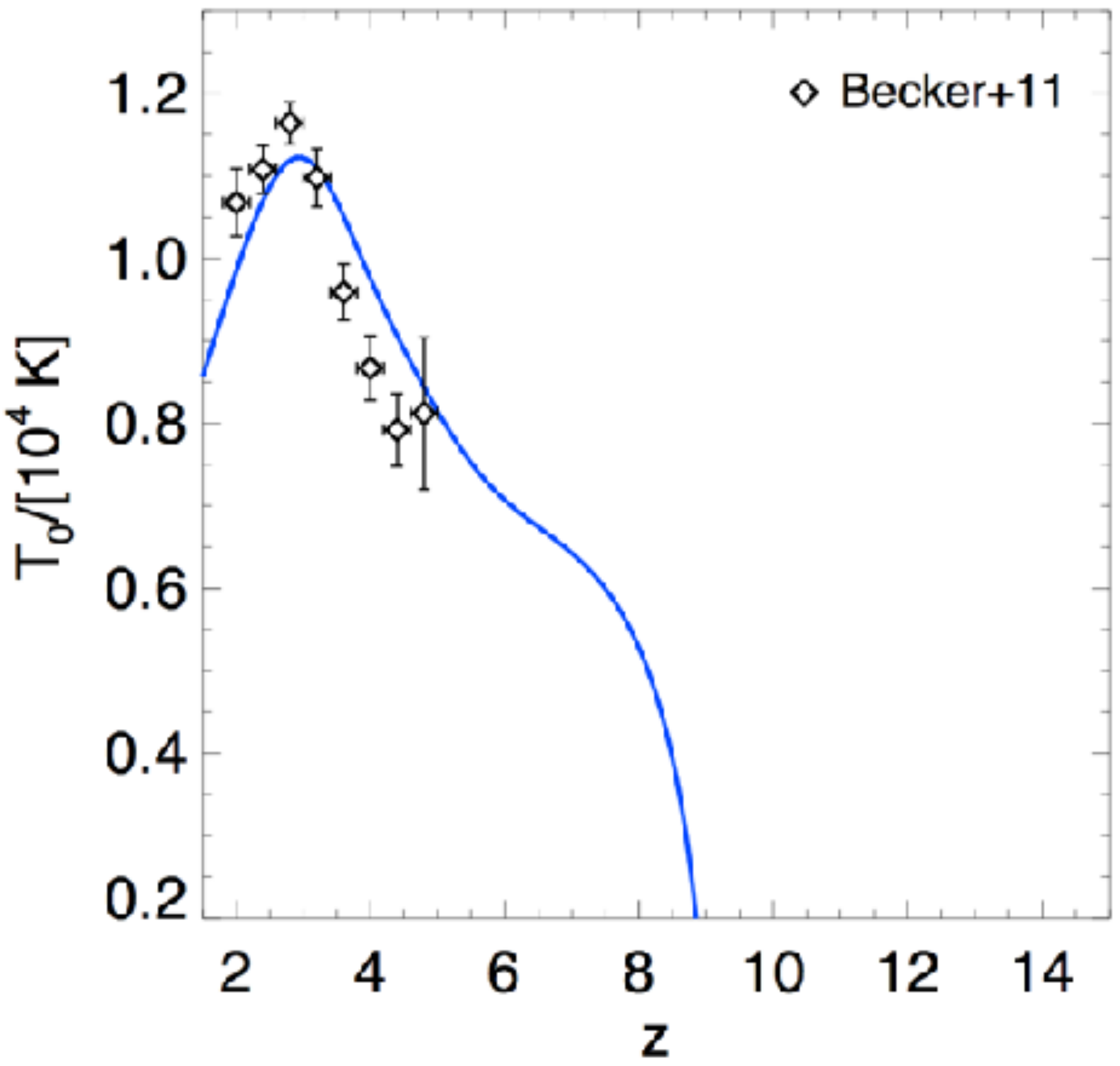
Blue = b-N cut-off
Green = differential median statistic

Rorai et al. (2018), see also Garzilli+15

Pressure smoothing at z~5

Nasir et al. (2016)



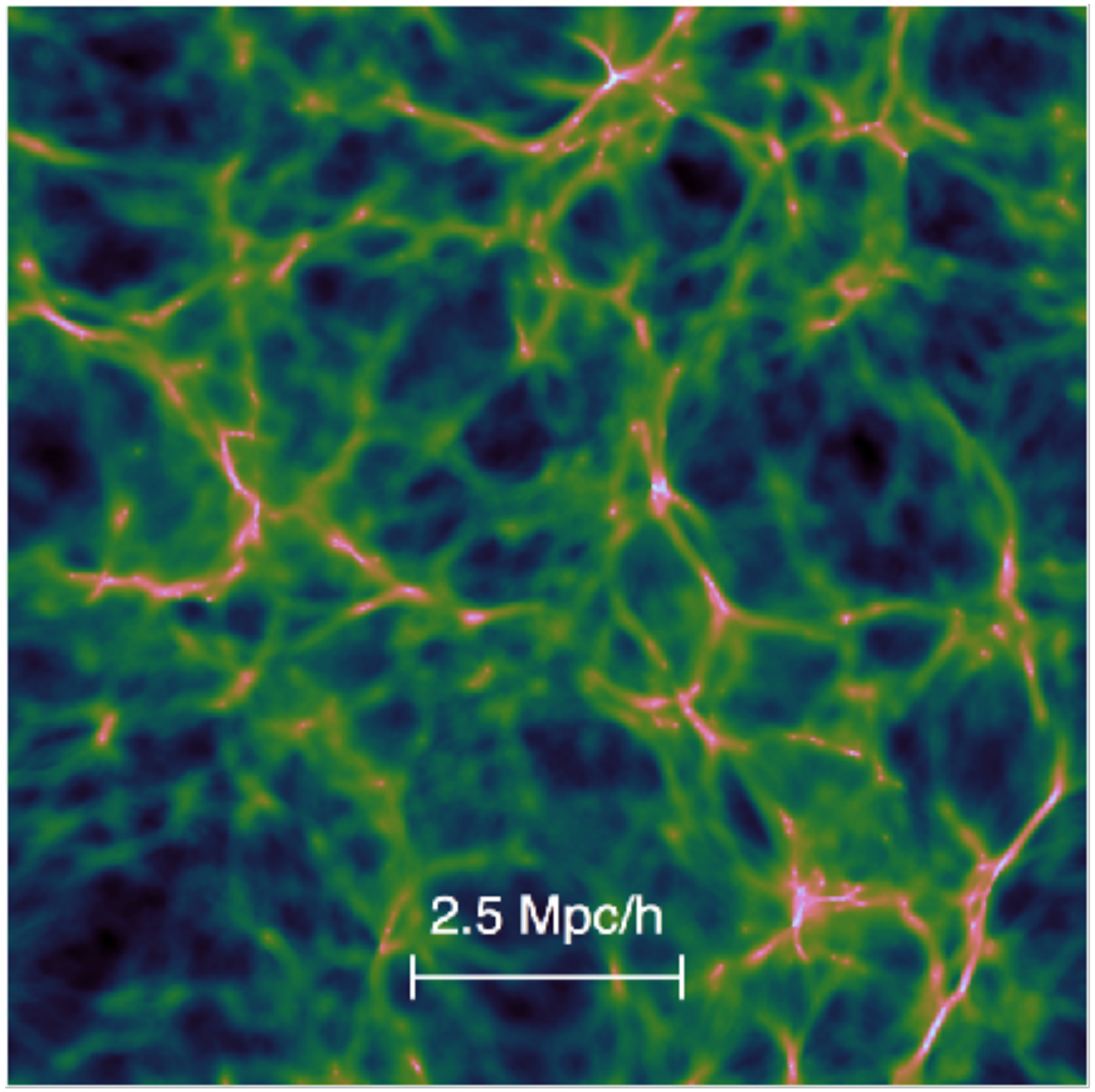


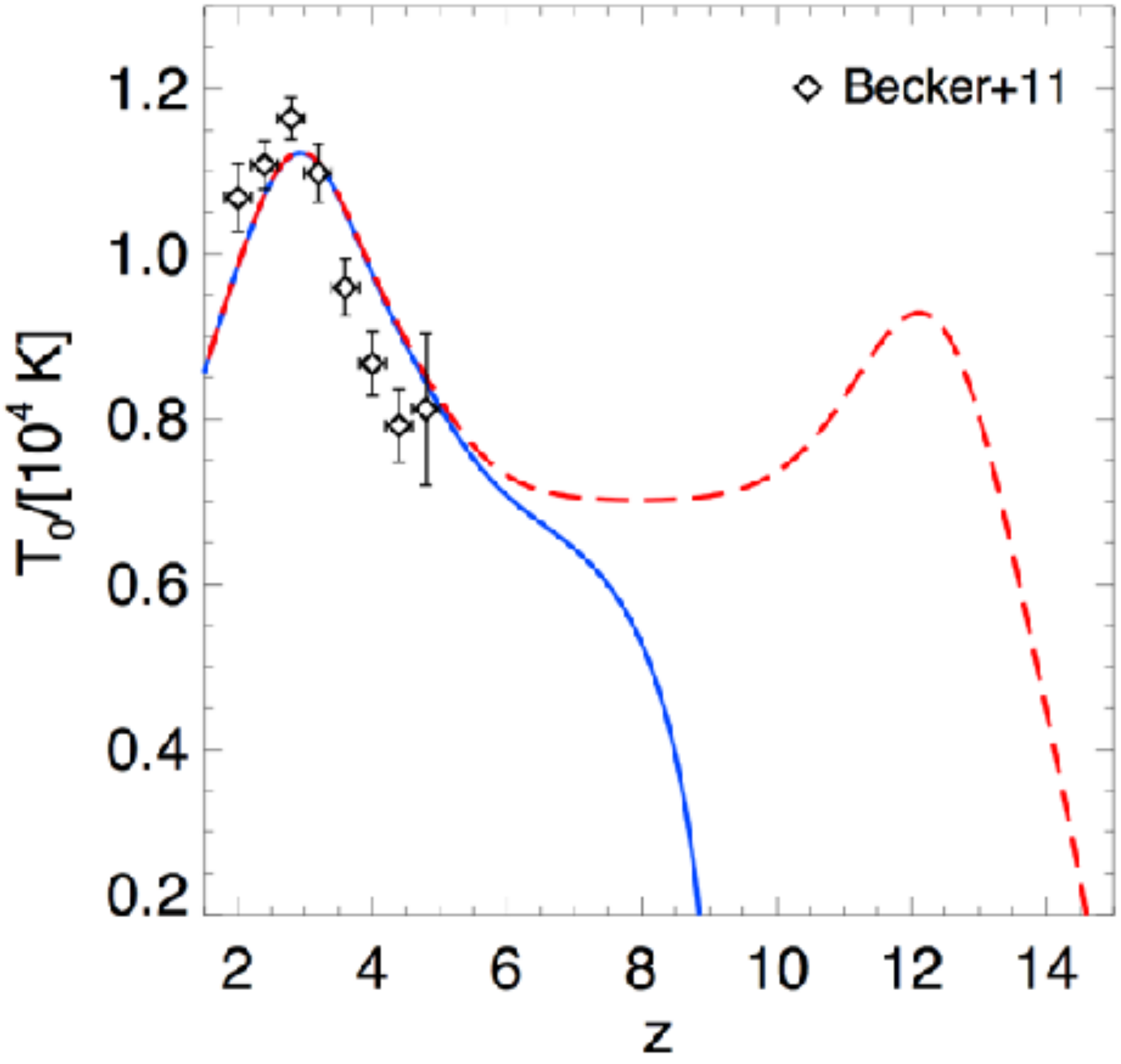
see also Hui & Gnedin 98, Pawlik+09, Peeples+10, Rorai+13, Kulkarni+15, Garzilli+15, Onorbe+17

See talks by Elisa Boera, Jose Oborbe

Pressure smoothing at z~5

Nasir et al. (2016)



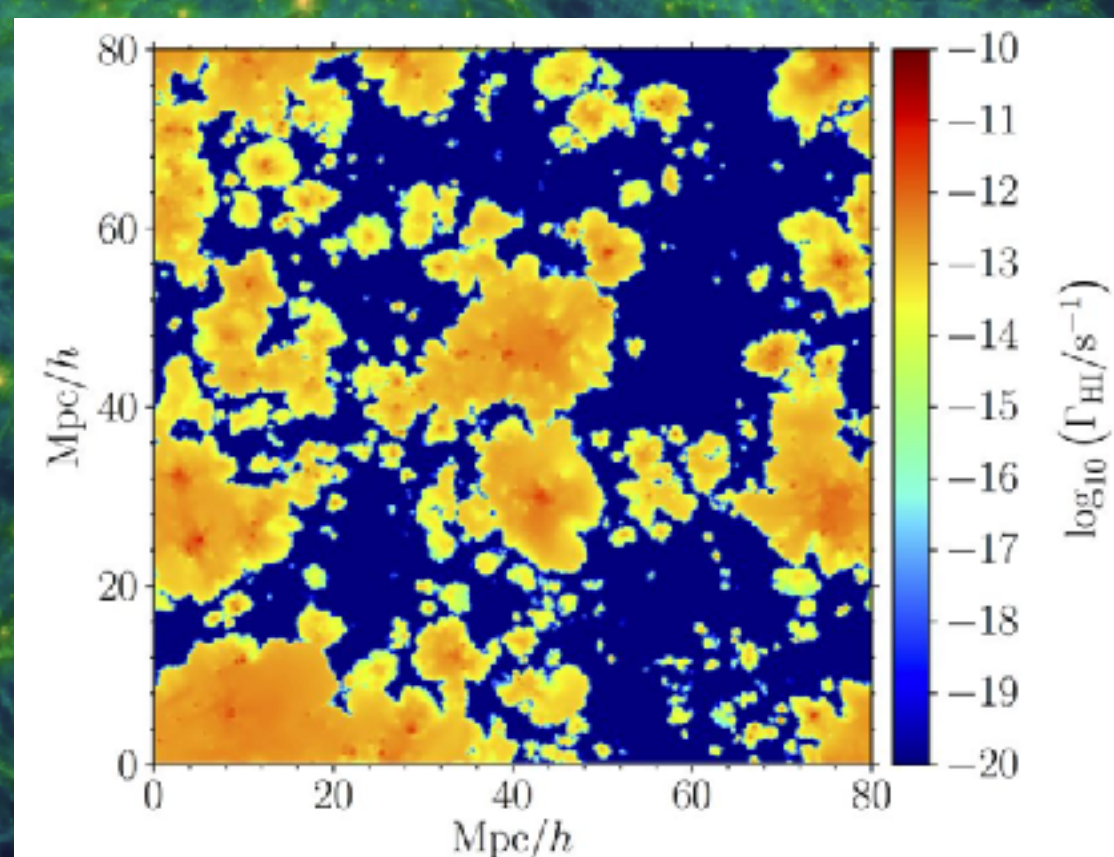


see also Hui & Gnedin 98, Pawlik+09, Peeples+10, Rorai+13, Kulkarni+15, Garzilli+15, Onorbe+17

See talks by Elisa Boera, Jose Oborbe

PRACE

Ewald Puchwein (PI, Cambridge)
George Becker (UCR)
James Bolton (Nottingham)
Jonathan Chardin (Cambridge)
Martin Haehnelt (Cambridge)
Vid Irsic (UW)
Laura Keating (CITA)
Girish Kulkarni (Cambridge)
Avery Meiksin (Edinburgh)
Debora Sijacki (Cambridge)
Matteo Viel (SISSA)



- Hydrodynamical IGM simulations with P-Gadget-3, building on **Sherwood** (Bolton+17);
- 20 million hours on Curie through PRACE (PI Puchwein);
- Runs are coupled to the output of empirically calibrated RT simulations (ATON) to model patchy ionisation and heating