Title: The thermal state of the IGM

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Abstract:

The thermal state of the IGM

Ewald Puchwein & Martin Haehnelt

Collaborators: James Bolton, George Becker, Alberto Rorai, Matteo Viel ,
Francesco Haardt, Piero Madau, the DEEP spectrum team
, Christoph Pfrommer, Volker Springel, Avery Broderick, Phil Chang

Institute of Astronomy &
Kavli Institute for Cosmology, Cambridge

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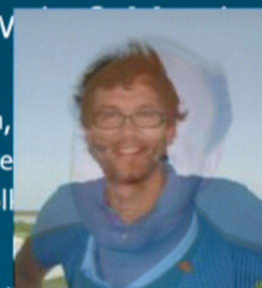
The thermal state of the IGM

Ewald Puchw  Haehnelt

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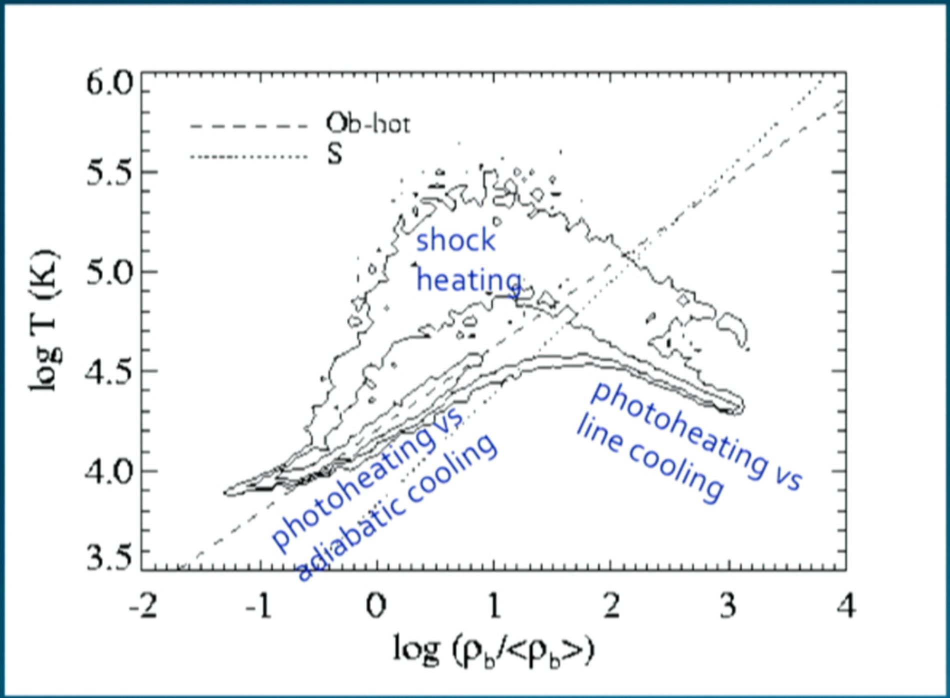
Temperature-density relation of the IGM (optical thin approximation)



$$T \propto \rho^{\gamma-1}$$

$$1 < \gamma < 1.6$$

Schaye et al. 1999

Helium photo-heating?
radiative transfer effects?

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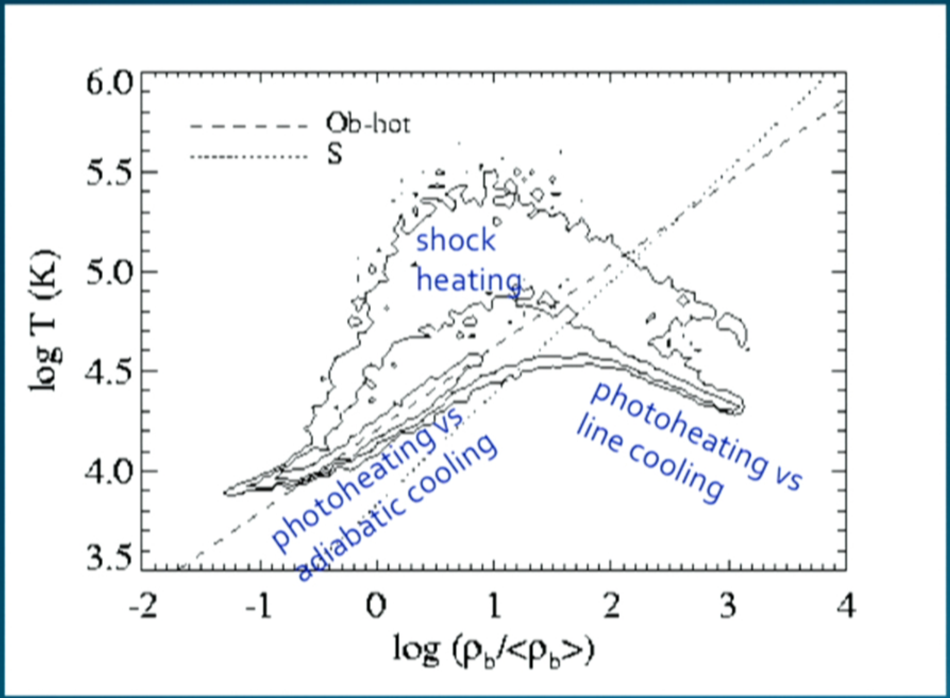
Temperature-density relation of the IGM (optical thin approximation)



$$T \propto \rho^{\gamma-1}$$

$$1 < \gamma < 1.6$$

Schaye et al. 1999

Helium photo-heating?
radiative transfer effects?

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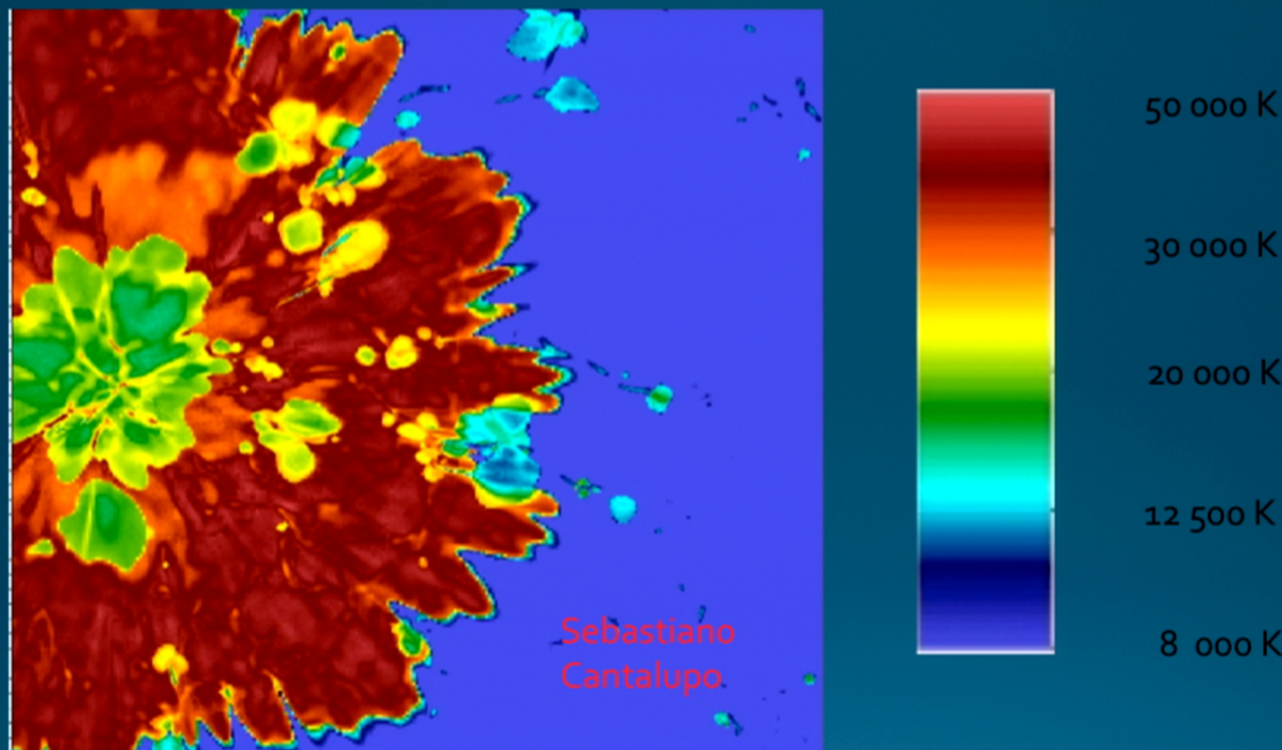
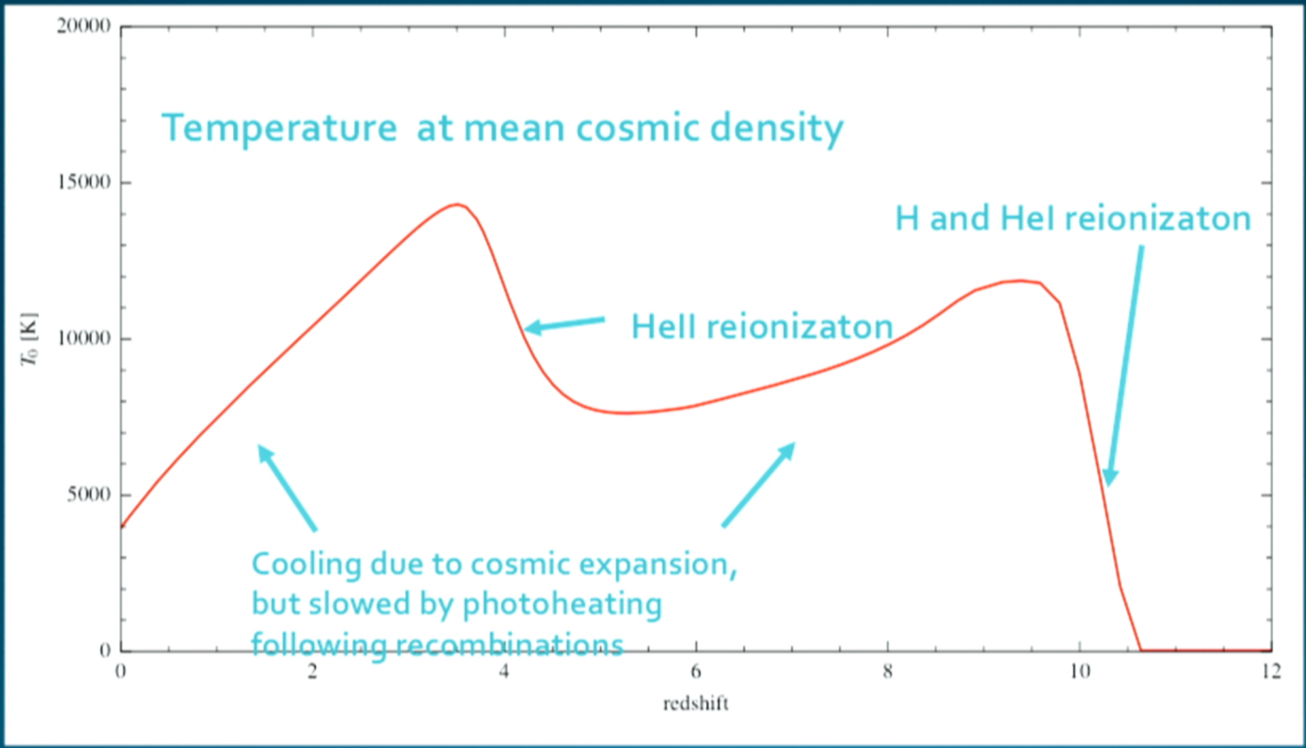
QSO ionization front overtaking HI regions produced by galaxies



The thermal state of the IGM is rather sensitive to how and when hydrogen and helium become reionized.

The thermal history of the IGM

(without blazar heating)



Height and shape of peaks will depend on radiative transfer effects and spectral shape of ionizing sources.

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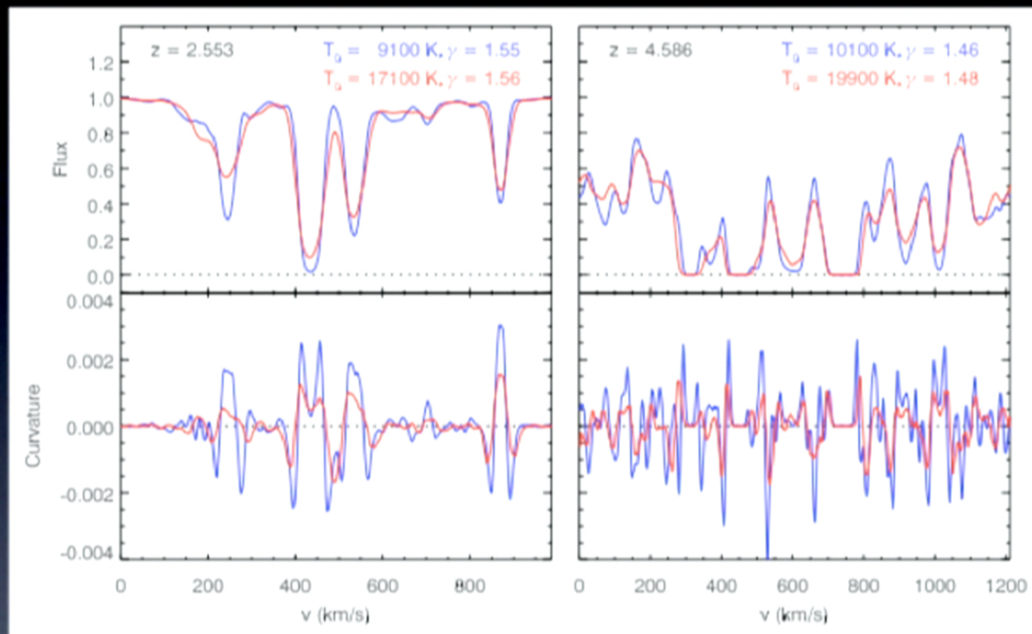
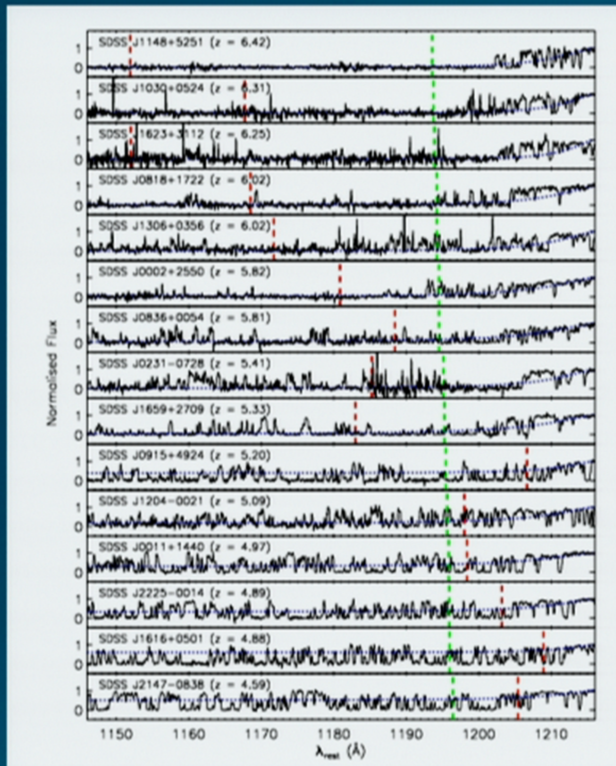
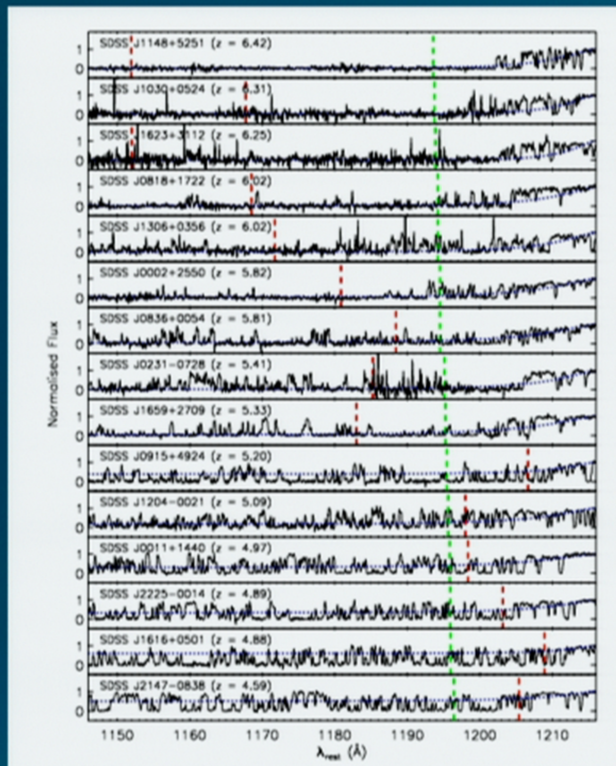
5

Temperature from the Lyα forest



- "Classic" methods of measuring IGM temperatures:
  - Power spectrum / Wavelets — Becker *et al.* (2010)
  - Line widths
- **New method -- Curvature**


SDSS J1148+5251 (z = 6.42)
SDSS J1030+0524 (z = 6.31)
SDSS J1623+3112 (z = 6.25)
SDSS J0818+1722 (z = 6.02)
SDSS J1306+0356 (z = 6.02)
SDSS J0002+2550 (z = 5.82)
SDSS J0836+0054 (z = 5.81)
SDSS J0231−0728 (z = 5.41)
SDSS J1659+2709 (z = 5.33)
SDSS J0915+4924 (z = 5.20)
SDSS J1204−0021 (z = 5.09)
SDSS J0011+1440 (z = 4.97)
SDSS J2225−0014 (z = 4.89)
SDSS J1616+0501 (z = 4.88)
SDSS J2147−0838 (z = 4.59)
Normalised Flux
1150 1160 1170 1180 1190 1200 1210
λrest (Å)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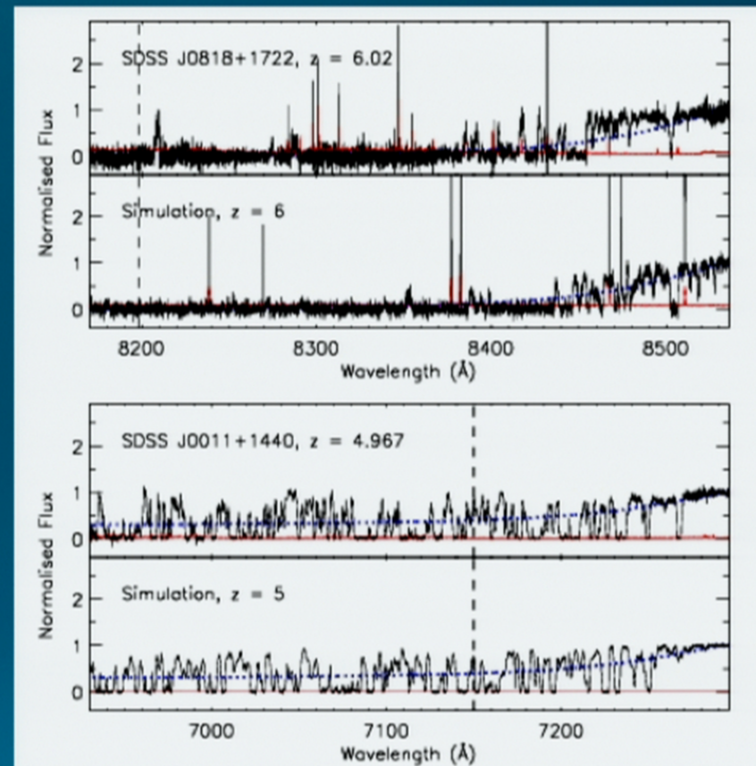
SDSS J2147−0838 (z = 4.59)
Normalised Flux
1150
1160
1170
1180
1190
1200
1210
λrest (Å)


SDSS J0818+1722, z = 6.02
Simulation, z = 6
Normalised Flux
8200
8300
8400
8500
Wavelength (Å)
SDSS J0011+1440, z = 4.967
Simulation, z = 5
Normalised Flux
7000
7100
7200
Wavelength (Å)

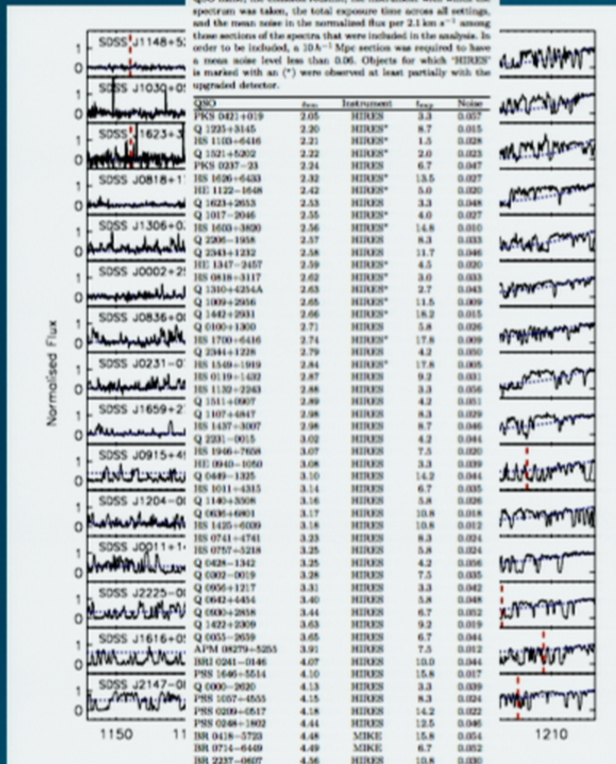
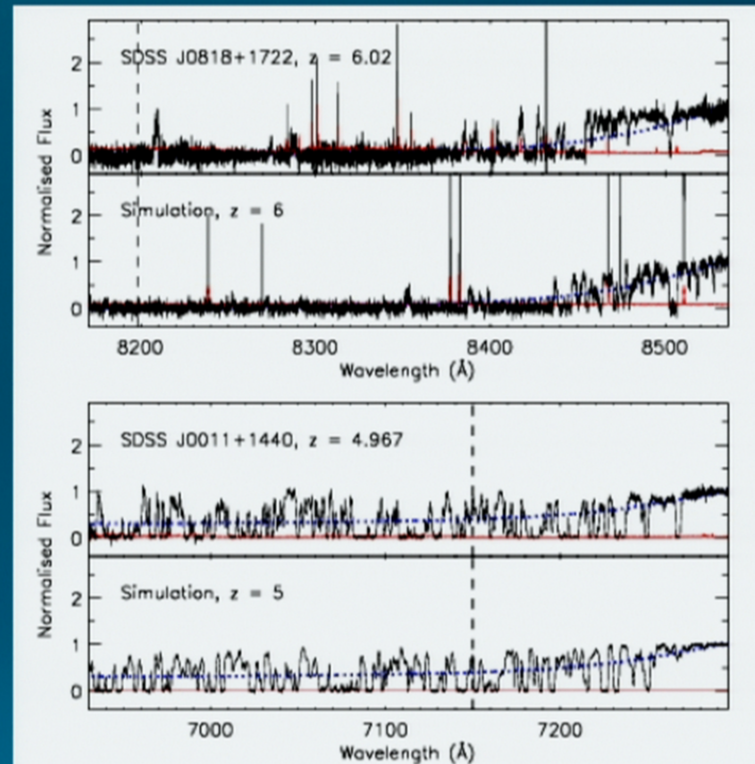


Table 1. List of QSOs analyzed in this work. Columns give the QSO name, the emission redshift, the instrument with which the spectrum was taken, the total exposure time across all settings, and the mean noise in the normalized flux per 2.1 km s^{-1} among those sections of the spectra that were included in the analysis. In order to be included, a 10 h^{-1} Mpc section was required to have a mean noise level less than 0.06. Objects for which 'HIRES' is marked with an (*) were observed at least partially with the upgraded detector.

QSO	z_{em}	Instrument	t_{exp}	Noise
PKS 0421+019	2.05	HIRES	3.3	0.057
Q 1225+3145	2.20	HIRES*	8.7	0.015
HS 1103+6416	2.21	HIRES*	1.5	0.028
Q 1521+5202	2.22	HIRES*	2.0	0.023
PKS 0237−23	2.24	HIRES	6.7	0.047
HS 1626+6433	2.32	HIRES*	13.5	0.027
HE 1122−1648	2.42	HIRES*	5.0	0.020
Q 1623+2653	2.53	HIRES	3.3	0.048
Q 1017−2046	2.55	HIRES*	4.0	0.027
HS 1603+3820	2.56	HIRES*	14.8	0.010
Q 2206−1958	2.57	HIRES	8.3	0.033
Q 2343+1232	2.58	HIRES	11.7	0.046
HE 1347−2457	2.59	HIRES*	4.5	0.020
HS 0818+3117	2.62	HIRES*	3.0	0.033
Q 1310+4254A	2.63	HIRES*	2.7	0.043
Q 1009+2956	2.65	HIRES*	11.5	0.009
Q 1442+2931	2.66	HIRES*	18.2	0.015
Q 0100+1300	2.71	HIRES	5.8	0.026
HS 1700+6416	2.74	HIRES*	17.8	0.009
Q 2344+1228	2.79	HIRES	4.2	0.050
HS 1549+1919	2.84	HIRES*	17.8	0.005
HS 0119+1432	2.87	HIRES	9.2	0.031
HS 1132+2243	2.88	HIRES	3.3	0.056
Q 1511+0907	2.89	HIRES	4.2	0.051
Q 1107+4847	2.98	HIRES	8.3	0.029
HS 1437+3007	2.98	HIRES	8.7	0.046
Q 2231−0015	3.02	HIRES	4.2	0.044
HS 1946+7658	3.07	HIRES	7.5	0.020
HE 0940−1050	3.08	HIRES	3.3	0.039
Q 0449−1325	3.10	HIRES	14.2	0.044
HS 1011+4315	3.14	HIRES	6.7	0.035
Q 1140+3508	3.16	HIRES	5.8	0.026
Q 0636+6801	3.17	HIRES	10.8	0.018
HS 1425+6039	3.18	HIRES	10.8	0.012
HS 0741+4741	3.23	HIRES	8.3	0.024
HS 0757+5218	3.25	HIRES	5.8	0.024
Q 0428−1342	3.25	HIRES	4.2	0.056
Q 0302−0019	3.28	HIRES	7.5	0.035
Q 0956+1217	3.31	HIRES	3.3	0.042
Q 0642+4454	3.40	HIRES	5.8	0.048
Q 0930+2858	3.44	HIRES	6.7	0.052
Q 1422+2309	3.63	HIRES	9.2	0.019
Q 0055−2659	3.65	HIRES	6.7	0.044
APM 08279+5255	3.91	HIRES	7.5	0.012
BRI 0241−0146	4.07	HIRES	10.0	0.044
PSS 1646+5514	4.10	HIRES	15.8	0.017
Q 0000−2620	4.13	HIRES	3.3	0.039
PSS 1057+4555	4.15	HIRES	8.3	0.024
PSS 0209+0517	4.18	HIRES	14.2	0.022
PSS 0248+1802	4.44	HIRES	12.5	0.046
BR 0418−5723	4.48	MIKE	15.8	0.054
BR 0714−6449	4.49	MIKE	6.7	0.052
BR 2237−0607	4.56	HIRES	10.8	0.030
BR 0353−3820	4.59	MIKE	9.2	0.032
SDSS 2147−0838	4.59	MIKE	8.3	0.050
BR 1202−0725	4.69	HIRES*	9.2	0.038
SDSS 0011+1446	4.95	HIRES*	6.7	0.026



Excellent data and accurate simulations are key!

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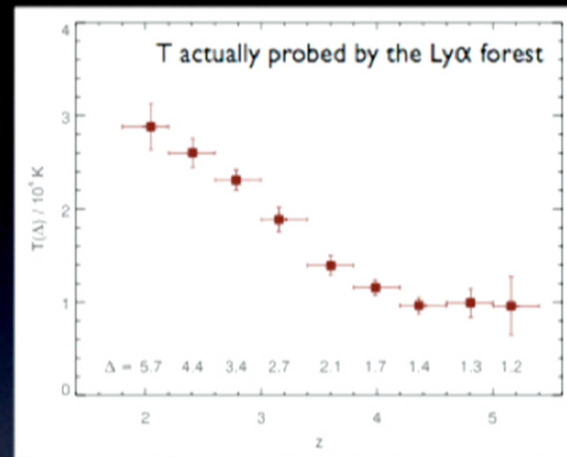
Temperature Measurements

- Compare large set of high-resolution QSO spectra to a suite of hydro simulations
- Measure temperatures in the density range probed by the Lyα forest
- Most precise temperature measurements to date
- Results consistent with extended He II reionization ending at z~3



Becker *et al.* (2010)

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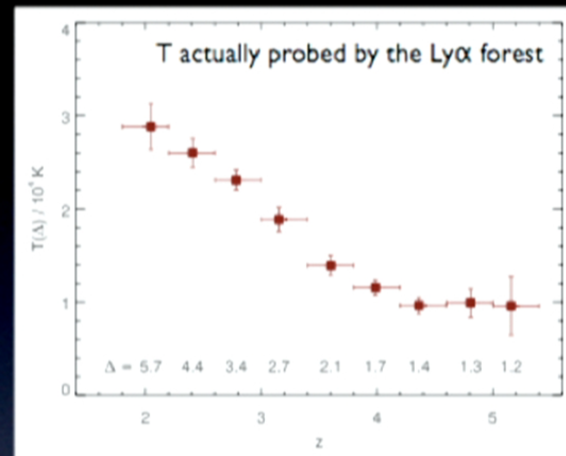

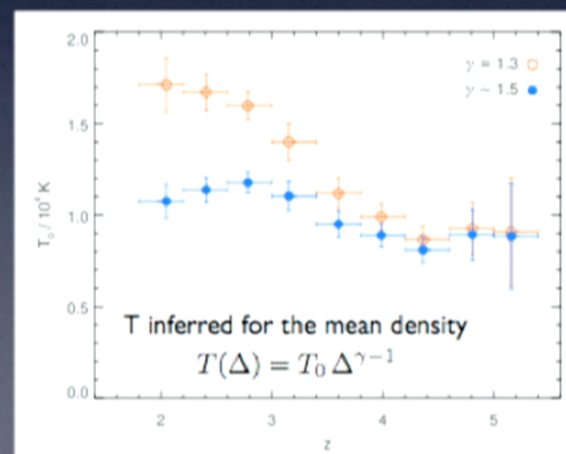

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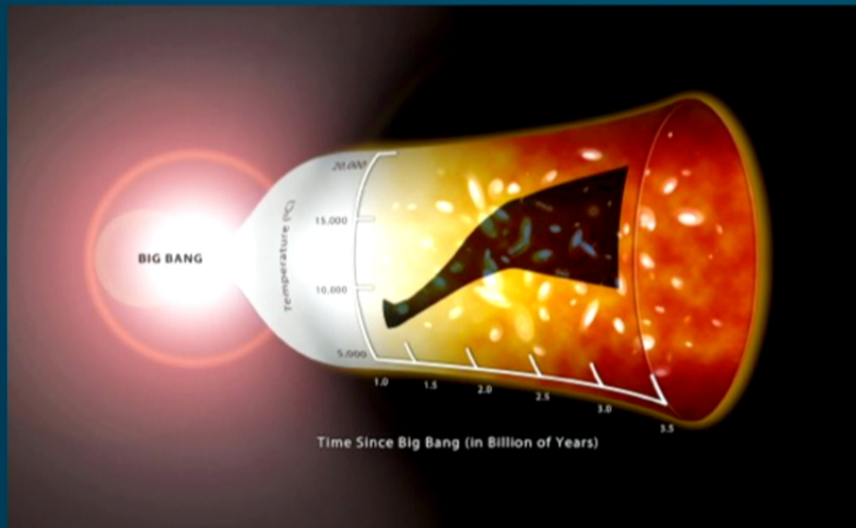

Do we need to re-write the thermal history of the IGM at z<4? (talk in 2011)

Martin Haehnelt

in collaboration with:

Alex Calverley, George Becker , James Bolton, Matteo Viel, Sudhir Raskutti, Wal Sargent, Stuart Wyithe

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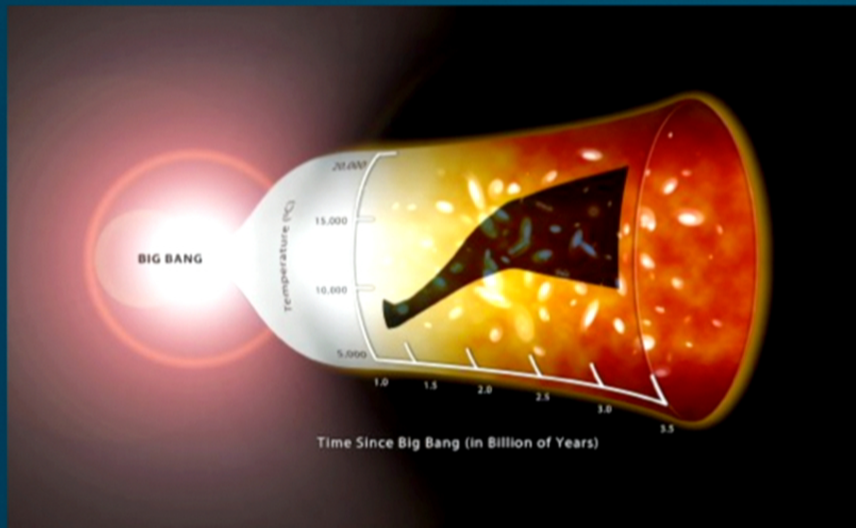

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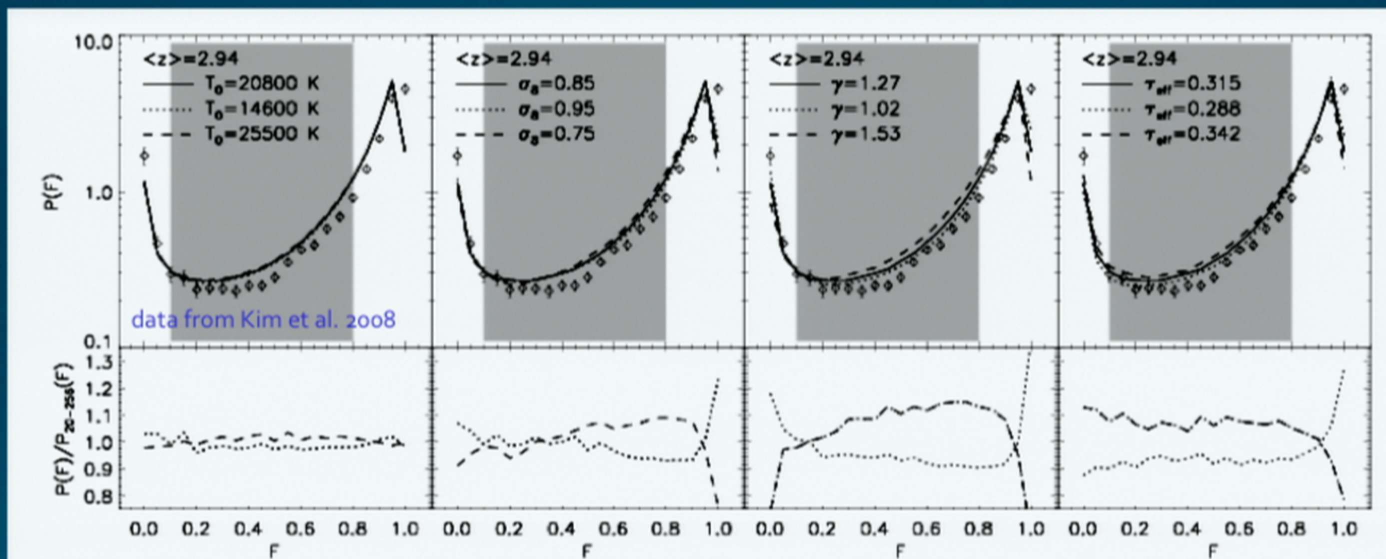
“Problems” with the flux PDF

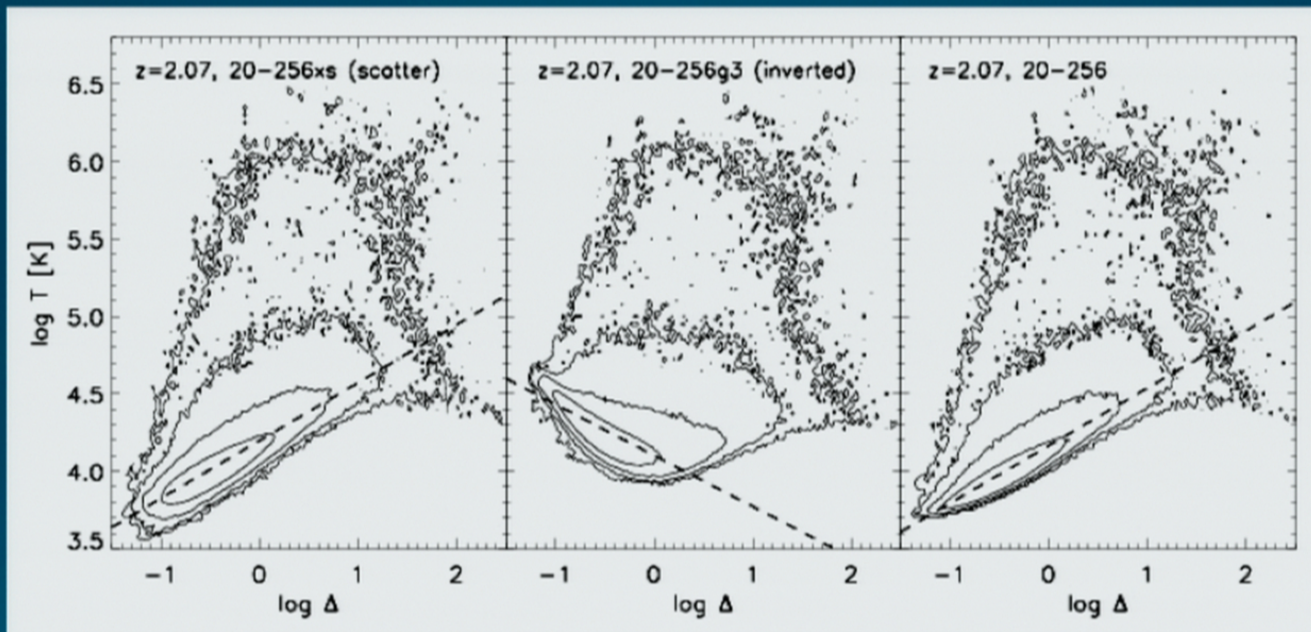
Possible evidence for an inverted temperature–density relation in the intergalactic medium from the flux distribution of the Lyα forest

J. S. Bolton,[1★] M. Viel,[2,3] T.-S. Kim,[4] M. G. Haehnelt[5] and R. F. Carswell[5]



The shape of the flux PDF depends mainly on the slope of the temperature-density relation and the effective optical depth.

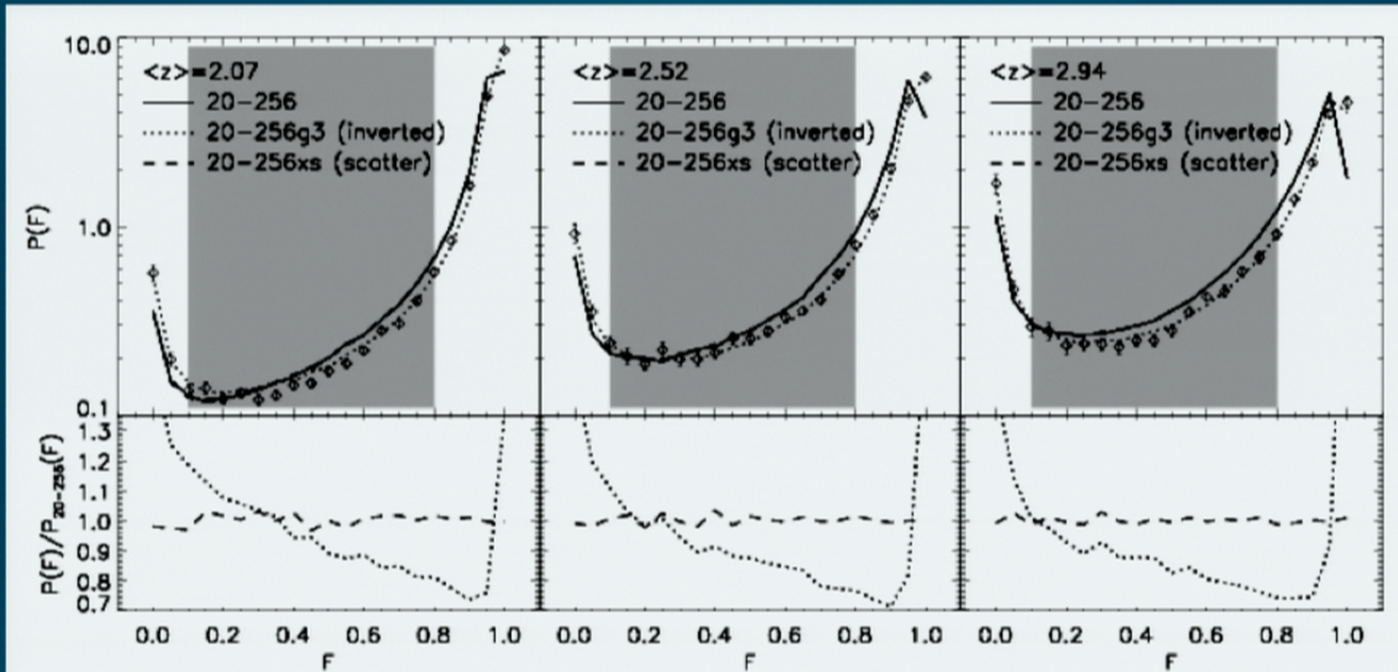
An inverted temperature density relation?



Recombination coefficient: $\alpha \propto T^{-0.7}$

→ hotter gas absorbs less

Bolton et al. 2008



Bolton et al. 2008

Underdense regions appear to be hotter than generally assumed!
Radiative transfer effects during helium reionization?
Other heating processes?

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Finally, we must also not lose sight of the possibility that other processes may contribute to the heating of the IGM (e.g. Madau & Efstathiou 1999; Nath, Sethi & Shchekinov 1999; Inoue & Kamaya 2003; Ricotti & Ostriker 2004; Samui, Subramanian & Srianand 2005). Our results may instead indicate that an alternative modification to the current models for the Lyα forest and the thermal state of the IGM is required.

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It is, however, difficult to heat the voids!

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THE COSMOLOGICAL IMPACT OF LUMINOUS TEV BLAZARS I:
IMPLICATIONS OF PLASMA INSTABILITIES FOR THE INTERGALACTIC MAGNETIC FIELD AND EXTRAGALACTIC GAMMA-RAY BACKGROUND

AVERY E. BRODERICK[1,2,3], PHILIP CHANG[1,4], AND CHRISTOPH PFROMMER[5,1]

THE COSMOLOGICAL IMPACT OF LUMINOUS TEV BLAZARS II:
REWRITING THE THERMAL HISTORY OF THE INTERGALACTIC MEDIUM

PHILIP CHANG[1,2], AVERY E. BRODERICK[1,3,4], AND CHRISTOPH PFROMMER[5,1]

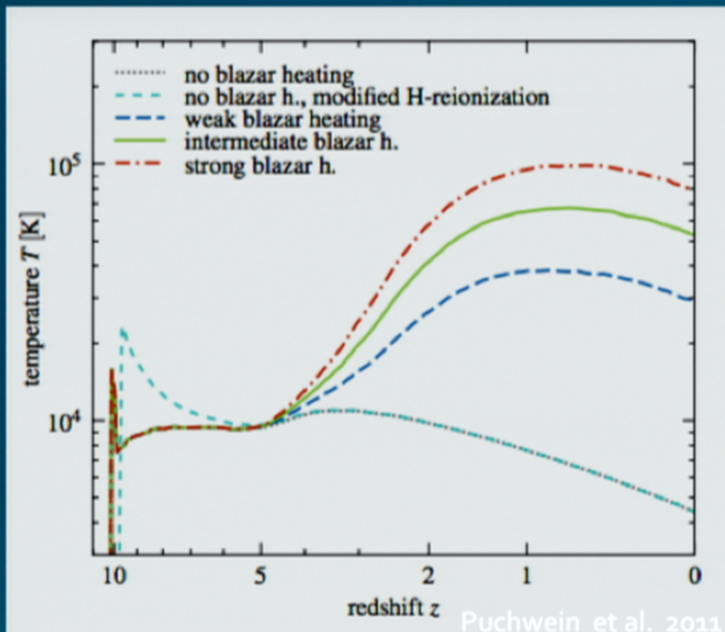
THE COSMOLOGICAL IMPACT OF LUMINOUS TEV BLAZARS III:
IMPLICATIONS FOR GALAXY CLUSTERS AND THE FORMATION OF DWARF GALAXIES

CHRISTOPH PFROMMER[1,2], PHILIP CHANG[2,3], AND AVERY E. BRODERICK[2,4,5]

The Lyman-α forest in a blazar-heated Universe

Ewald Puchwein[1⋆], Christoph Pfrommer[1], Volker Springel[1,2],
Avery E. Broderick[3,4,5], and Philip Chang[3,6]

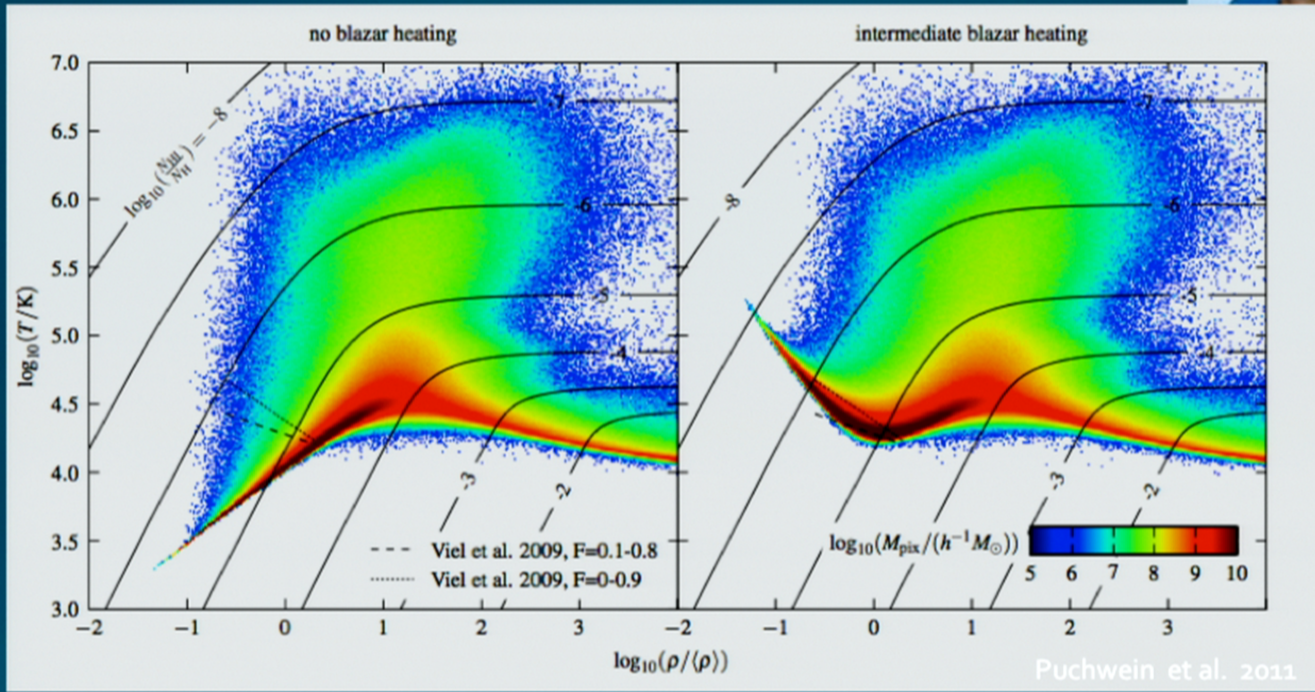
A new thermal history?



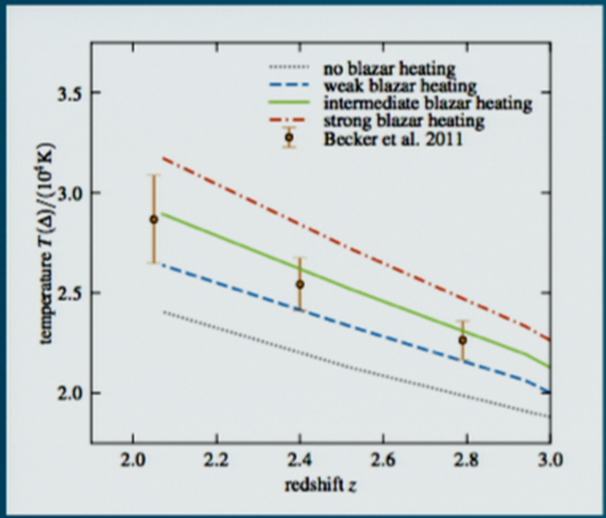
Puchwein et al. 2011

The relativistic electron-positron jets produced when TeV photons from blazars hit a CMB or IR background photon are proposed to loose their energy by collective plasma instabilities instead of Inverse Compton scattering as has been the standard asssumption. The corresponding IGM heating rate could significantly exceed the photoheating rate.

An inverted temperature density relation?

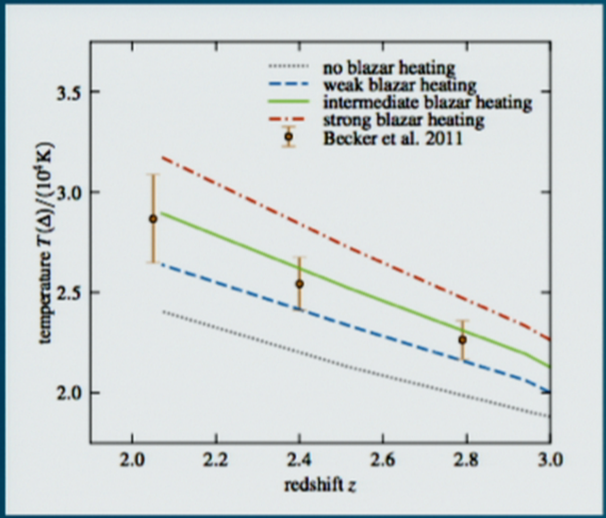


The heating is "volumetric" and exceeds photoheating in underdense regions. At low densities this results in a temperature rising with decreasing density.

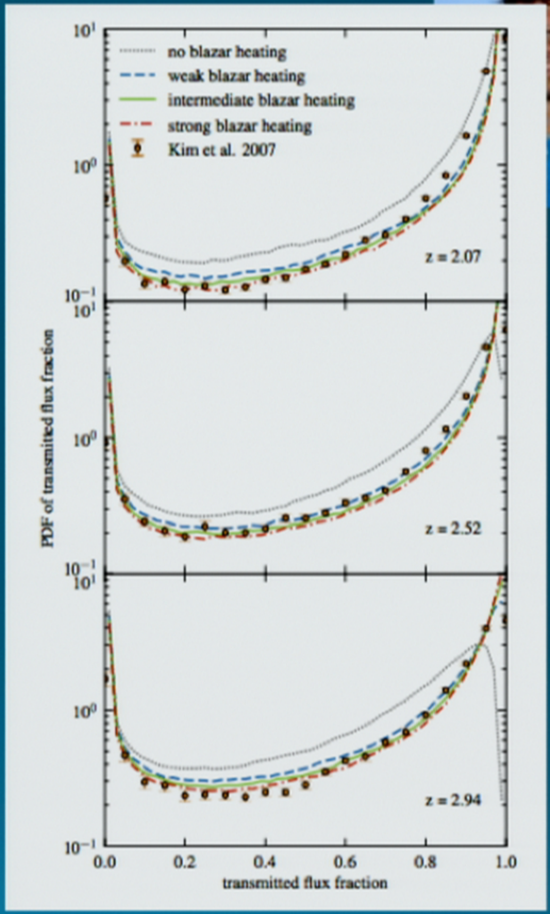


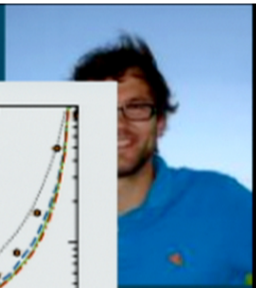
Puchwein et al. 2011

- the temperature evolution appears to fit



Puchwein et al. 2011





- the temperature evolution appears to fit

- the flux PDF looks promising

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Summary of talk in 2011

- ✧ accurate measurement of rising IGM temperature at 2<z<5
- ✧ tantalizing evidence for "hot" voids from flux PDF
- ✧ TeV blazars proposed to heat IGM "volumetrically" by plasma beam instabilities

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Summary of talk in 2011

- ✧ accurate measurement of rising IGM temperature at $2<z<5$
- ✧ tantalizing evidence for "hot" voids from flux PDF
- ✧ TeV blazars proposed to heat IGM "volumetrically" by plasma beam instabilities

What next?

- ➢ encourage plasma physicists to have a closer look
- ➢ scrutinize effect on Lyα more quantitatively
- ➢ explore the effect on IGM, galaxies and ICM
- ➢ look for independent evidence for or against high space density of TeV blazars at high redshift

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Should we take the flux PDF discrepancy seriously ?

Perimeter, 15 March 2016

THE ASTROPHYSICAL JOURNAL, 753:136 (7pp), 2012 July 10
doi:10.1088/0004-637X/753/2/136

SYSTEMATIC CONTINUUM ERRORS IN THE Lyα FOREST AND THE MEASURED TEMPERATURE–DENSITY RELATION

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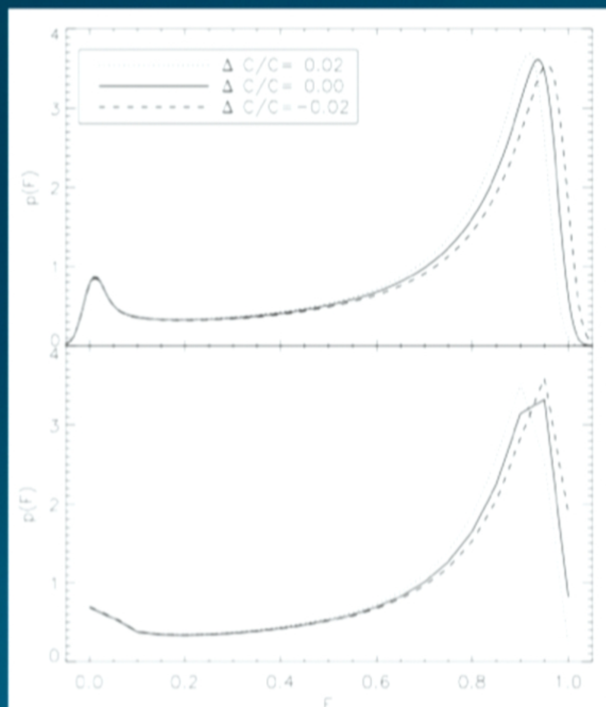
Received 2011 March 14; accepted 2012 May 8; published 2012 June 22



Continuum corrections go into the "right" direction for removing the discrepancy at low flux levels.

MNRAS **428,** 540–550 (2013) doi:10.1093/mnras/sts057

Sample variance and Lyman α forest transmission statistics

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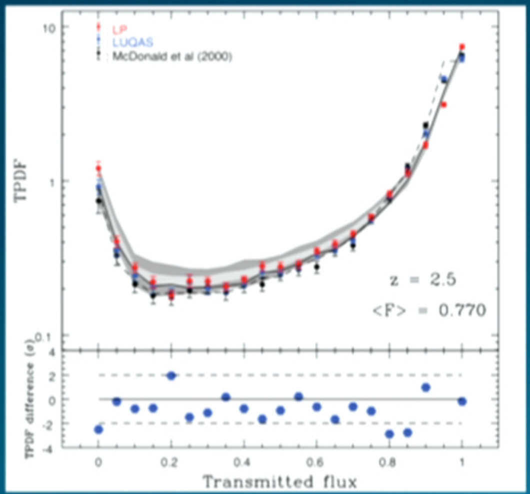
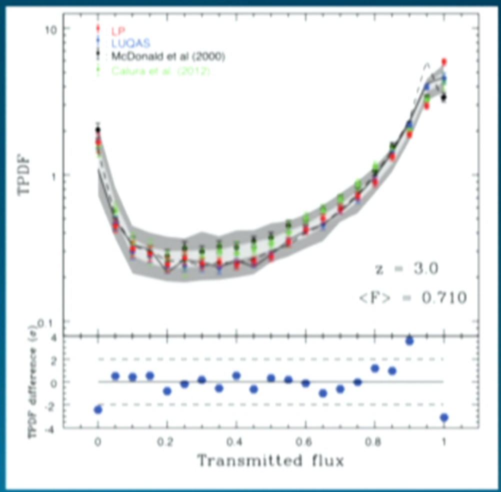
[2] *Institute of Computational Cosmology, Department of Physics, University of Durham, Science Laboratories, South Road, Durham DH1 3LE*
[3] *Universiteit Antwerpen, Campus Groenenborger, Groenenborgerlaan 171, B-2020 Antwerpen, Belgium*
[4] *Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, the Netherlands*





Improved measurements from Doppler parameters

Perimeter, 15 March 2016

The Astrophysical Journal Letters, 757:L30 (6pp), 2012 October 1
doi:10.1088/2041-8205/757/2/L30

THE TEMPERATURE–DENSITY RELATION IN THE INTERGALACTIC MEDIUM AT REDSHIFT $\langle z \rangle = 2.4$*

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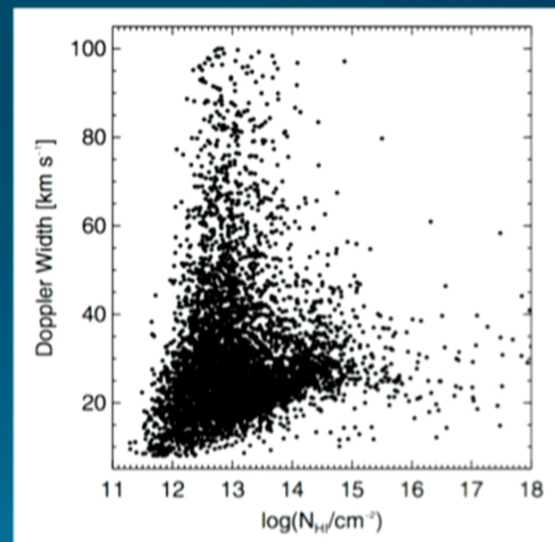
Received 2012 July 20; accepted 2012 August 30; published 2012 September 17

The Astrophysical Journal Letters, 757:L30 (6pp), 2012 October 1

Table 1
KBSS Absorption Line Sample

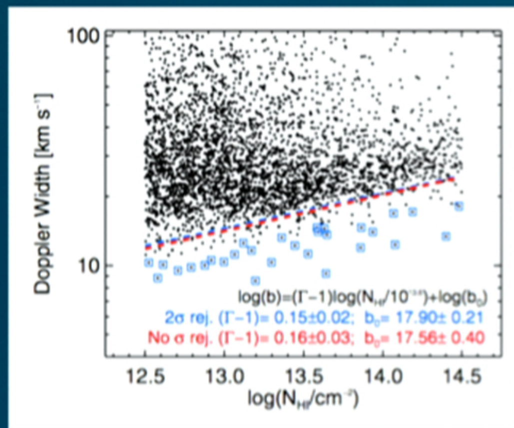
Name	z_{QSO}[a]	$z_{Ly\alpha}$ Range	S/N[b] Lyα	S/N[b] Lyβ
Q0100+130 (PHL957)	2.721	2.0617–2.6838	77	50
HS0105+1619	2.652	2.1561–2.6153	127	89
Q0142−09 (UM673a)	2.743	2.0260–2.7060	71	45
Q0207−003 (UM402)	2.872	2.1532–2.8339	82	55
Q0449−1645	2.684	2.0792–2.6470	73	41
Q0821+3107	2.616	2.1650–2.5794	50	33
Q1009+29 (CSO 38)	2.652	2.1132–2.6031	99	58
SBS1217+499	2.704	2.0273–2.6669	68	38
HS1442+2931	2.660	2.0798–2.6237	99	47
HS1549+1919	2.843	2.0926–2.8048	173	74
HS1603+3820	2.551	2.1087–2.5066	108	58
Q1623+268 (KP77)	2.535	2.0544–2.4999	48	28
HS1700+64	2.751	2.0668–2.7138	98	42
Q2206−199	2.573	2.0133–2.5373	88	46
Q2343+125	2.573	2.0884–2.5373	71	45

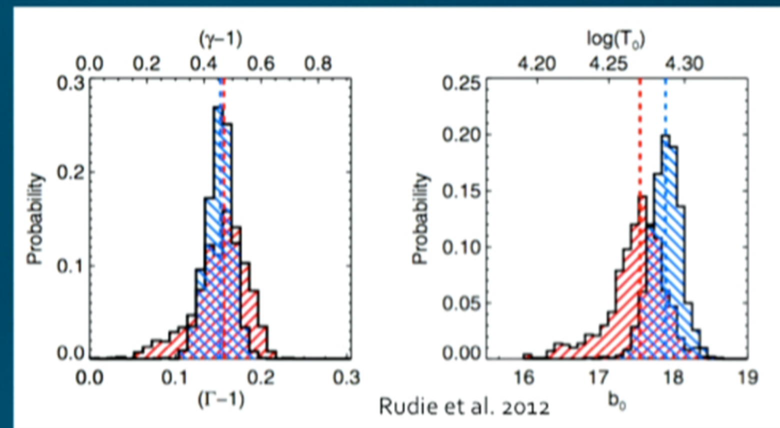
Notes.
[a] The redshift of the QSO (Trainor & Steidel 2012).
[b] The average signal-to-noise ratio per pixel of the QSO spectrum in the wavelength range pertaining to Lyα and Lyβ absorption.



A very large homogeneous sample in a narrow redshift range

Perimeter, 15 March 2016





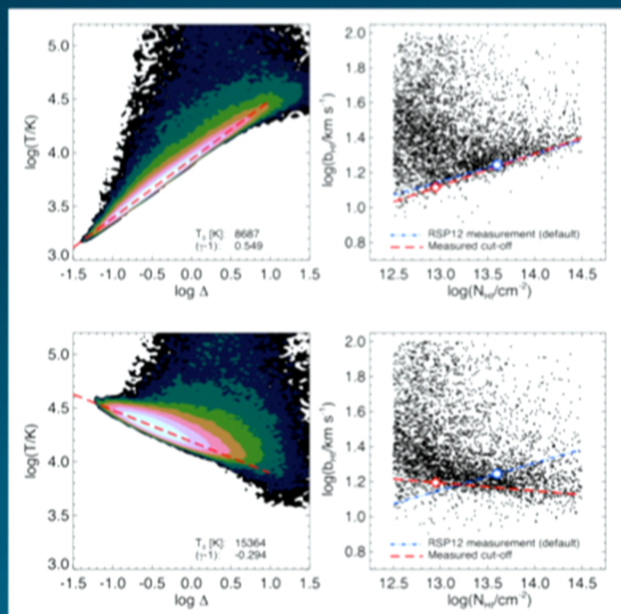
This gives a high $\gamma = 1.46 \pm 0.05$.

Advance Access publication 2014 January 10

A consistent determination of the temperature of the intergalactic medium at redshift $\langle z \rangle = 2.4$

James S. Bolton,[1★] George D. Becker,[2] Martin G. Haehnelt[2] and Matteo Viel[3,4]

[1]*School of Physics and Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, UK*
[2]*Kavli Institute for Cosmology and Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK*
[3]*INAF - Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, I-34131 Trieste, Italy*
[4]*INFN/National Institute for Nuclear Physics, Via Valerio 2, I-34127 Trieste, Italy*



We got $\gamma = 1.54 \pm 0.11$
and thus confirmed the high
value of Rudie et al. 2012.

erc
European Research Council

Advance Access publication 2014 January 10

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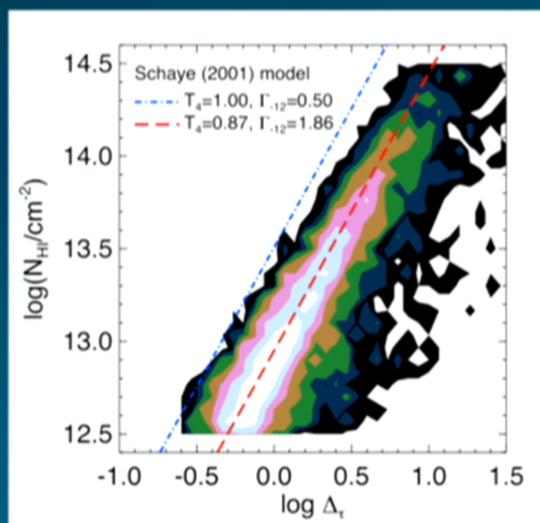
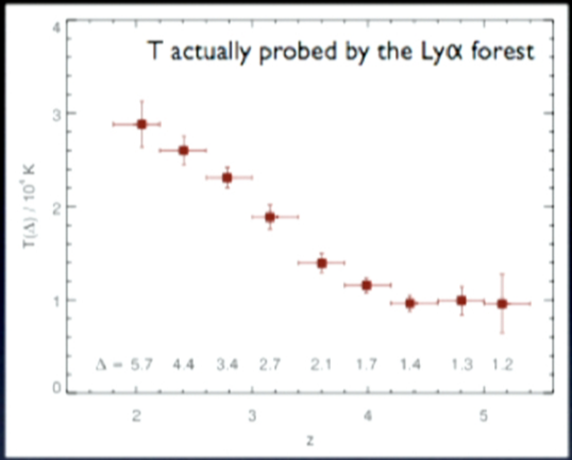


But Rudie et a al. assumed an inappropriate normalisation for the density-column density Relation. This lowers the inferred Temperature at mean density by almost a factor 2.

Temperature Measurements



- Compare large set of high-resolution QSO spectra to a suite of hydro simulations
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- Most precise temperature measurements to date
- Results consistent with extended He II reionization ending at z~3

$$T \propto \rho^{(\gamma-1)}$$

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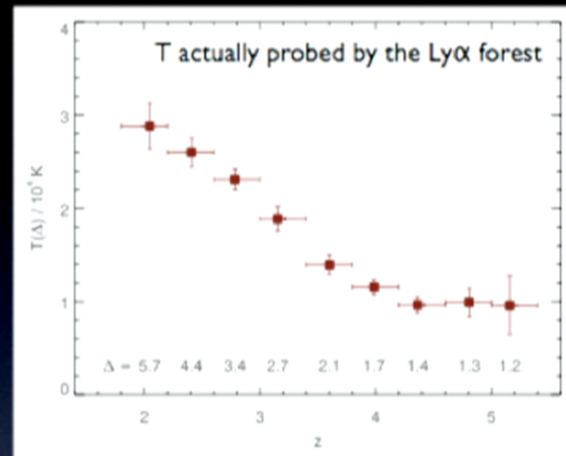
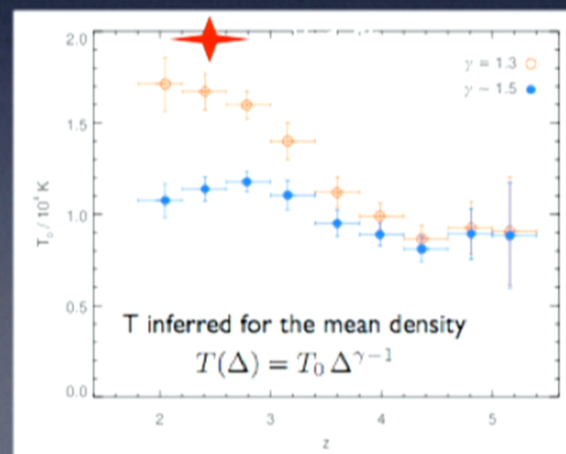
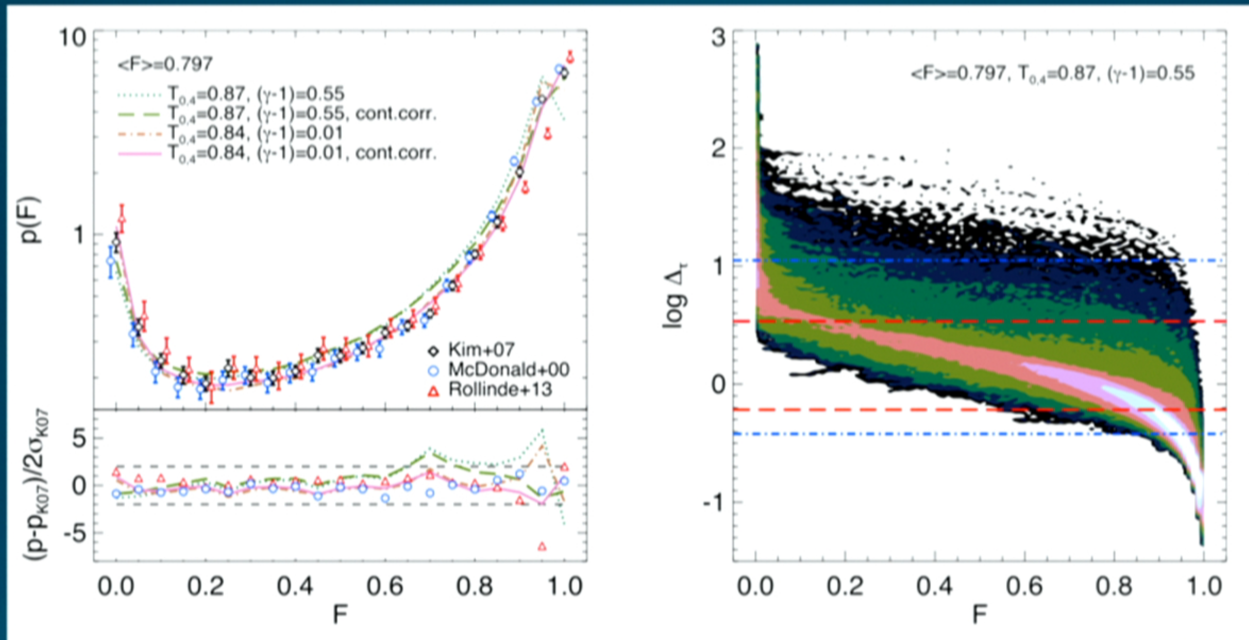


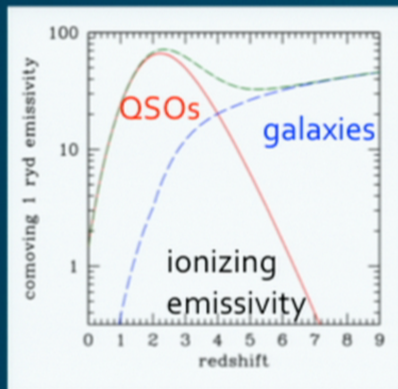


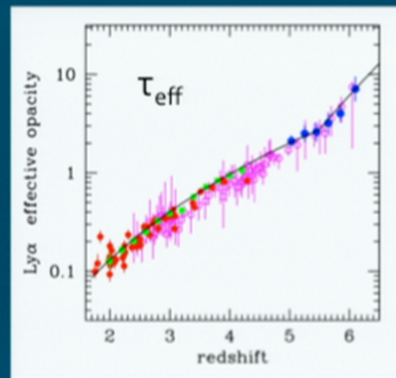


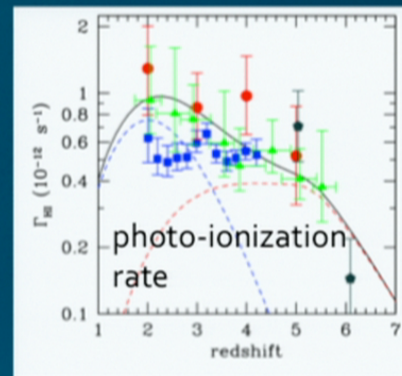
Perimeter, 15 March 2016

Modelling

Haardt& Madau 2012 – The benchmark model







This assumes reionization is driven by faint! galaxies

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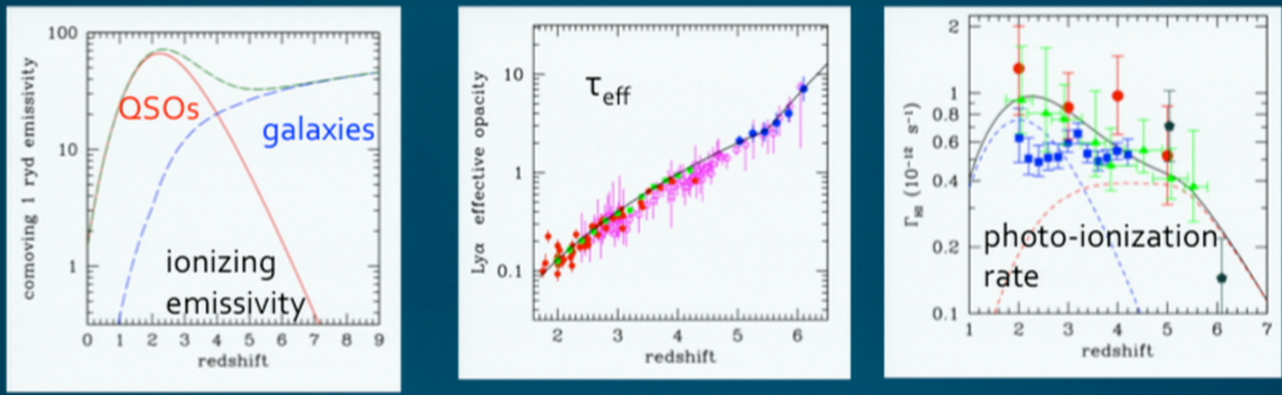
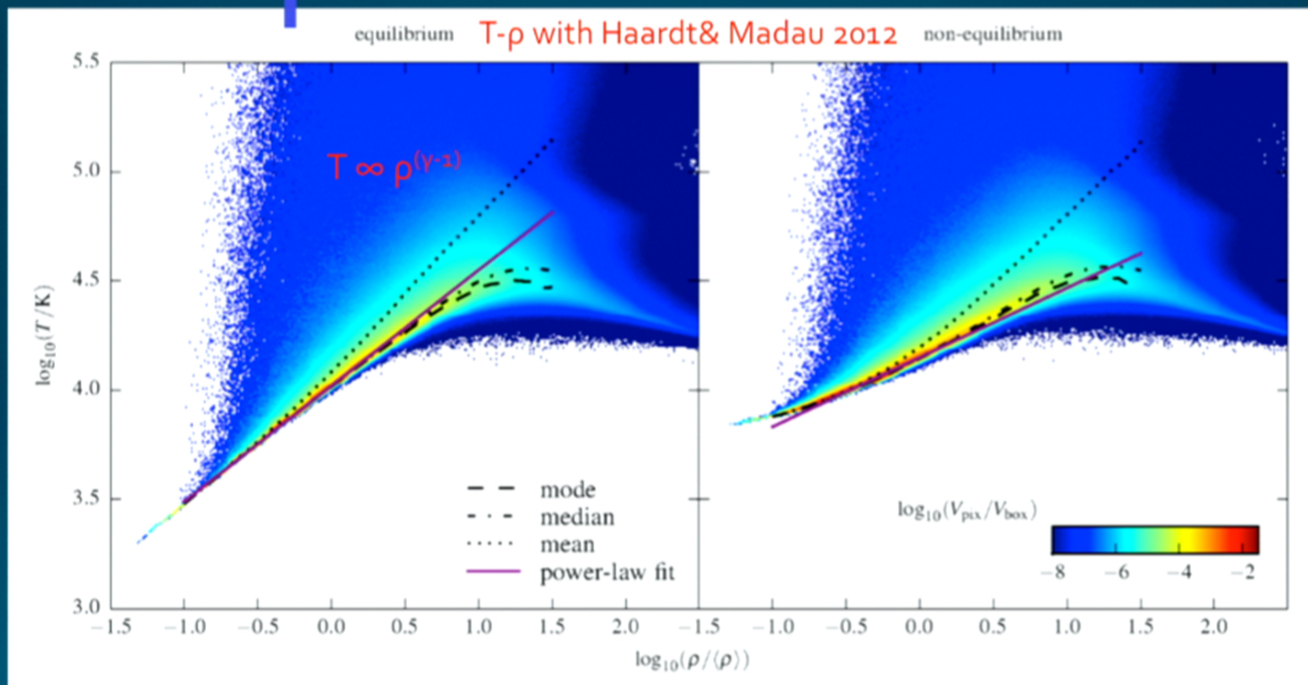


This assumes reionization is driven by faint! galaxies

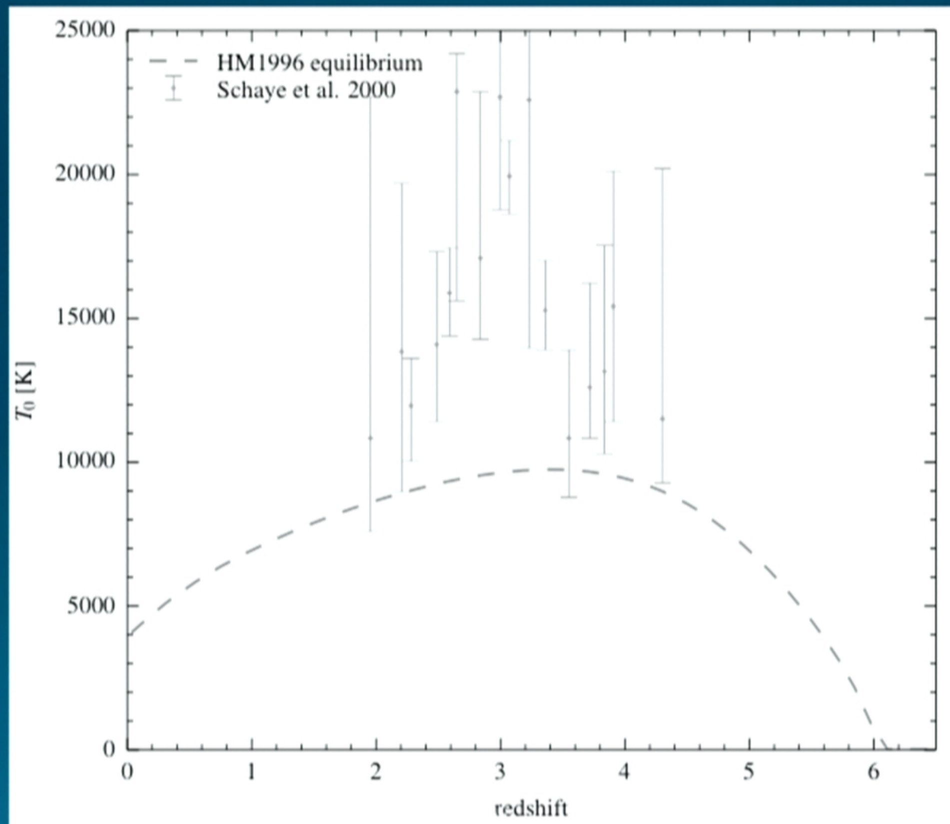
The photoheating of the intergalactic medium in synthesis models of the UV background

Ewald Puchwein,[1★] James S. Bolton,[2] Martin G. Haehnelt,[1] Piero Madau,[3,4] George D. Becker[1] and Francesco Haardt[5,6]



Taking non-equilibrium effects during the reionization and helium affects the temperatures noticably.

The thermal history of the IGM
(first without blazar heating)



vein et al.

33

The thermal history of the IGM

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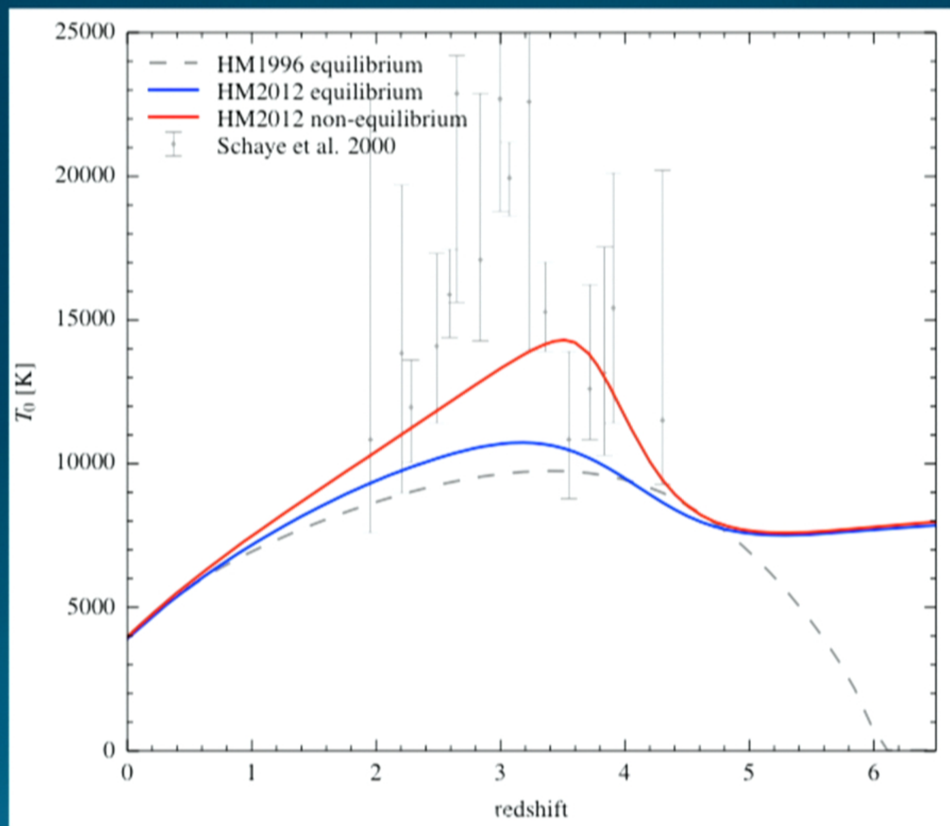

…vein et al.

35

The thermal history of the IGM

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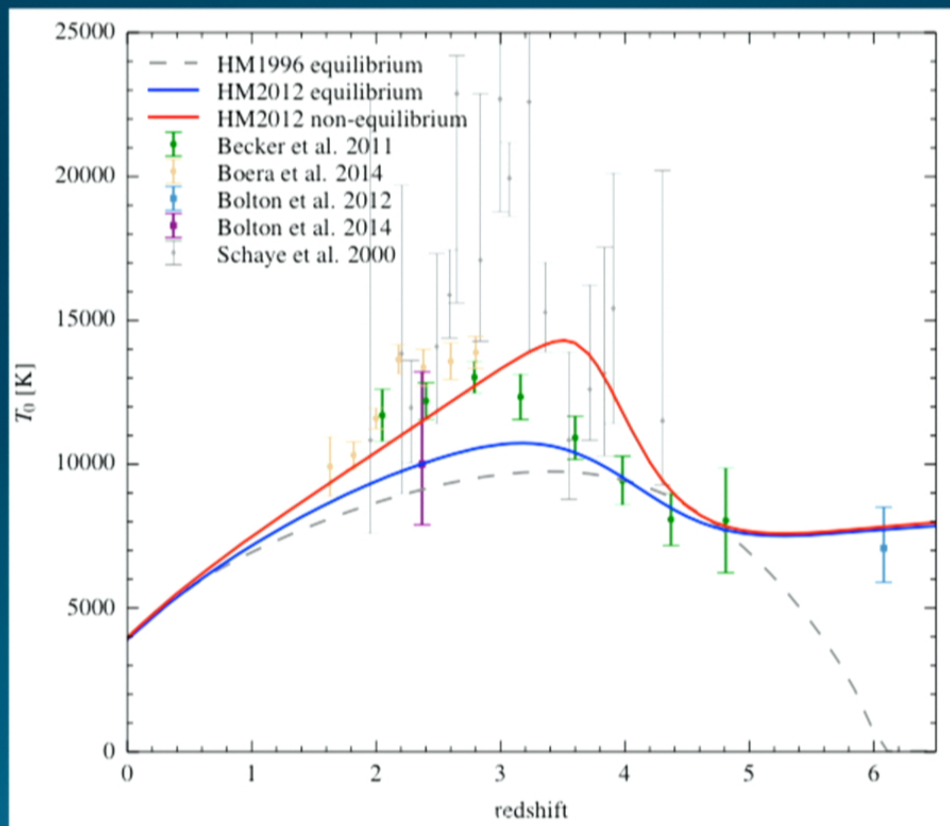

vein et al.

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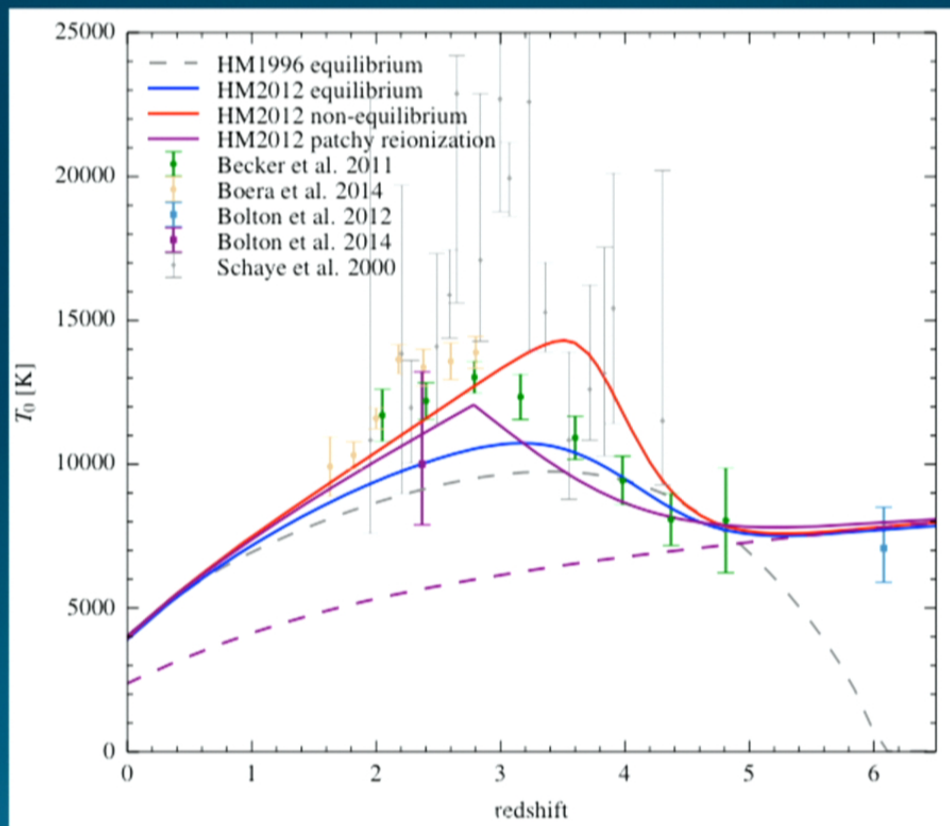
The thermal history of the IGM

(first without blazar heating)



vein et al.

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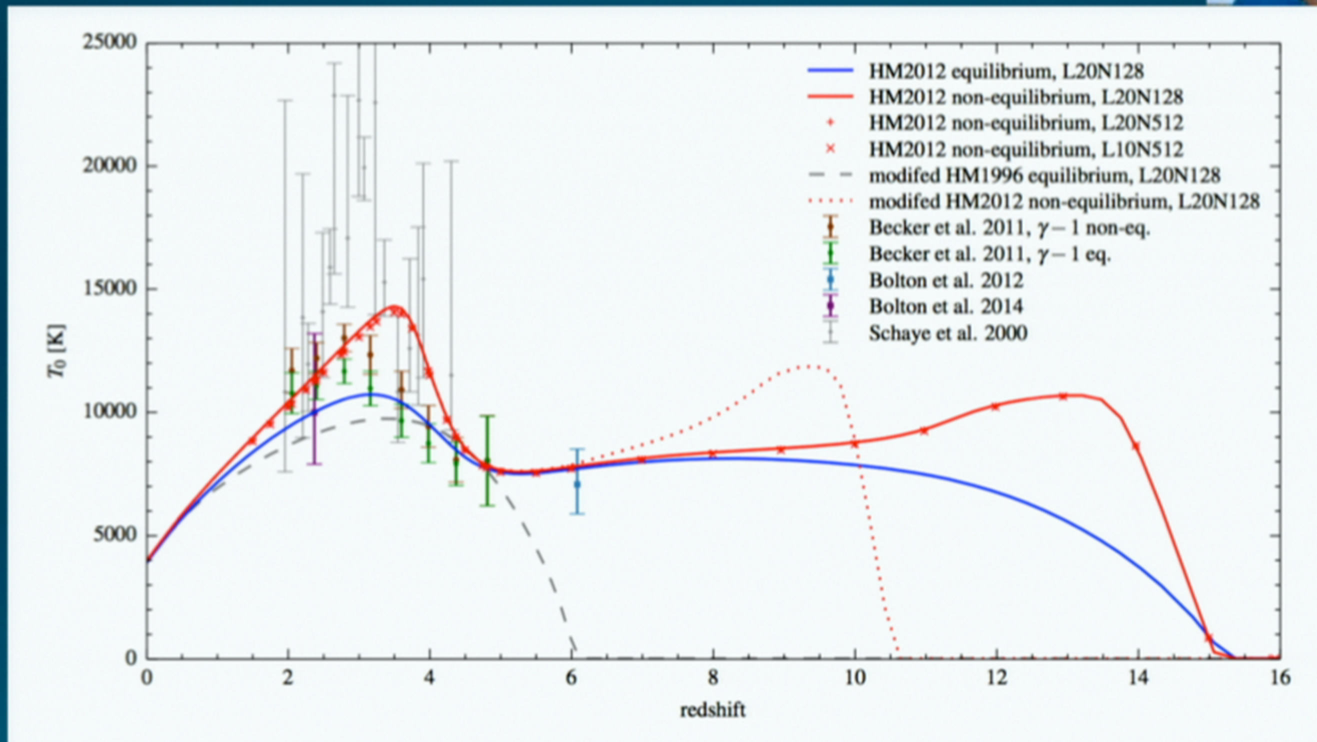
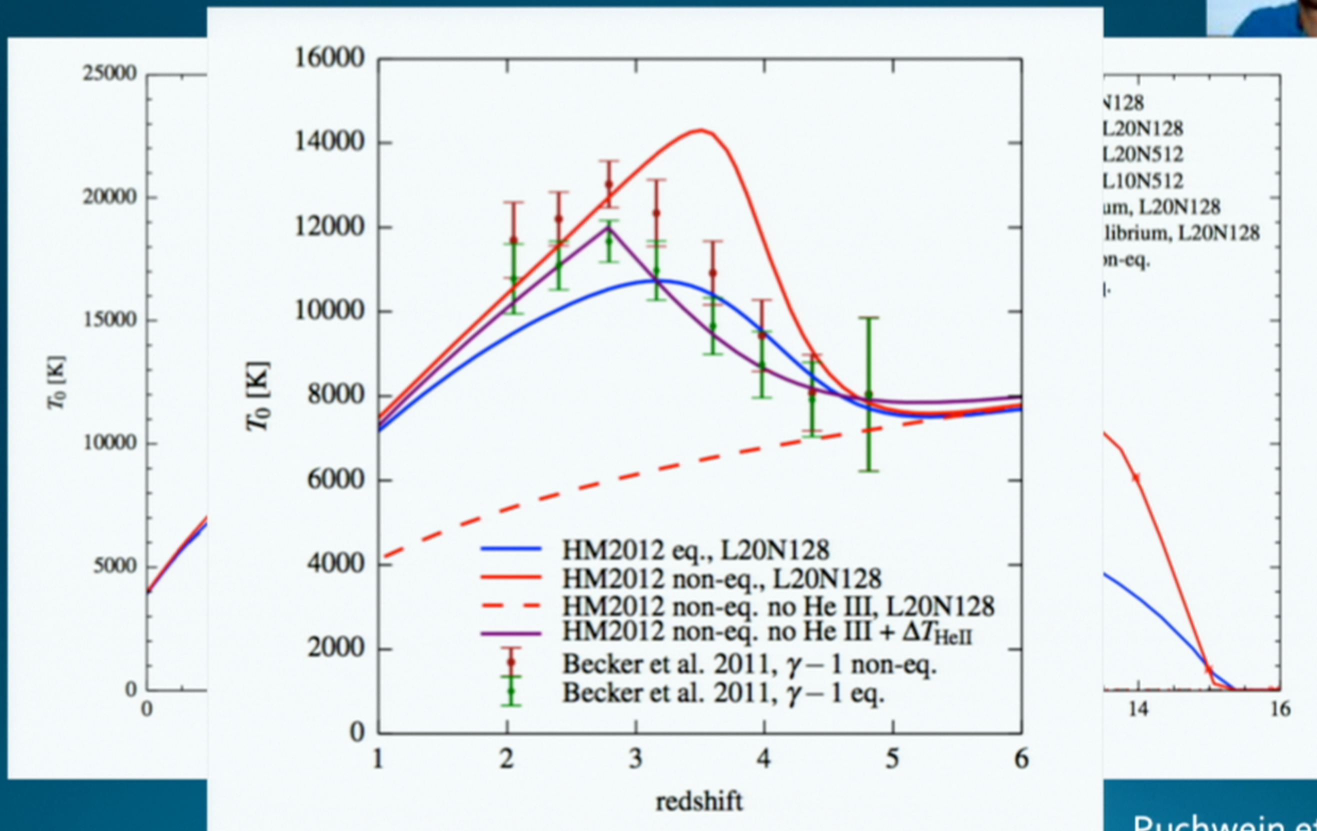
The thermal history with Haardt& Madau 2012



Puchwein et al. 2014

The thermal history with Haardt& Madau 2012



Puchwein et al. 2014

Works remarkably well with non-equilibrium solver once corrected for HeIII volum filling factor


What is new?
erc
Perimeter, 15 March 2016
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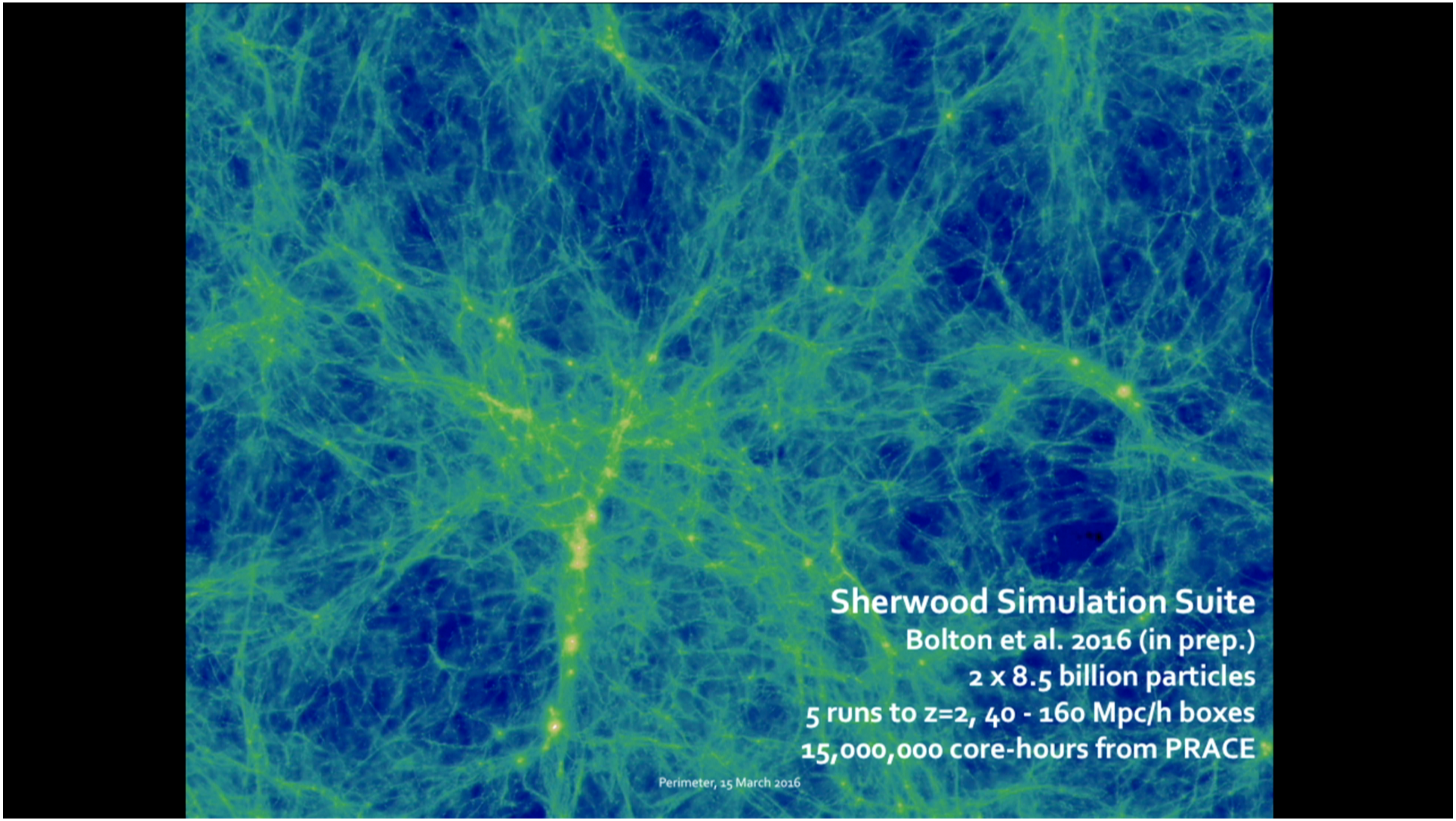
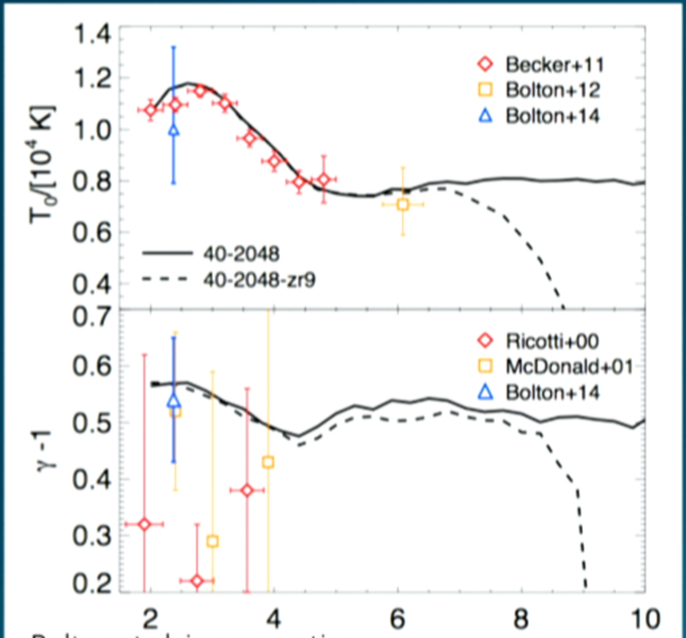
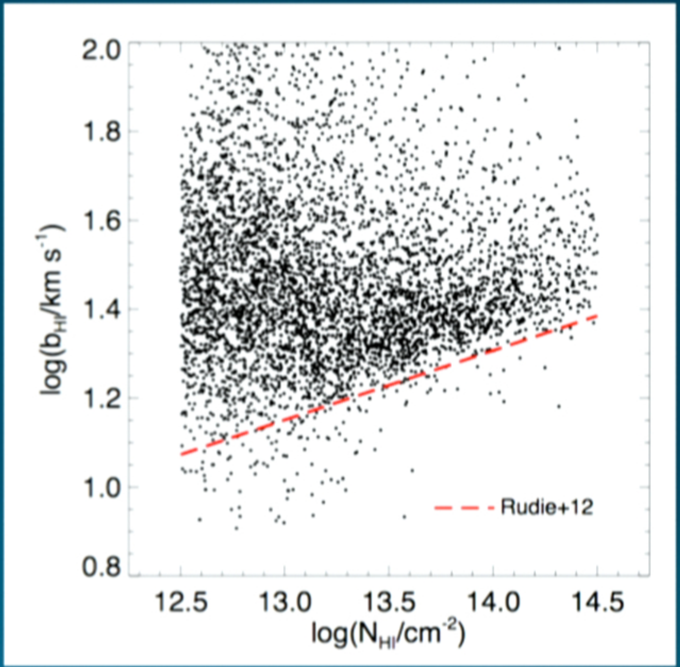

Sherwood Simulation Suite
Bolton et al. 2016 (in prep.)
2 x 8.5 billion particles
5 runs to z=2, 40 - 160 Mpc/h boxes
15,000,000 core-hours from PRACE
Perimeter, 15 March 2016

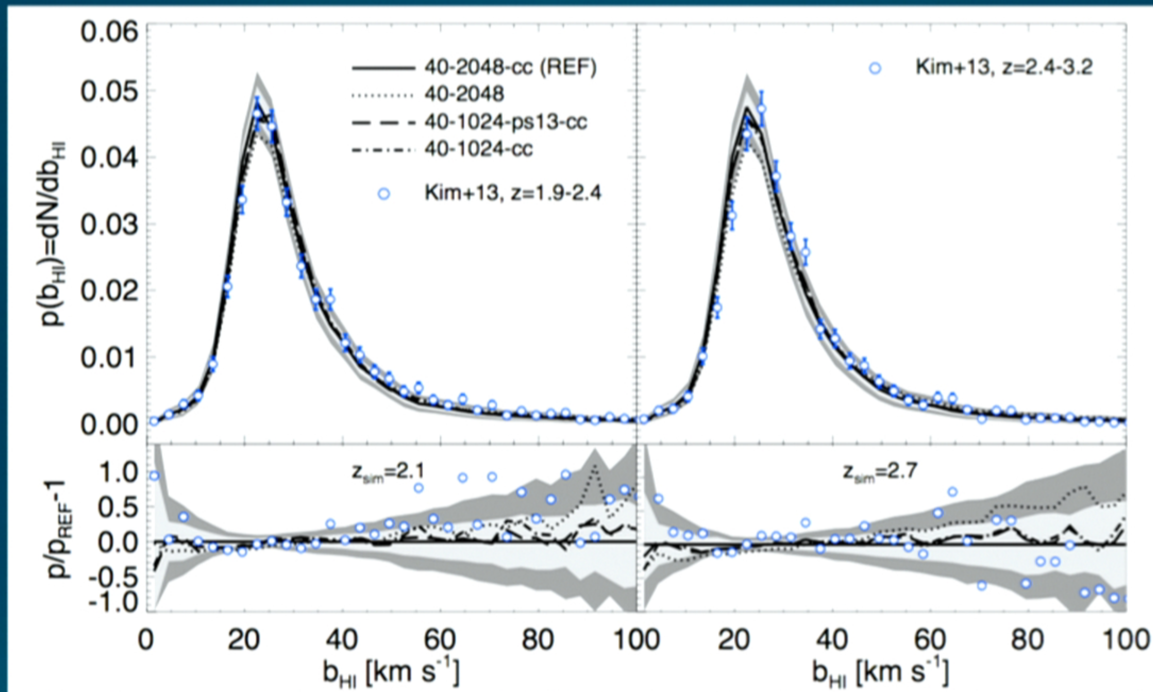
Well matched thermal evolution by contruction



Bolton et al. in preparation

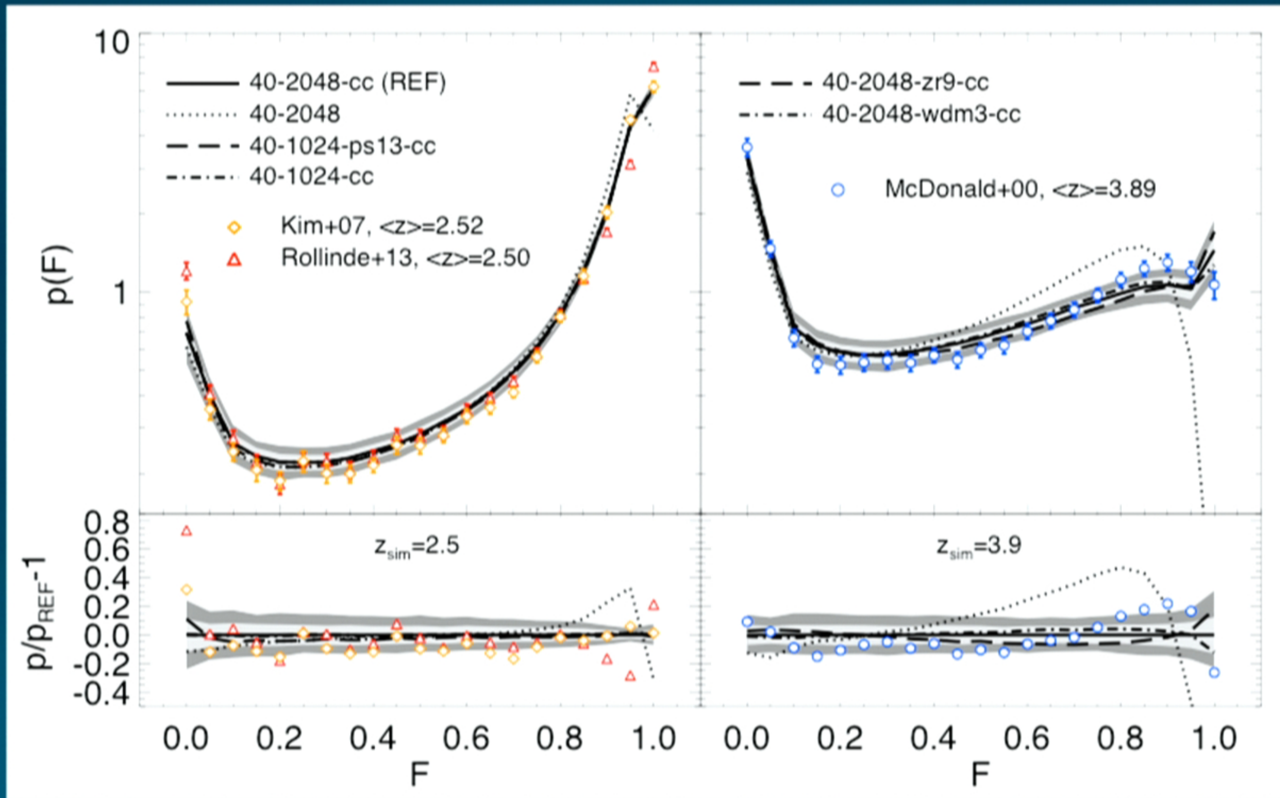


Cut-off in b-N distribution well reproduced



Doppler parameter distribution fits remarkably well

Constraints from the flux PDF

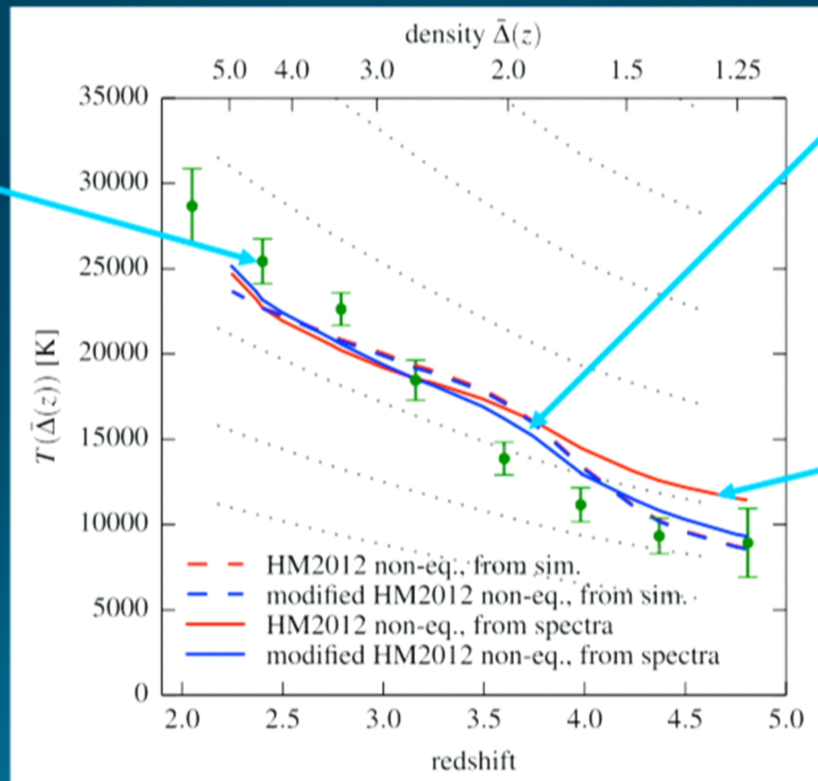


on et al. 2016 (in prep.)

But

Temperature at the density probed by the Lyman-alpha forest

Missing heating at low z ?



Probably slightly too early HeII reionization in simulations with Haardt & Madau 2012

Bias due to different Jeans smoothing (compared to calibrations simulations)

vein et al. 2015

46

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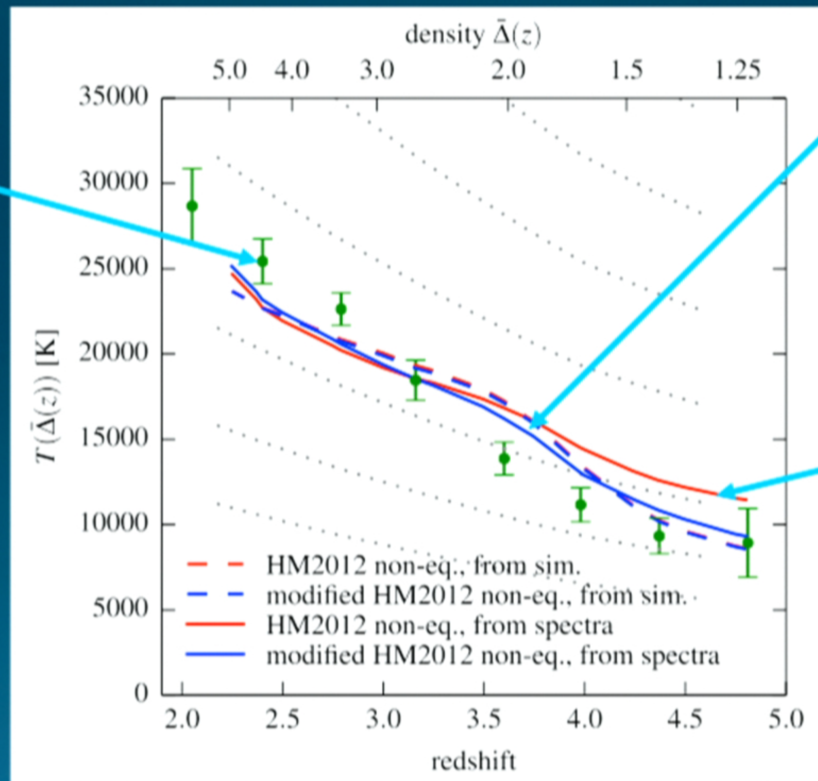

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vein et al. 2015

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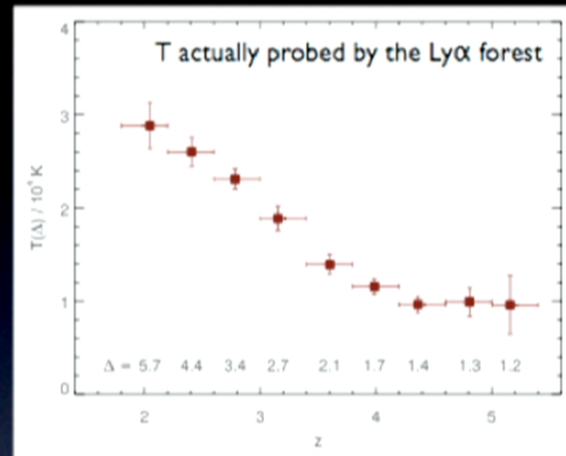
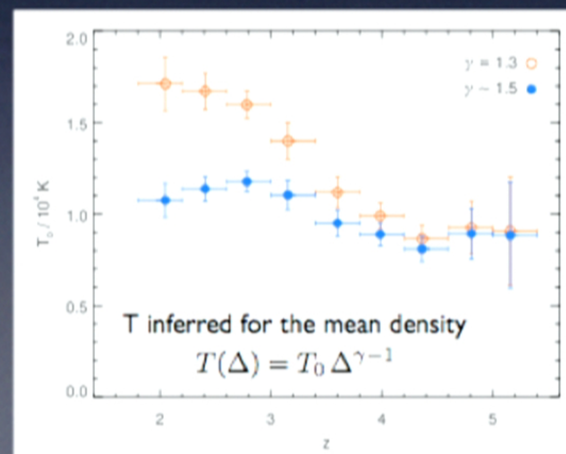
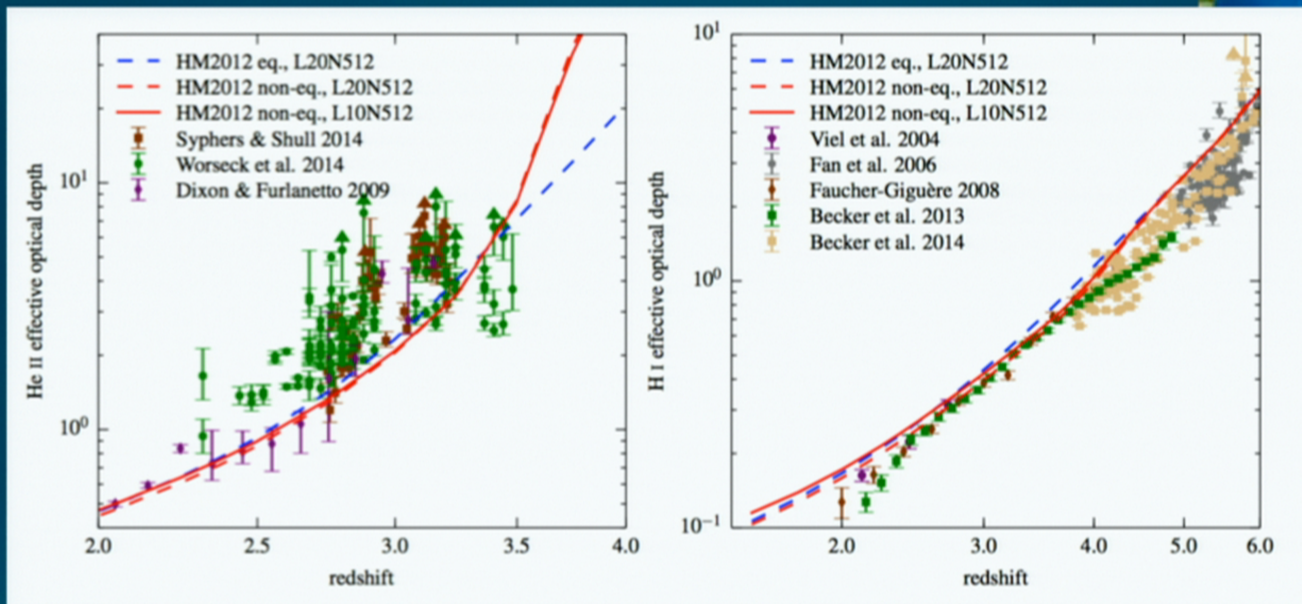




Becker *et al.* (2010)

Perimeter, 15 March 2016

τ_{eff} with Haardt& Madau 2012



Puchwein et al. 2014

But the evidence for hot gas at low densities does not go away

1. Title Category: **A–7**

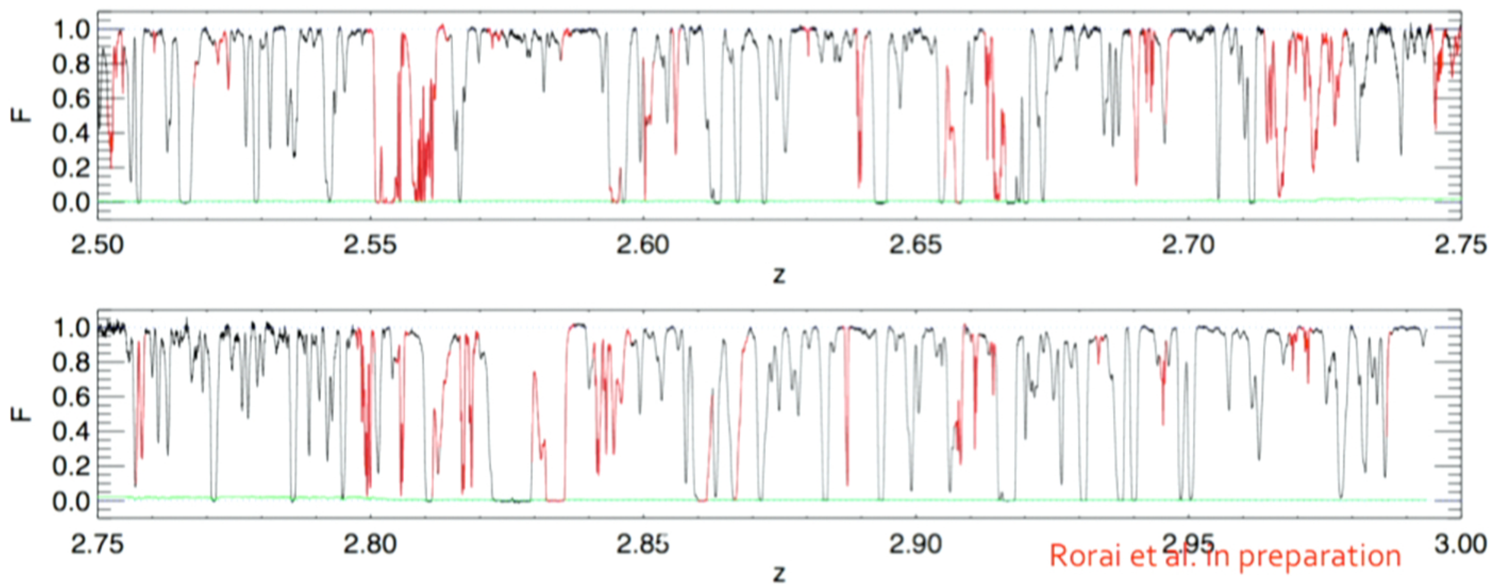
Hic sunt Leones: an ultra-deep quasar spectrum to explore the low-density Universe.

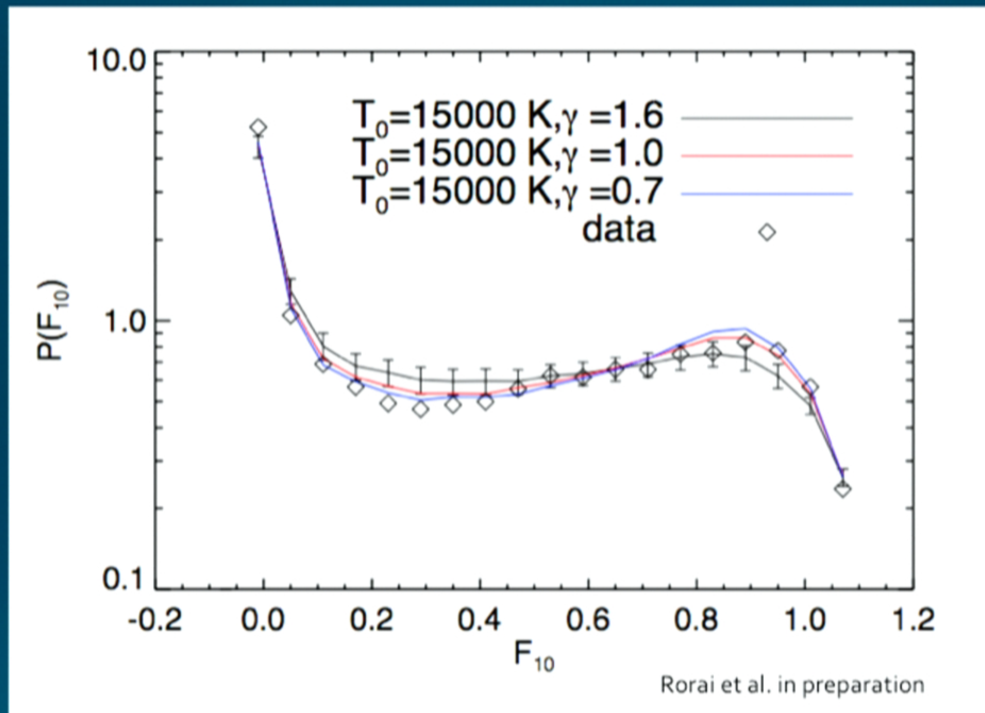
PI: Stefano Cristiani

2. Abstract / Total Time Requested

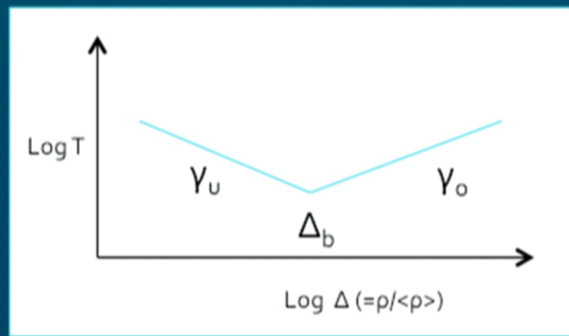
Total Amount of Time: 0 nights VM, 43 hours SM

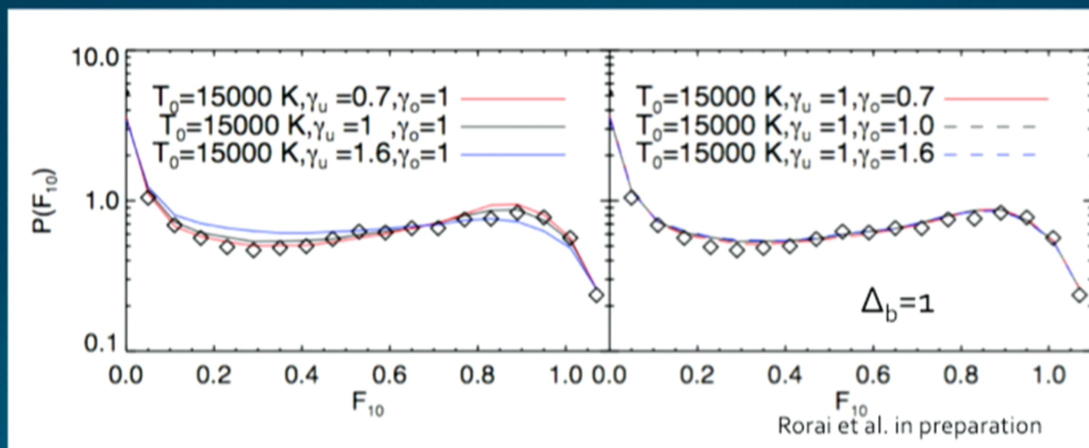
We propose to obtain an ultra-deep spectrum of the brightest quasar at $z \sim 3$ accessible from Paranal, HE 0940-1050 ($z_{\rm em} = 3.09$, $V_{\rm mag} = 16.9$), reaching a S/N of $\sim$ 500, 300 and 200 per resolution element in the C IV, Ly-α and O VI forests, respectively (after coadding to the $\sim$ 7h of observation already in the UVES archive). Pushing the spectroscopy of the IGM to unprecedented limits will open new possibilities in several fields: we will extend in particular the measurements of the metal content and the temperature of the IGM to low densities, providing key insight into the epoch and mechanisms of enrichment and significant clues for the understanding of the physics of galactic winds. The temperature measurements will allow us to directly investigate the helium reionization and other possible heating sources of the intergalactic medium, as well as to calibrate out the largest systematic uncertainty in the use of the Ly-α forest as a precision cosmological probe.



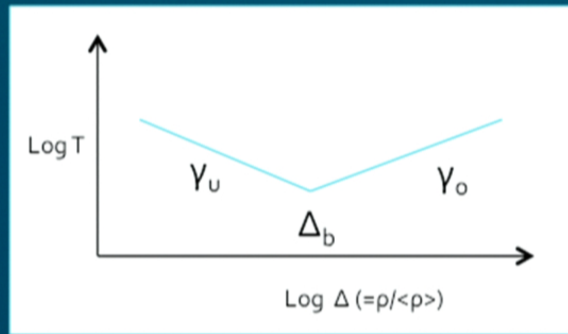


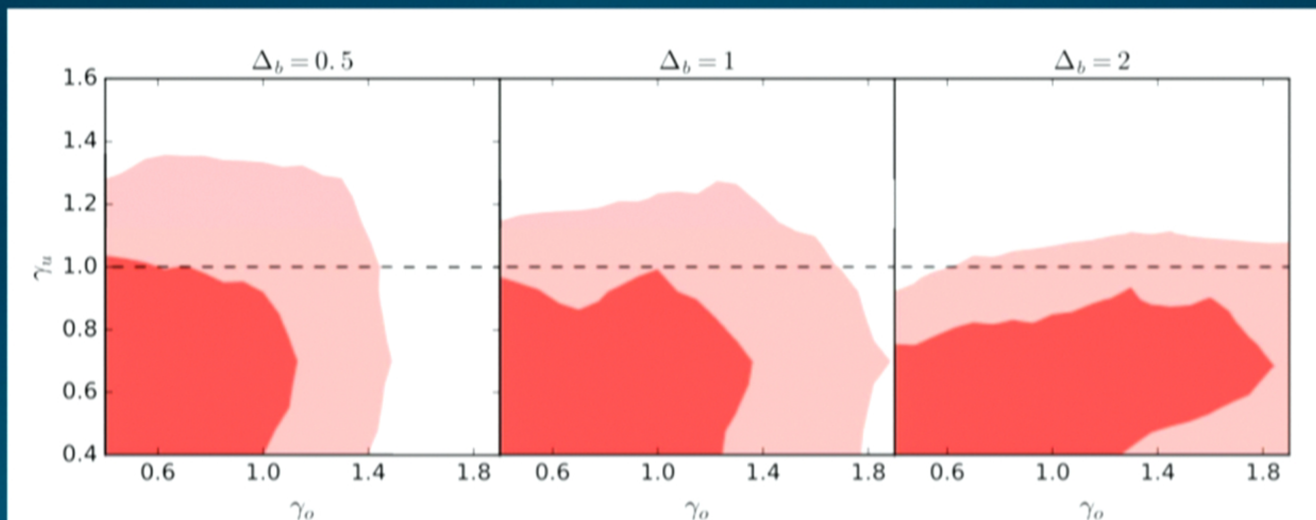
An iso-thermal (or inverted) temperature density relation still fits the data, while γ=1.5-1.6 does not.





For a broken power-law the PDF is only sensitive to the thermal state of the "underdense" regions with $\Delta < \Delta_b$. At densities above the mean γ=1.5-1.6 is consistent with the data

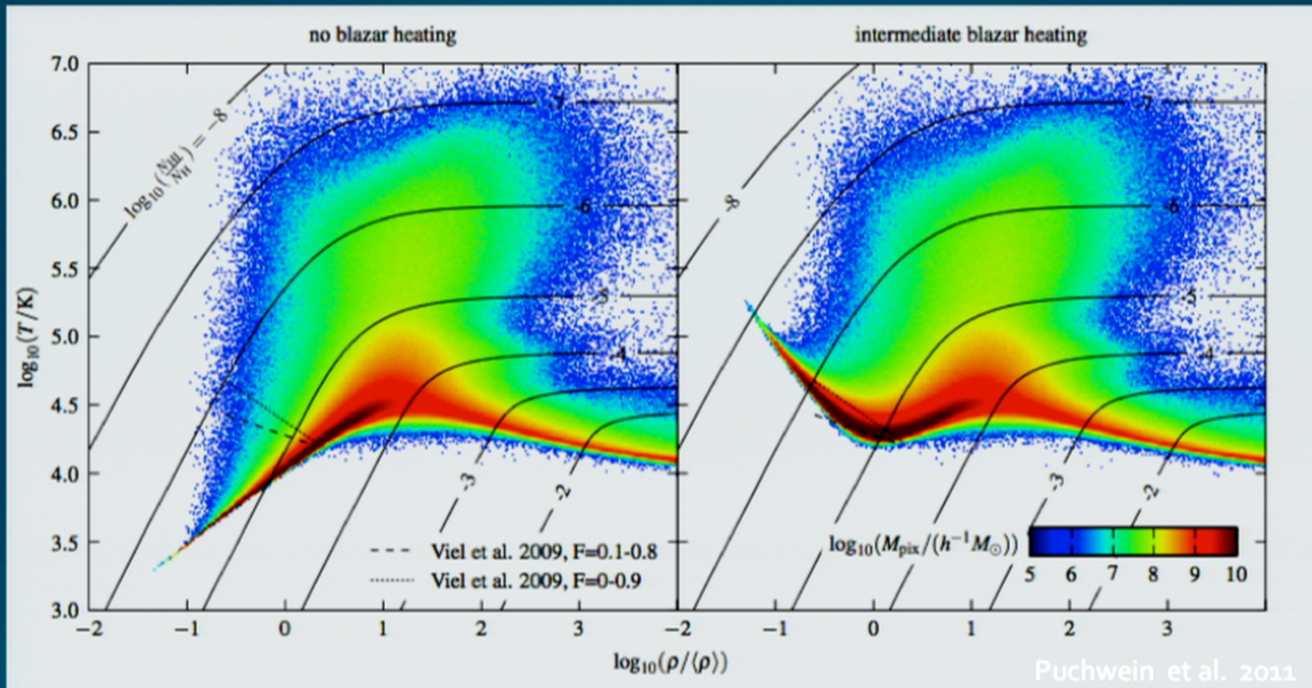




Rorai et al. in preparation

Gas at densities below the mean appears to be as hot or hotter as gas above the mean densities.

An inverted temperature density relation?



The heating is "volumetric" and exceeds photoheating in underdense regions. At low densities this results in a temperature rising with decreasing density.

Summary & Conclusions (by Ewald)

- Discrepancy between temperatures predicted from photoheating and measured temperatures came down (better modelling & new data)
- TeV blazars may heat the low density IGM (challenging to measure as the Lyman-alpha forest is mostly sensitive to higher densities at low z)
- Additional heating of the IGM by blazars may help matching:
  - IGM temperatures from spectral curvature at z<3
  - Observed flux PDF
- Other ingredients may also be important:
  - Continuum correction
  - UVB model

The End

Perimeter, 15 March 2016

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