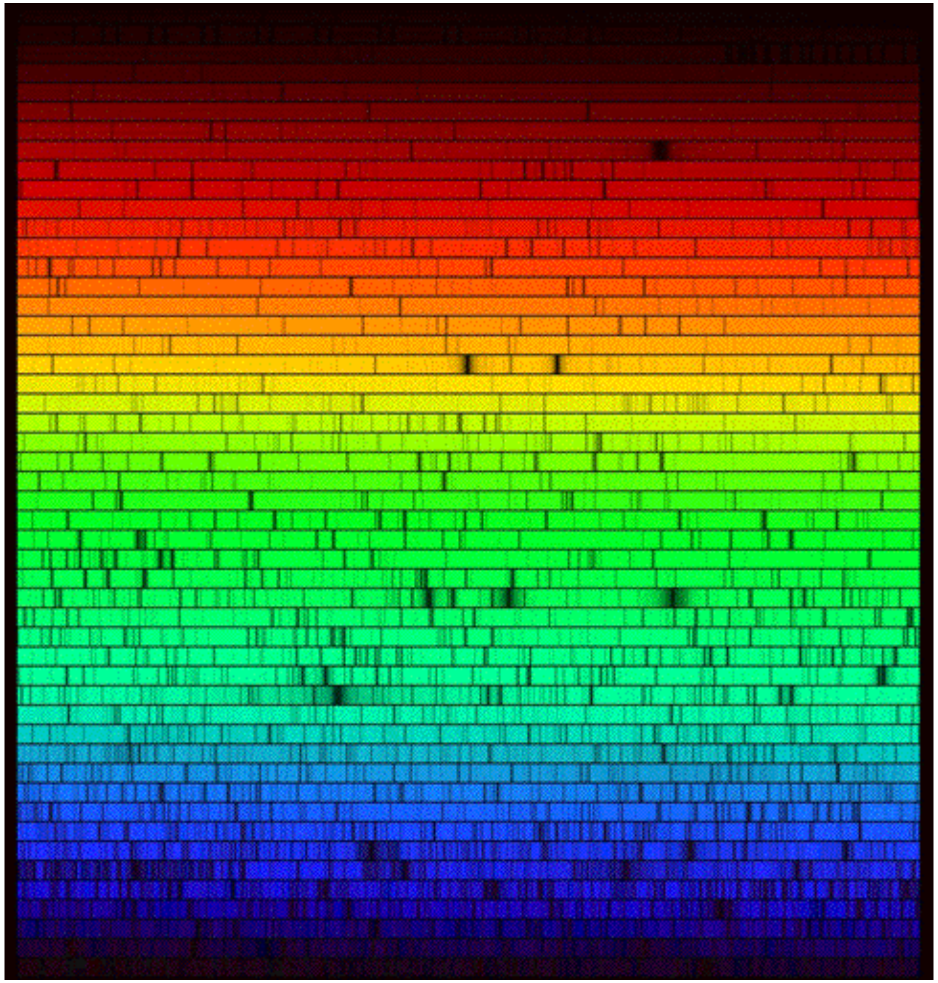

Probing dark matter and the physical state of the IGM with the Lyα forest

Martin Haehnelt

in collaboration with:

George Becker, James Bolton, Jonathan Chardin, Laura Keating, Ewald Puchwein, Debora Sijacki, Volker Springel, Matteo Viel (and quite a few more)

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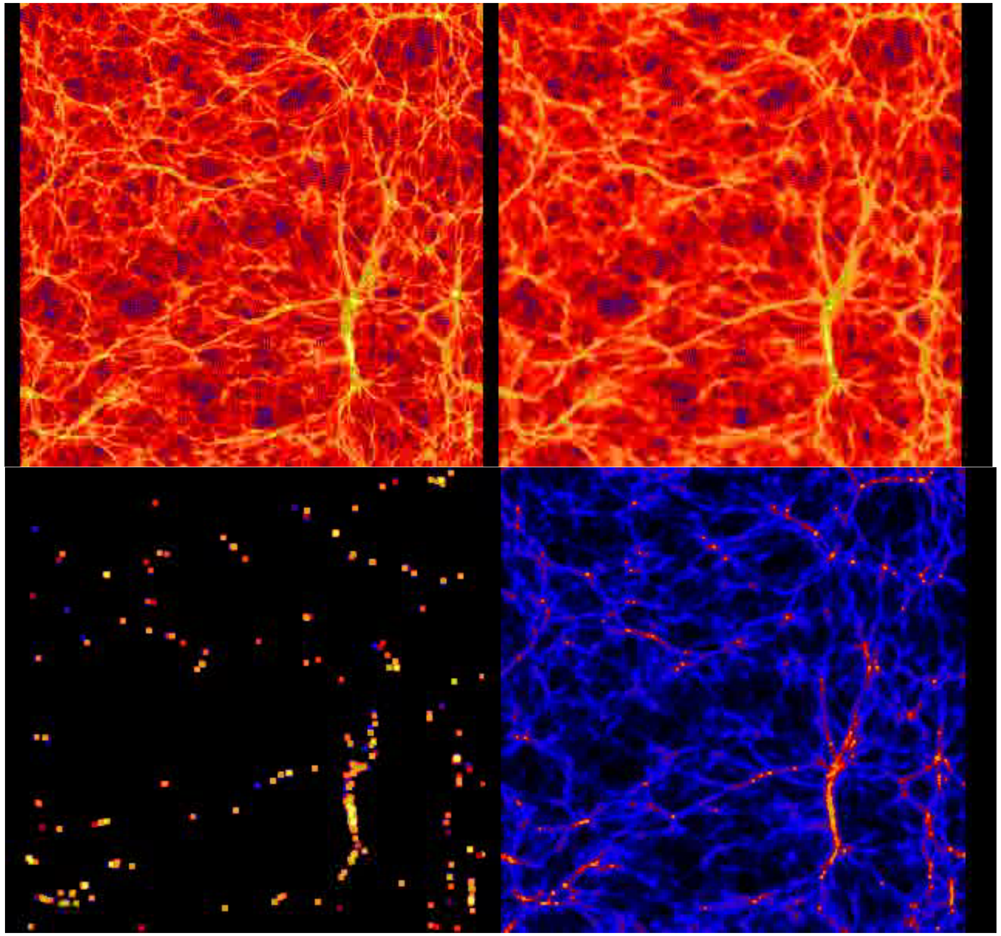
Dark Matter

Gas

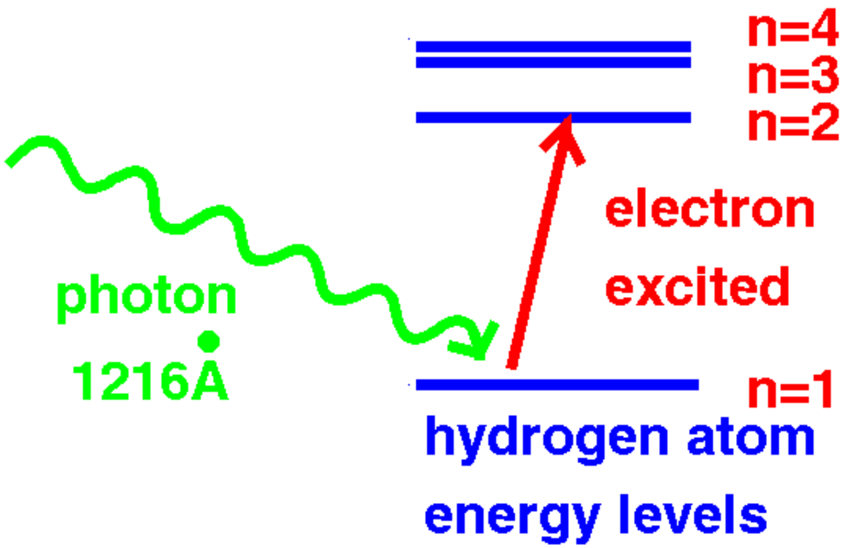


Galaxies

Neutral hydrogen

Neutral hydrogen is an excellent tracer of the matter distribution.

Lyα absorption by neutral hydrogen



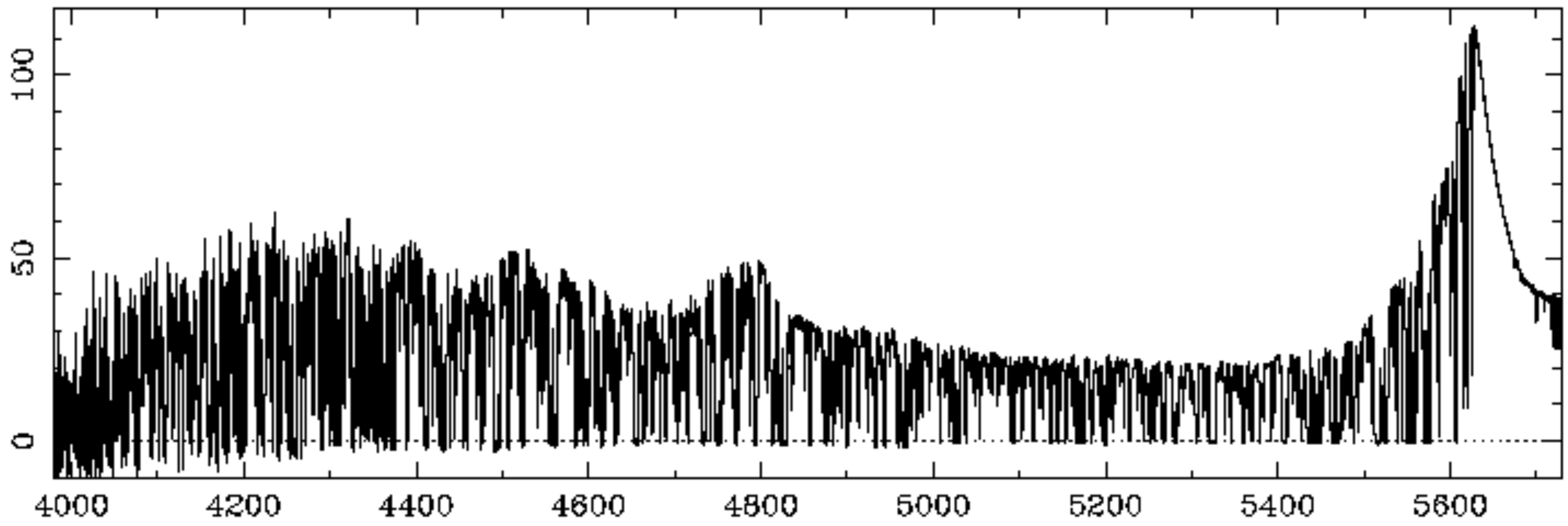
$\lambda_{obs} = 1216\,(1+z)$ Å

Hydrogen in the IGM is photoionized:

Recombination **Photoionization**

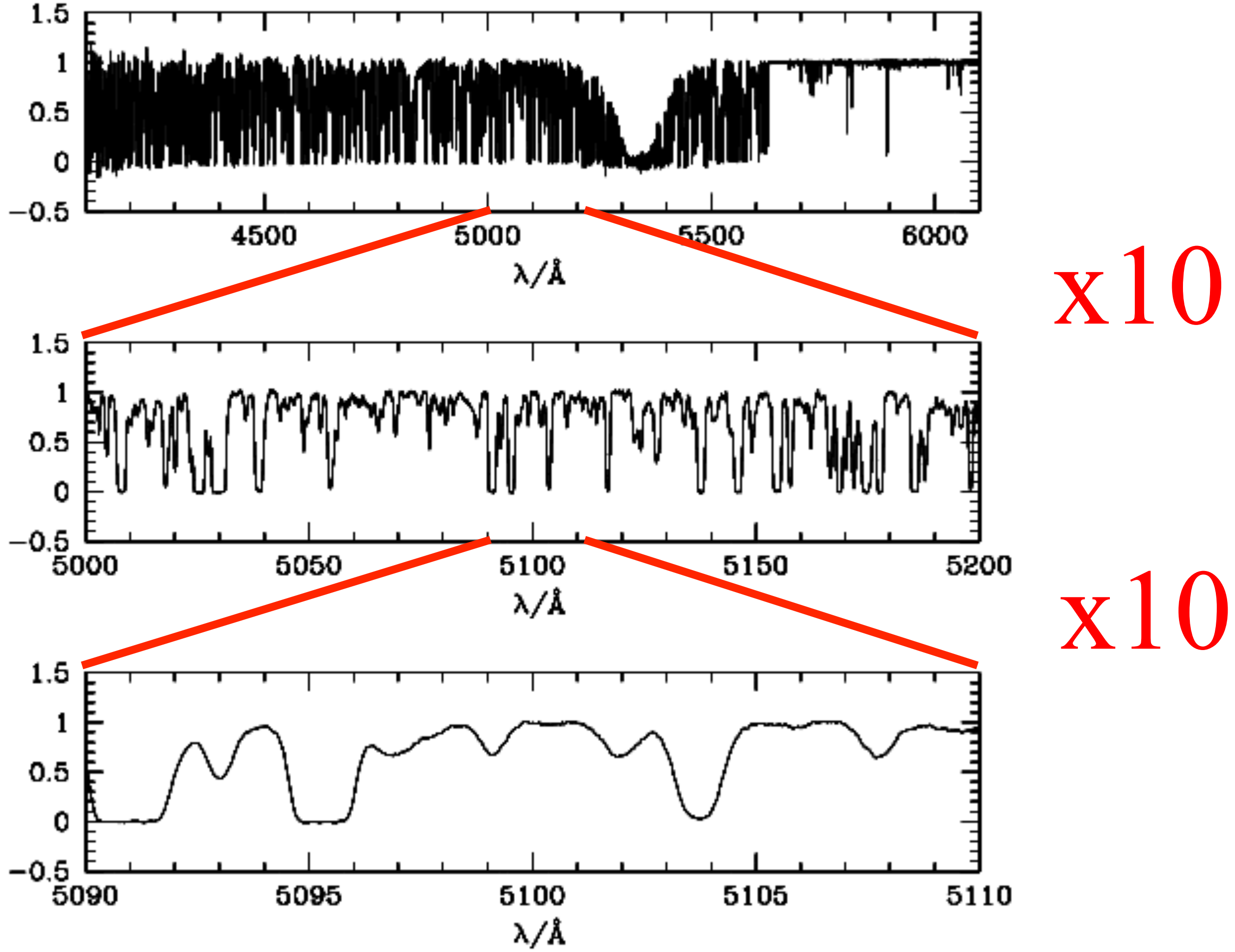
$$\alpha \; n_{HII} \; n_e = \Gamma \; n_{HI}$$

A real spectrum



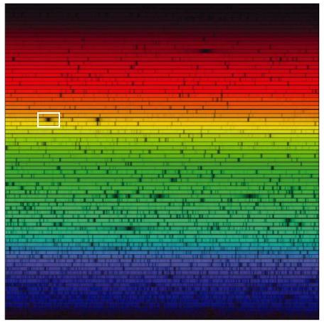
A prominent "forest" of Lyα absorption lines at $\lambda_{obs} = 1216\,(1+z)$ Å.

High resolution – High S/N!

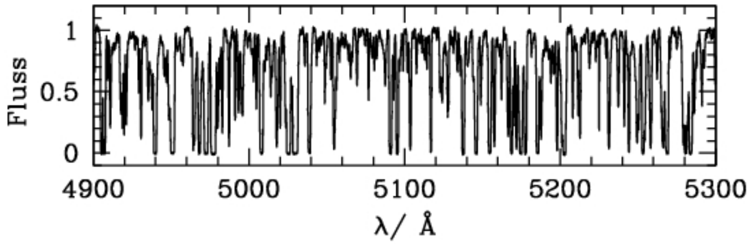


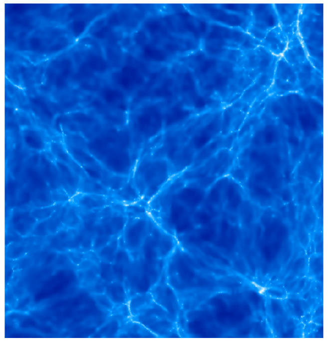
A treasure trove of information!

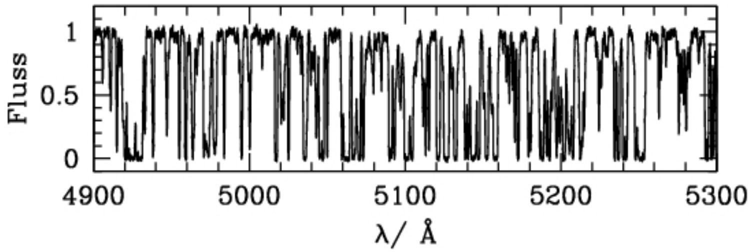
- matter power spectrum on small and intermediate scales
- thermal history of the IGM
- ionization state of the IGM
- reionization
- metal enrichment
- (high-redshift galaxies)



observed







simulated

Big telescopes and big computers!

How cold is cold dark matter?

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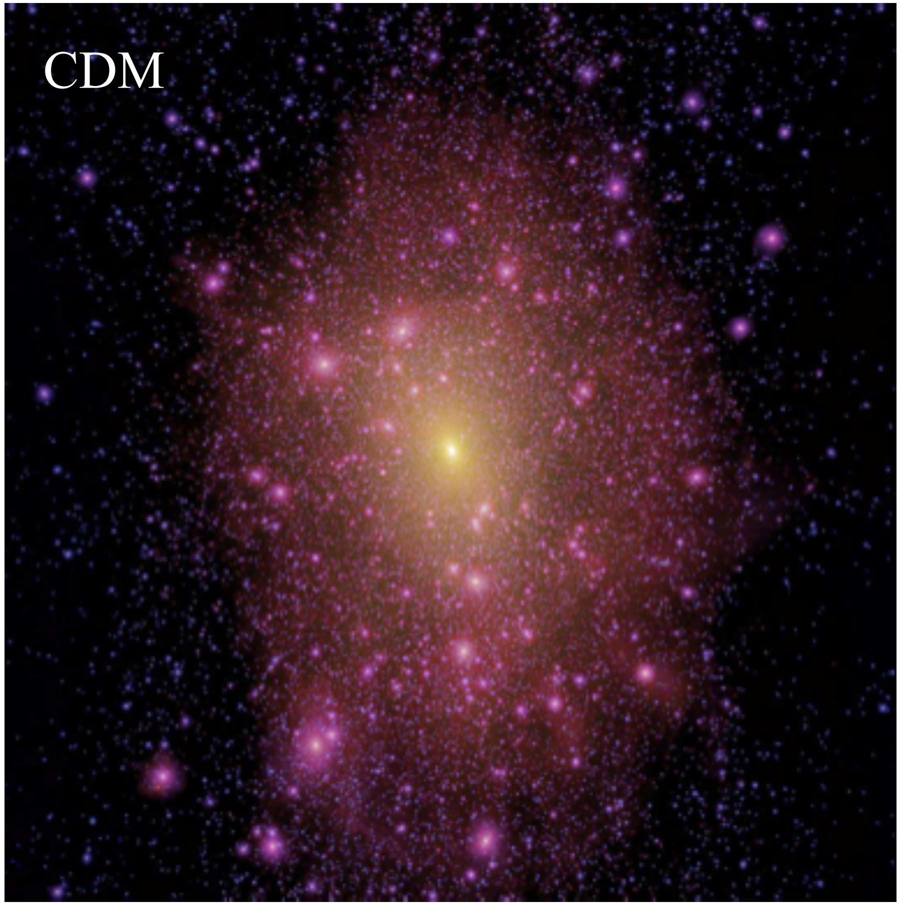
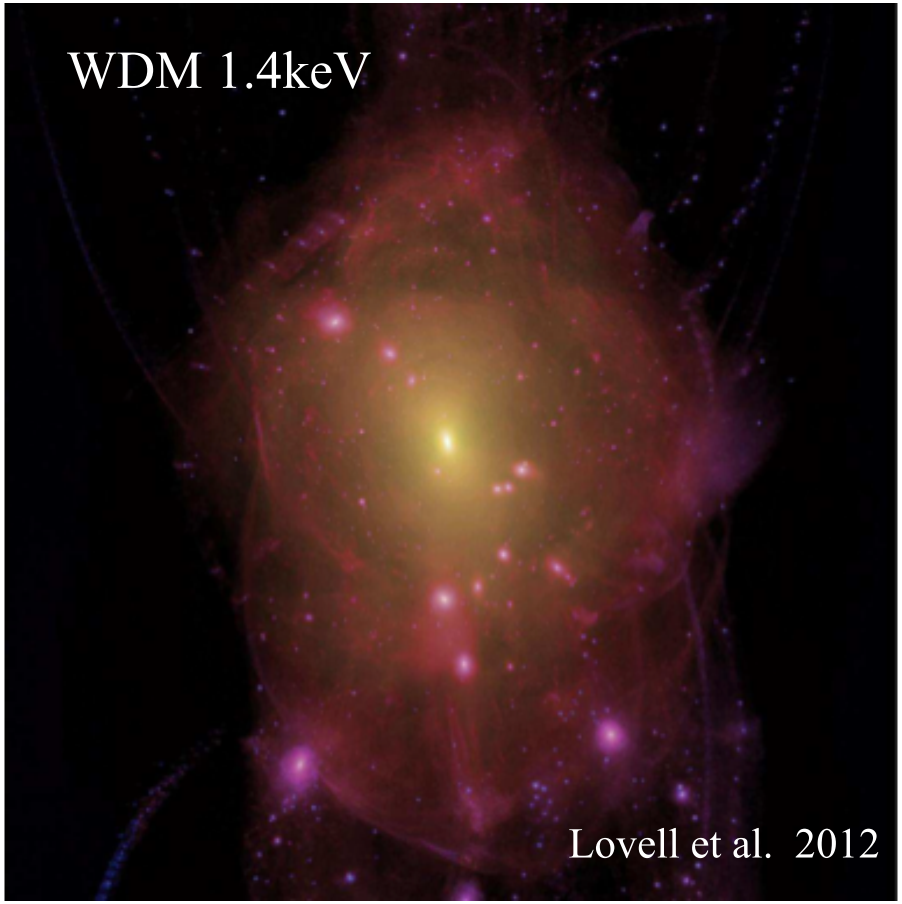
Mon. Not. R. Astron. Soc. **420**, 2318–2324 (2012)
doi:10.1111/j.1365-2966.2011.20200.x

The haloes of bright satellite galaxies in a warm dark matter universe

Mark R. Lovell,[1★] Vincent Eke,[1] Carlos S. Frenk,[1] Liang Gao,[1,2] Adrian Jenkins,[1] Tom Theuns,[1,3] Jie Wang,[1] Simon D. M. White,[4] Alexey Boyarsky[5,6]





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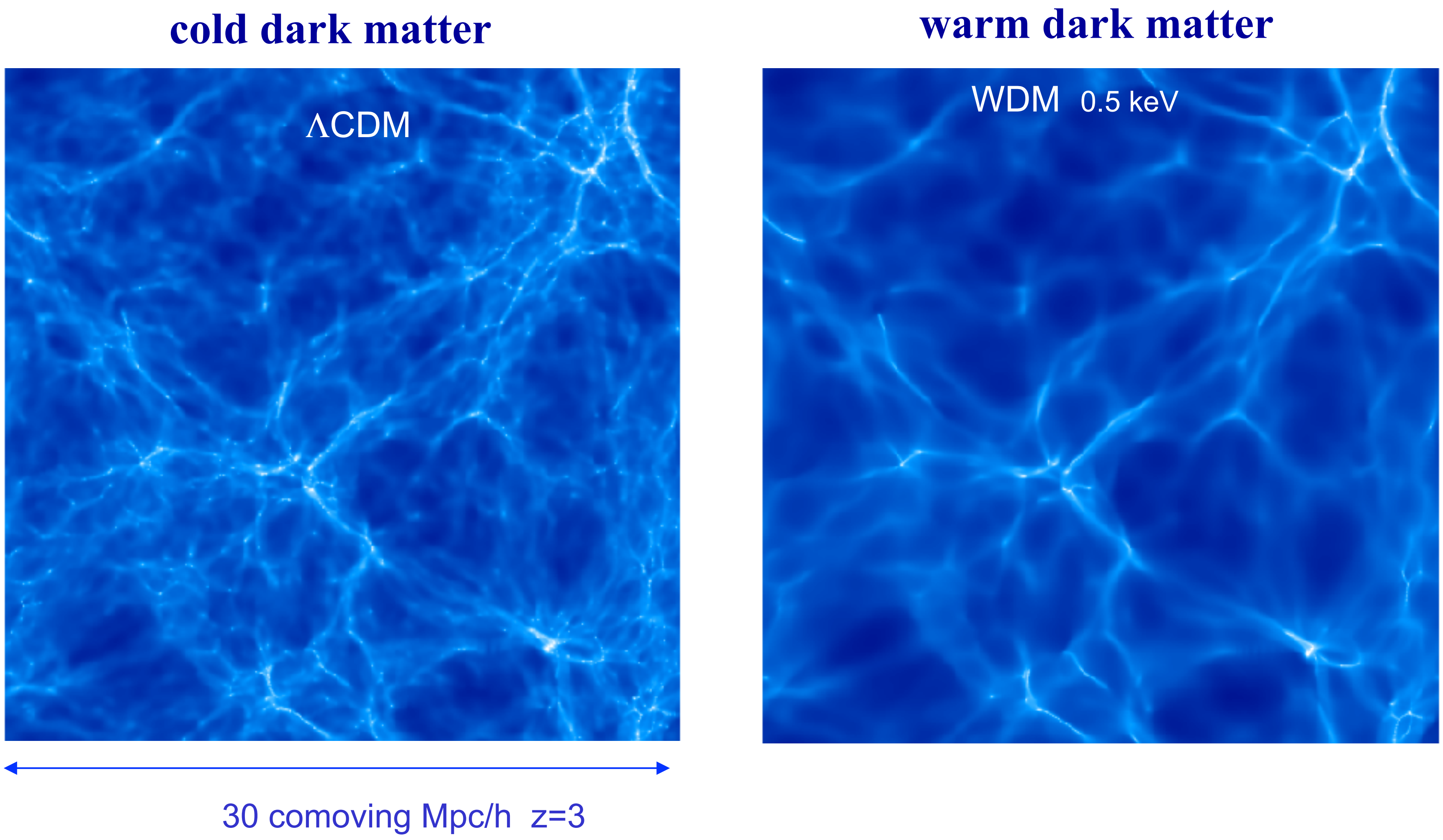
Free-streaming erases structure



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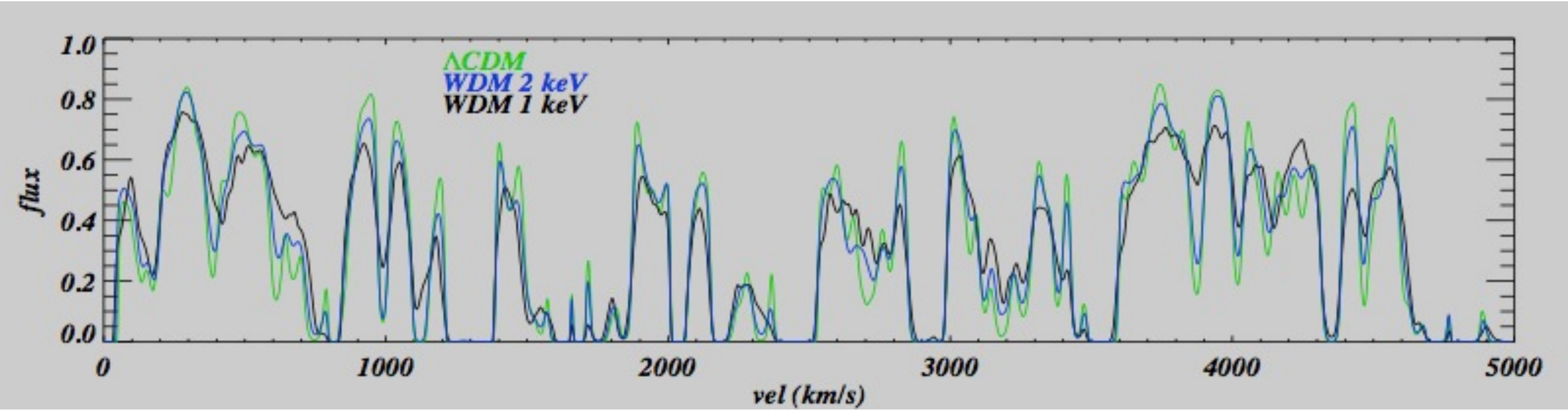
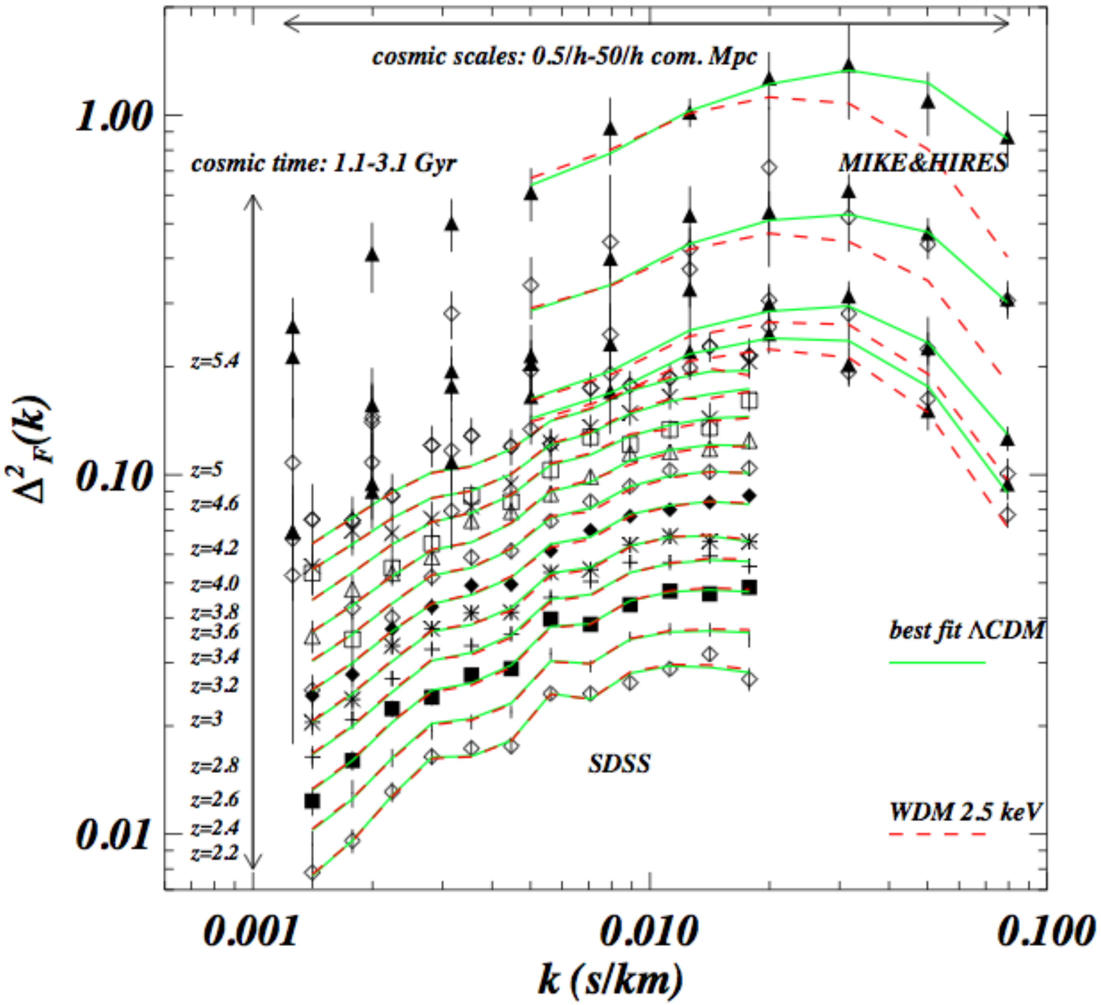


The effect of the free-streaming of (warm) dark matter on the small scale structure in the flux distribution.

Our latest WDM results

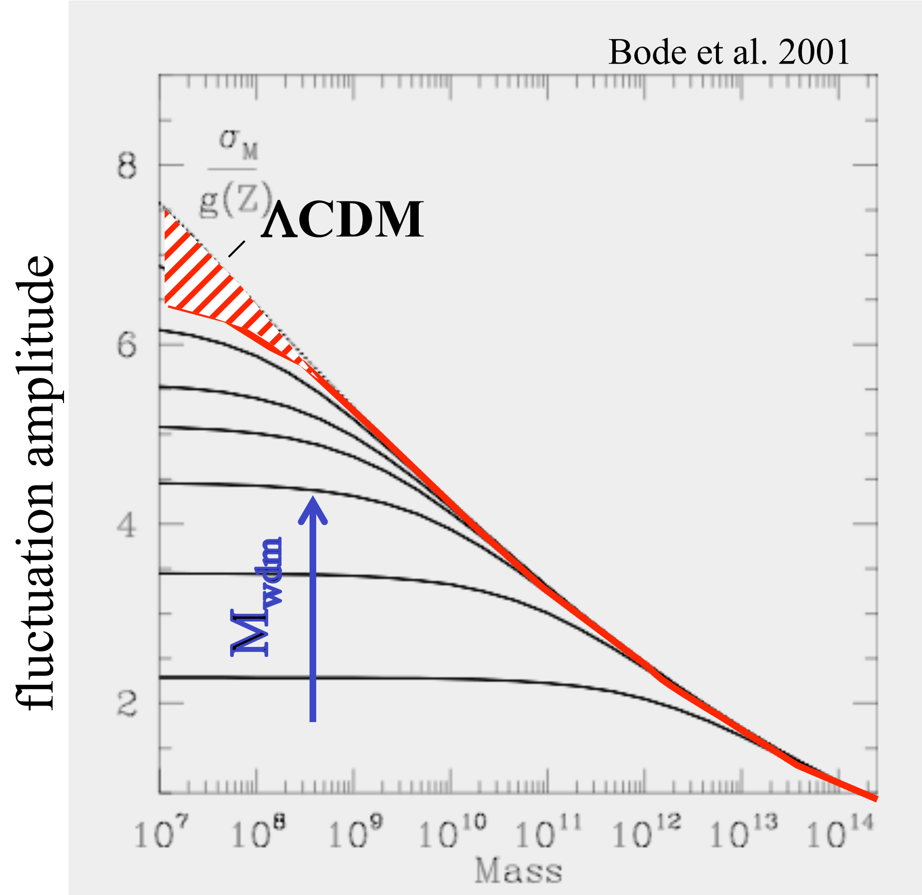


- more and better data
- more and better simulations
- extensive scrutiny for systematic errors
- improved and conservative analysis

M_{wdm} > 3.3 keV (2σ C.L)

2 keV WDM disfavoured at about 4σ!

DM is pretty cold

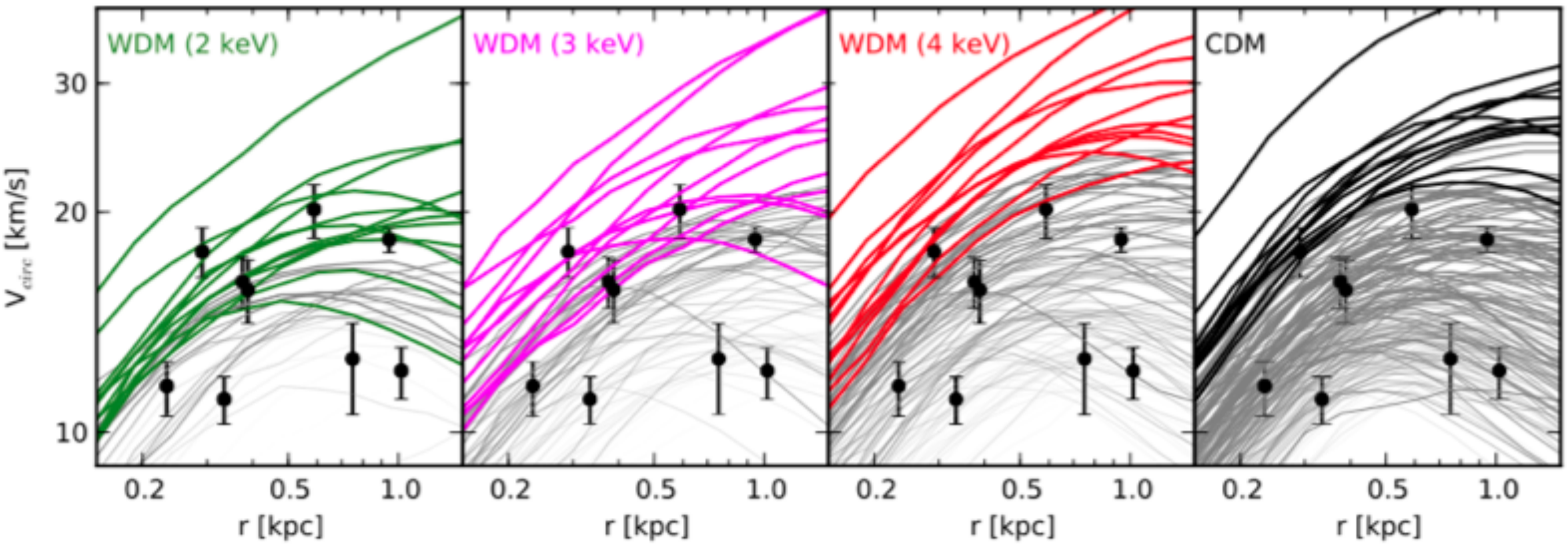


There is little room left for the effect of warm DM on the DM halo mass function (or DM halo profiles).

Our best bet to push this further is probably looking at neutral hydrogen before reionization with 21cm emission.

Warm Dark Matter: The End is Nigh

Aurel Schneider[1]*, Donnino Anderhalden[2], Andrea V. Macciò[3], and Jürg Diemand[2]
[1] *Department of Physics and Astronomy, University of Sussex, Brighton, BN1 9QH, UK*
[2] *Institute for Theoretical Physics, University of Zurich, 8057 Zurich, Switzerland*
[3] *Max Planck Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany*
(Dated: September 25, 2013)



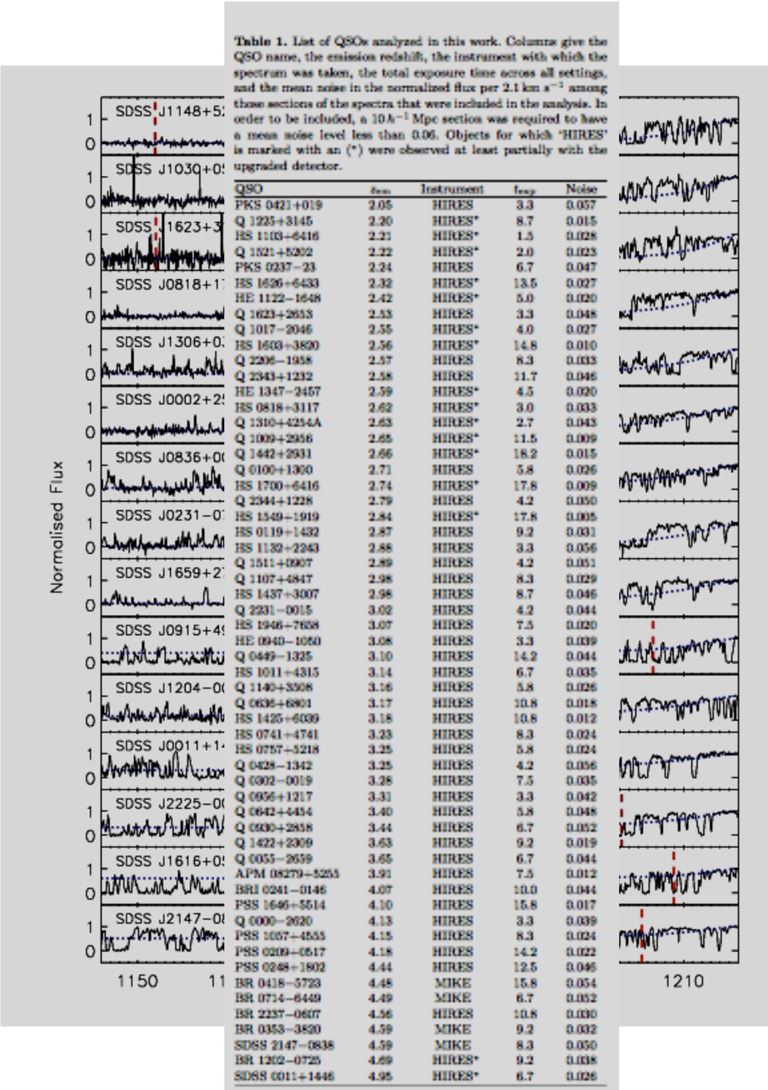
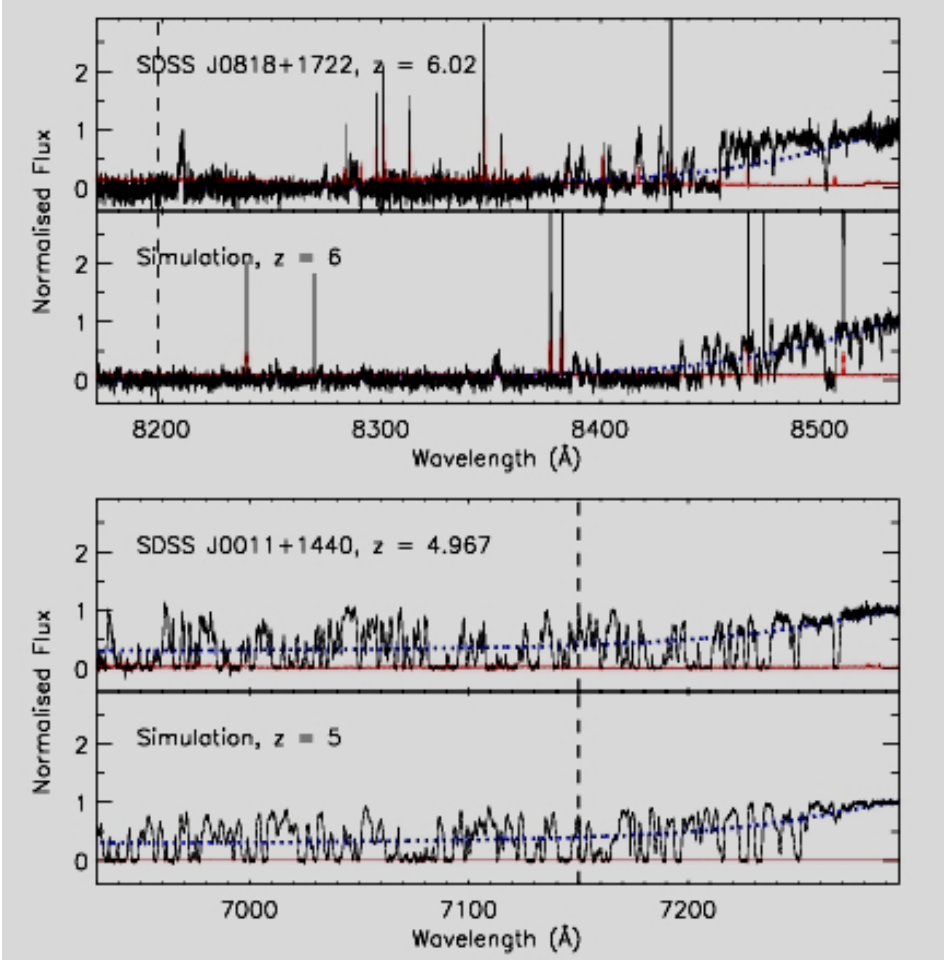


Table 1. List of QSOs analyzed in this work. Columns give the QSO name, the emission redshift, the instrument with which the spectrum was taken, the total exposure time across all settings, and the mean noise in the normalized flux per 2.1 km s^{-1} among those sections of the spectra that were included 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!

The thermal state of the IGM

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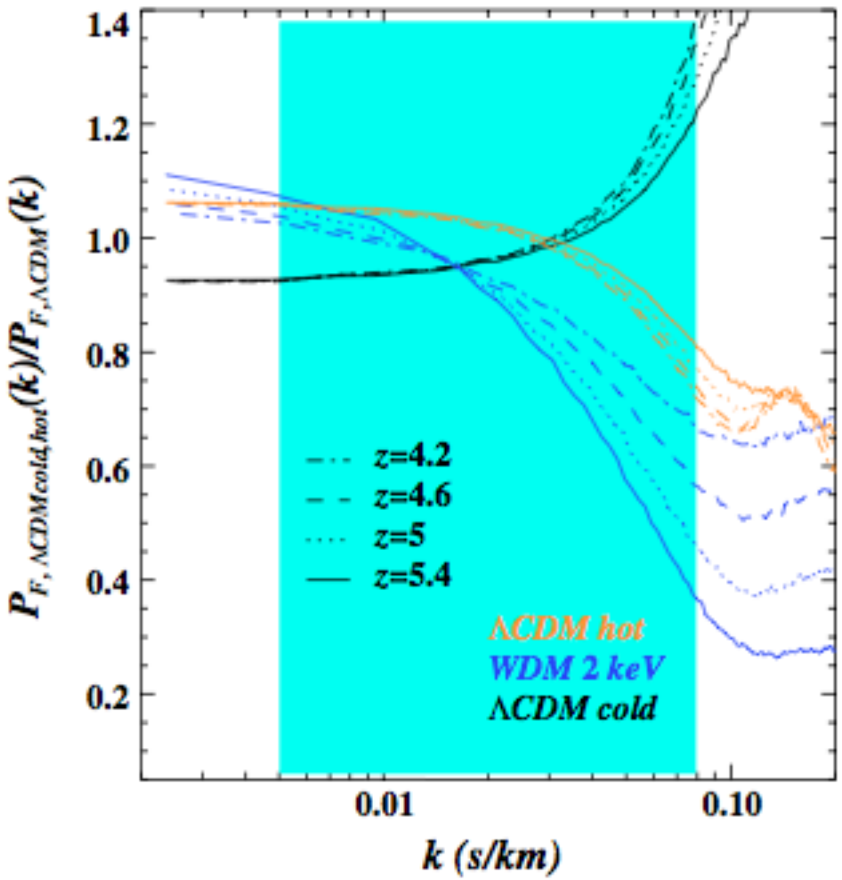
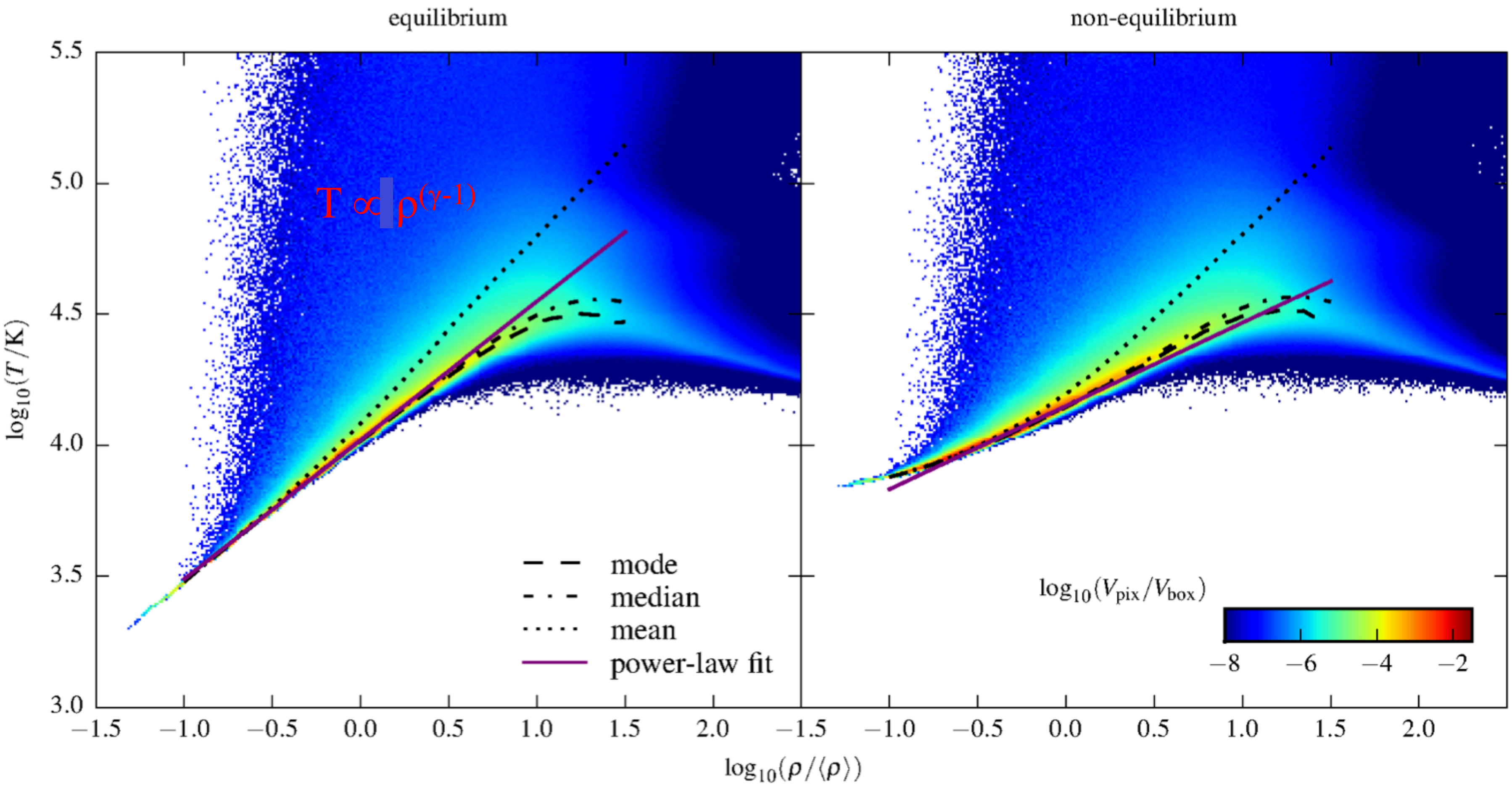
The effects of temperature and free streaming are not degenerate



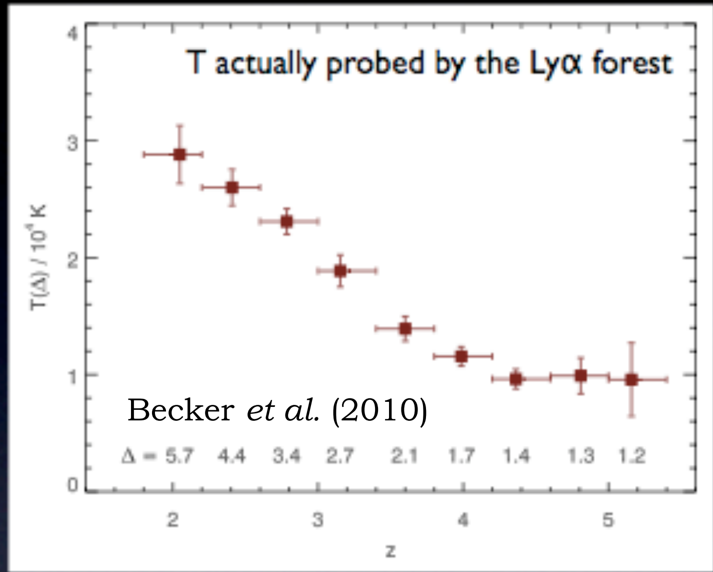
Viel, Becker, Bolton, Haehnelt 2013



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

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



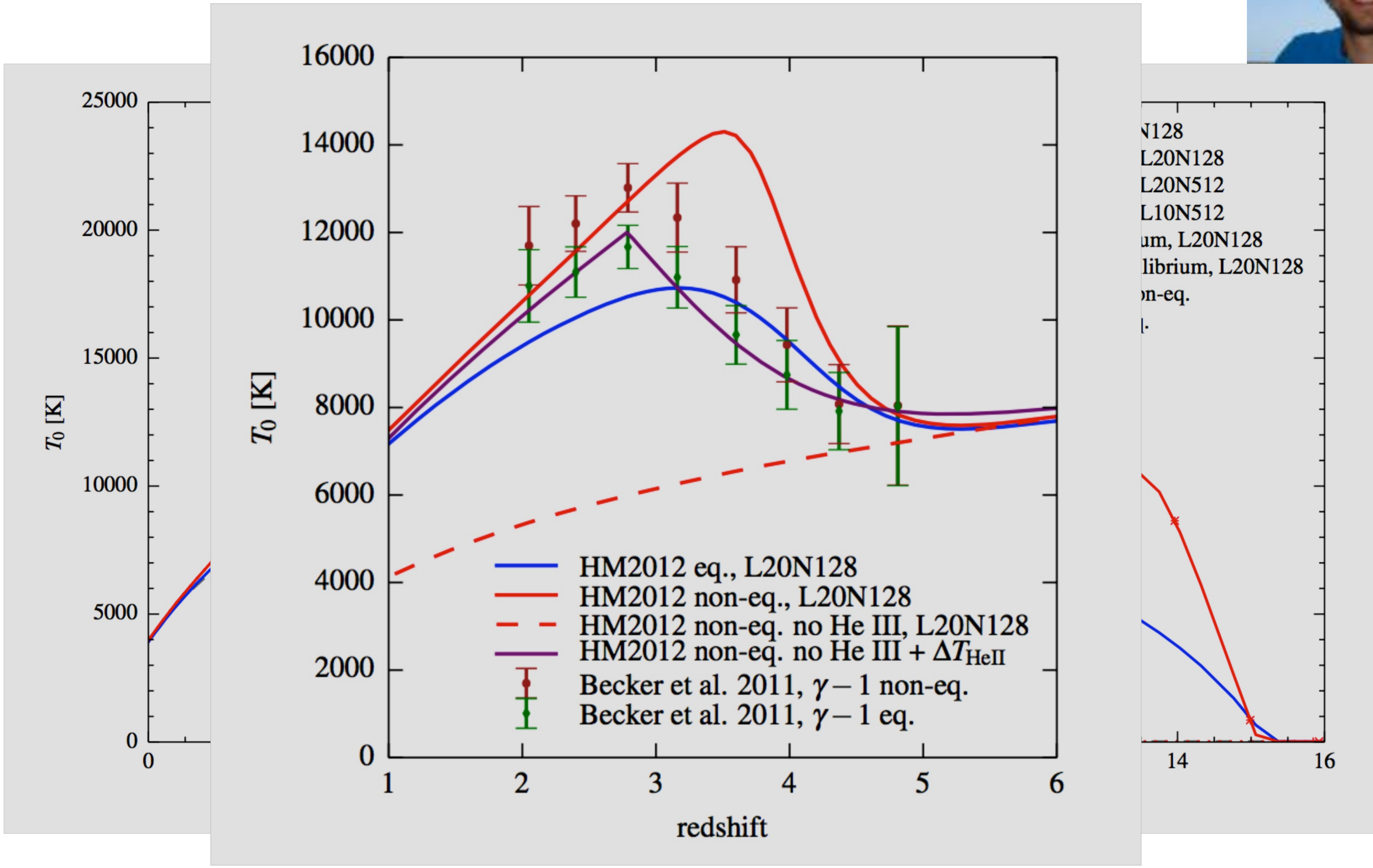
γ=1.56

Rudie et al. 2013

γ=1.56 Bolton et al 2014

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

The thermal history with Haardt& Madau 2012

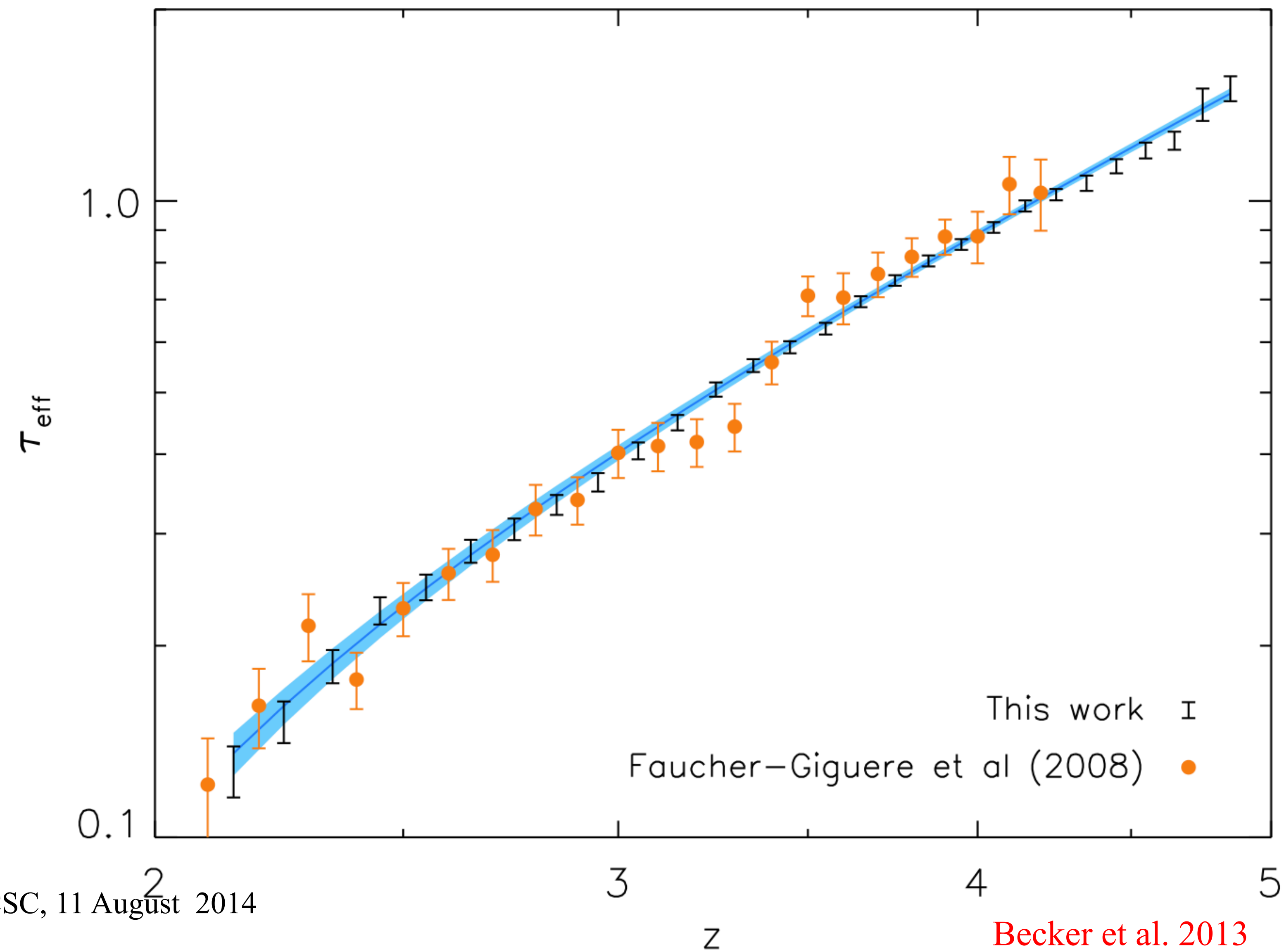


Puchwein et al. 2014

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

The ionization state of the IGM

A much improved measurement of the effective optical depth



Becker et al. 2013

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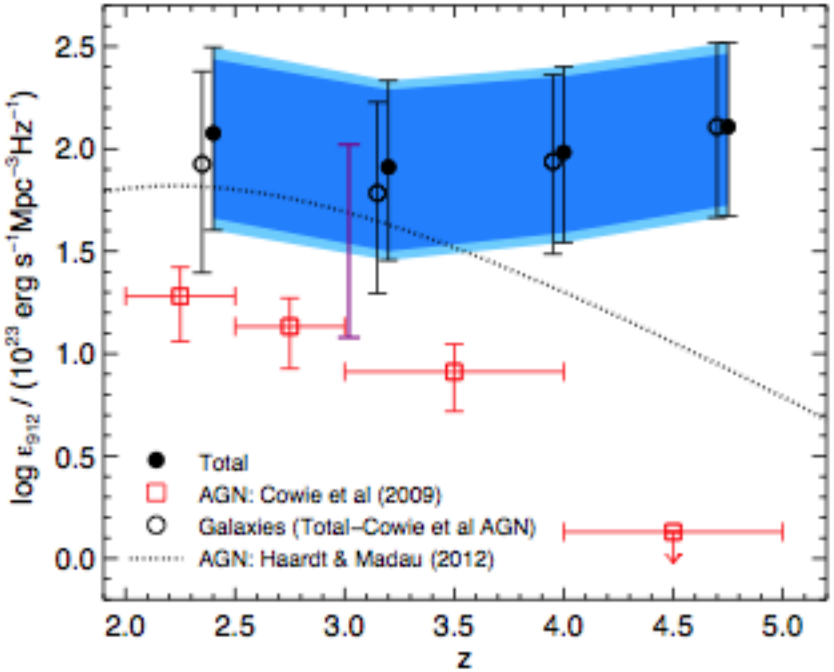
The ionizing emissivity



Becker &Bolton 2013

$$\tau \propto \frac{\alpha \hat{\rho}^2}{\Gamma_{\text{phot}}}$$

corresponds to about 1-2 ionizing photons per hydrogen atom
“photon-starved reionization”

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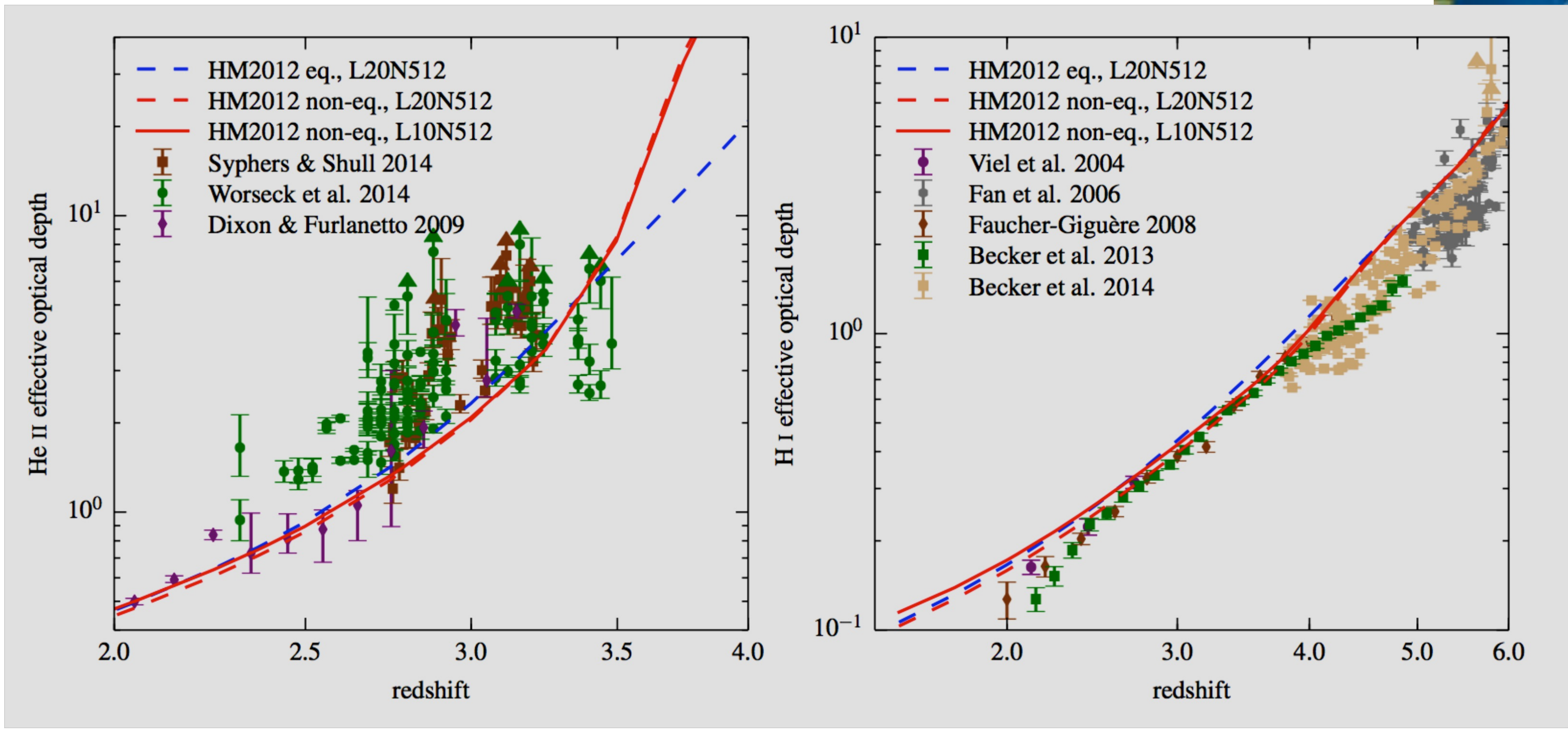
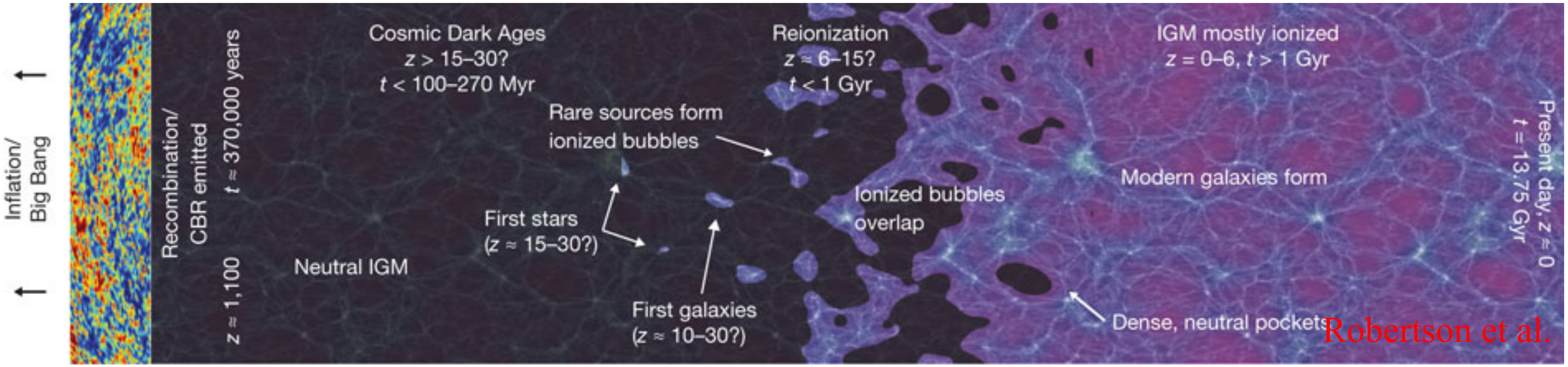
τ_{eff} with Haardt& Madau 2012



Puchwein et al. 2014



Robertson et al.

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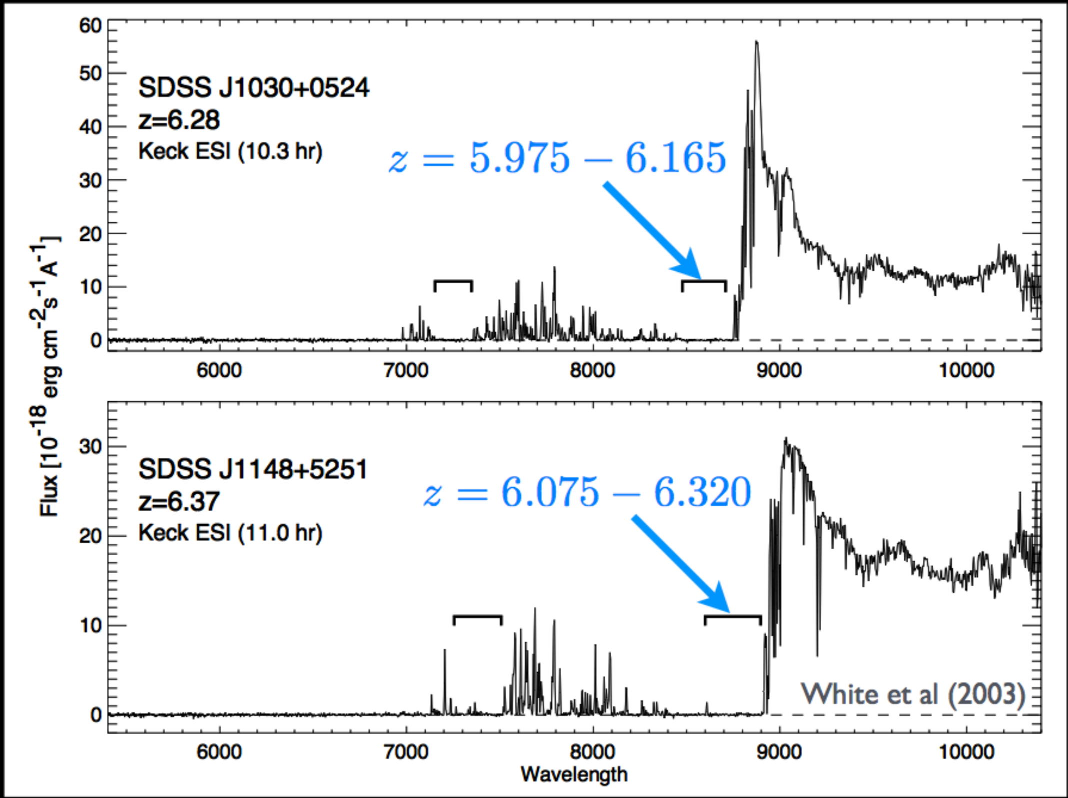
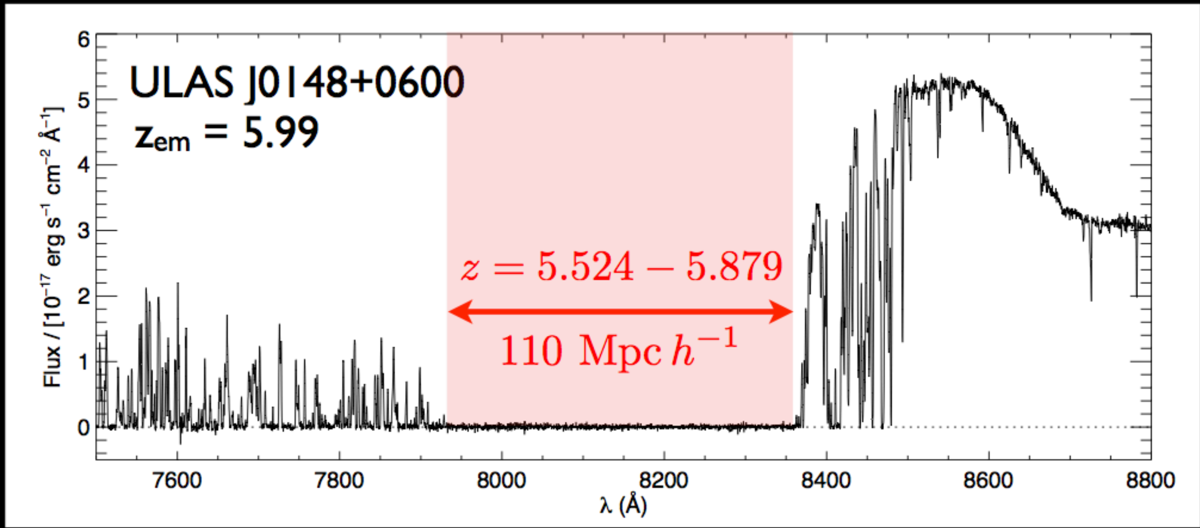
Compared to other deep Lyα troughs…

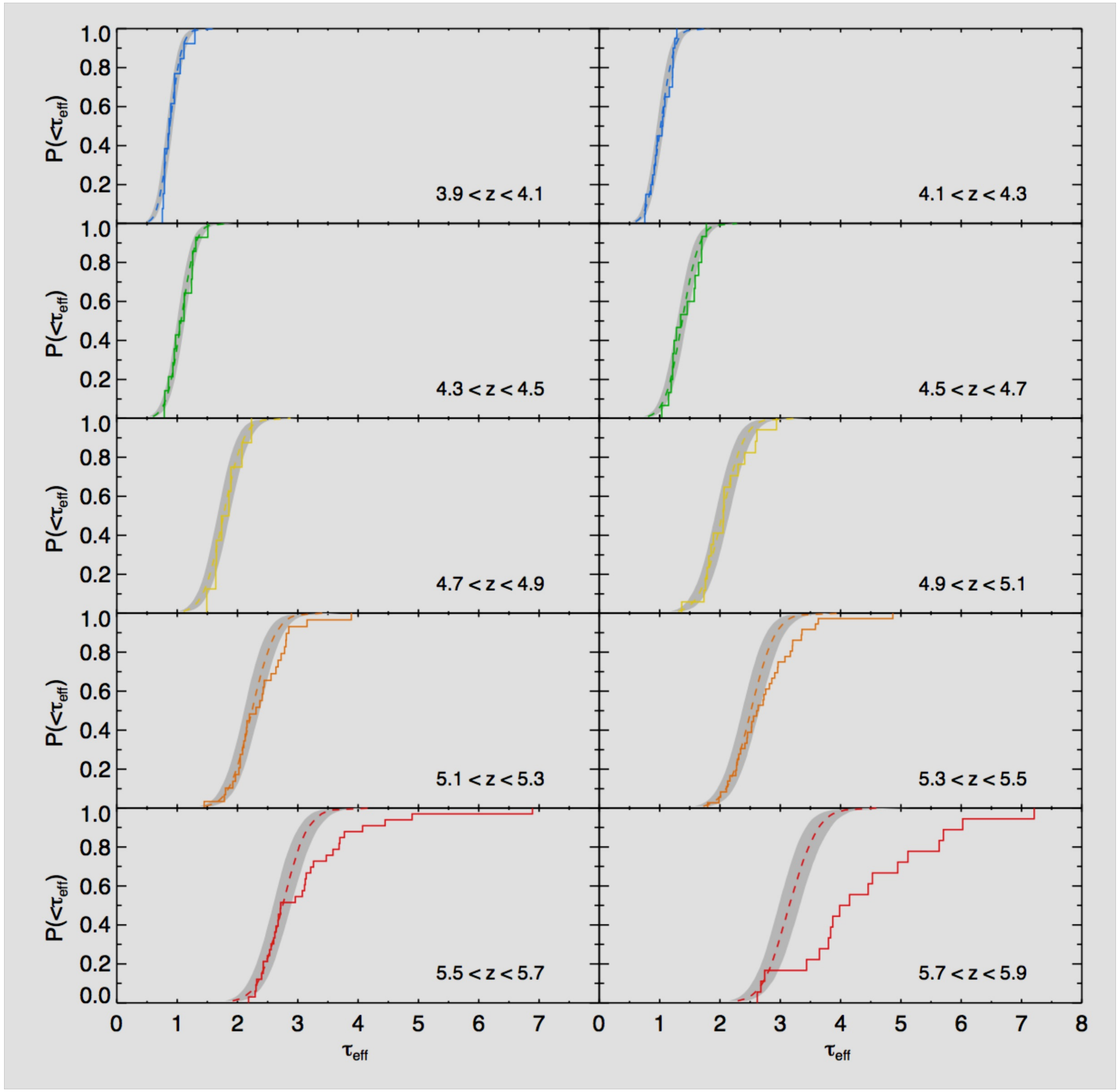


ULAS J0148 trough is longer and at substantially lower redshifts.



Becker et al, in prep

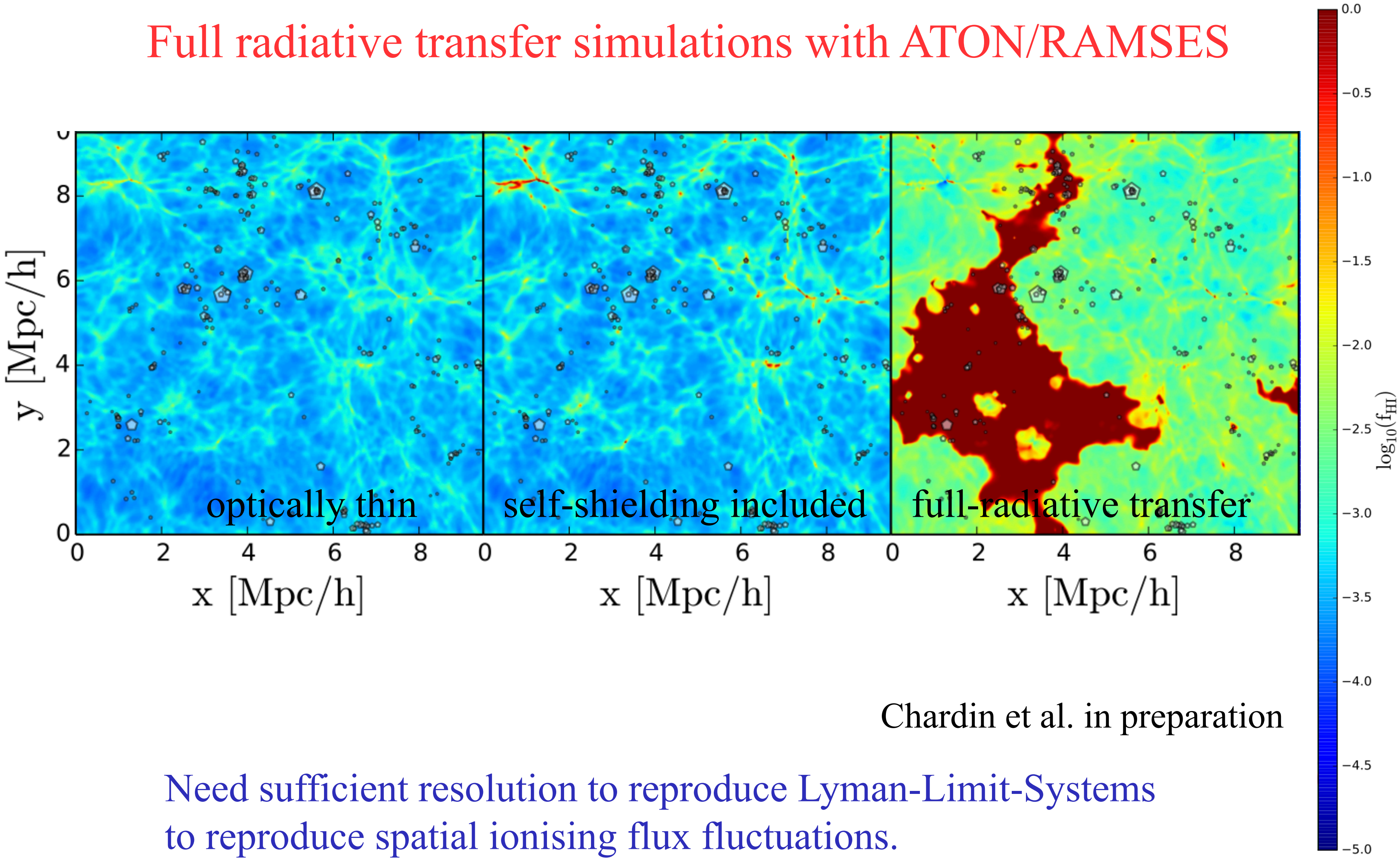
George Becker - IoA / KICC



Spatial fluctuations of hydrogen ionising flux at z>6 are now well quantified.

Becker et al. 2014

Full radiative transfer simulations with ATON/RAMSES

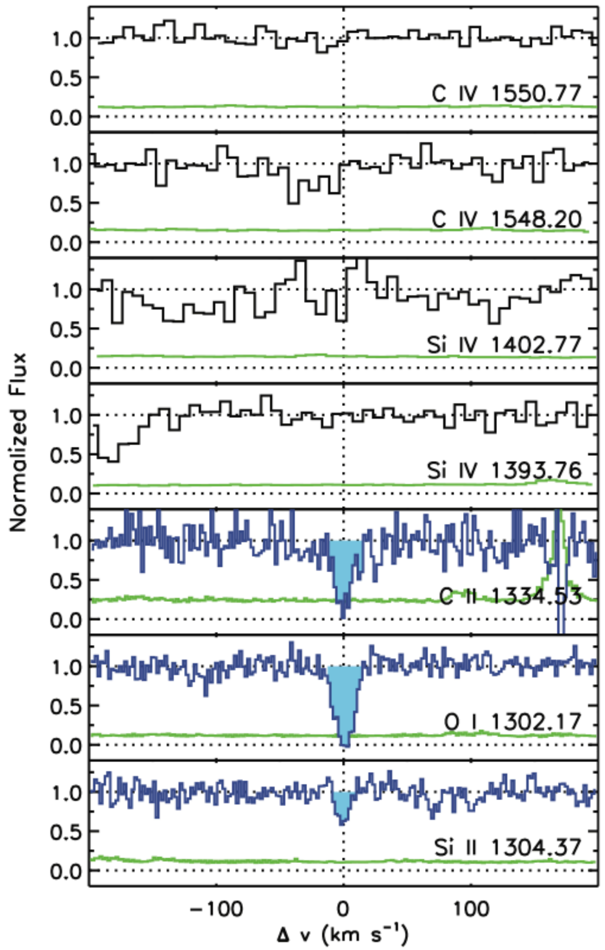


Chardin et al. in preparation

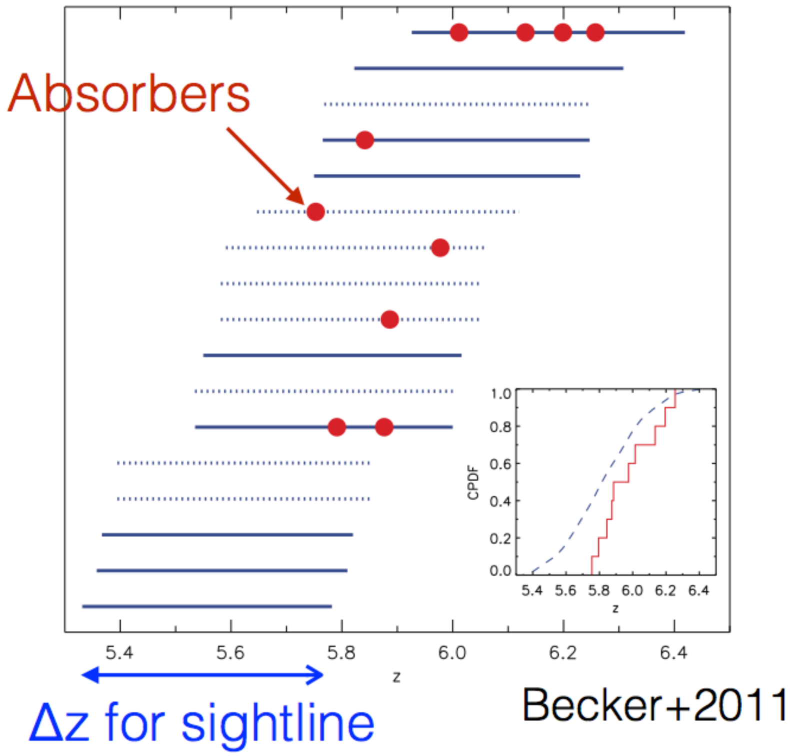
Need sufficient resolution to reproduce Lyman-Limit-Systems to reproduce spatial ionising flux fluctuations.

Metals at high redshift

Low ionization metal absorbers at z ~ 6



Becker+2011

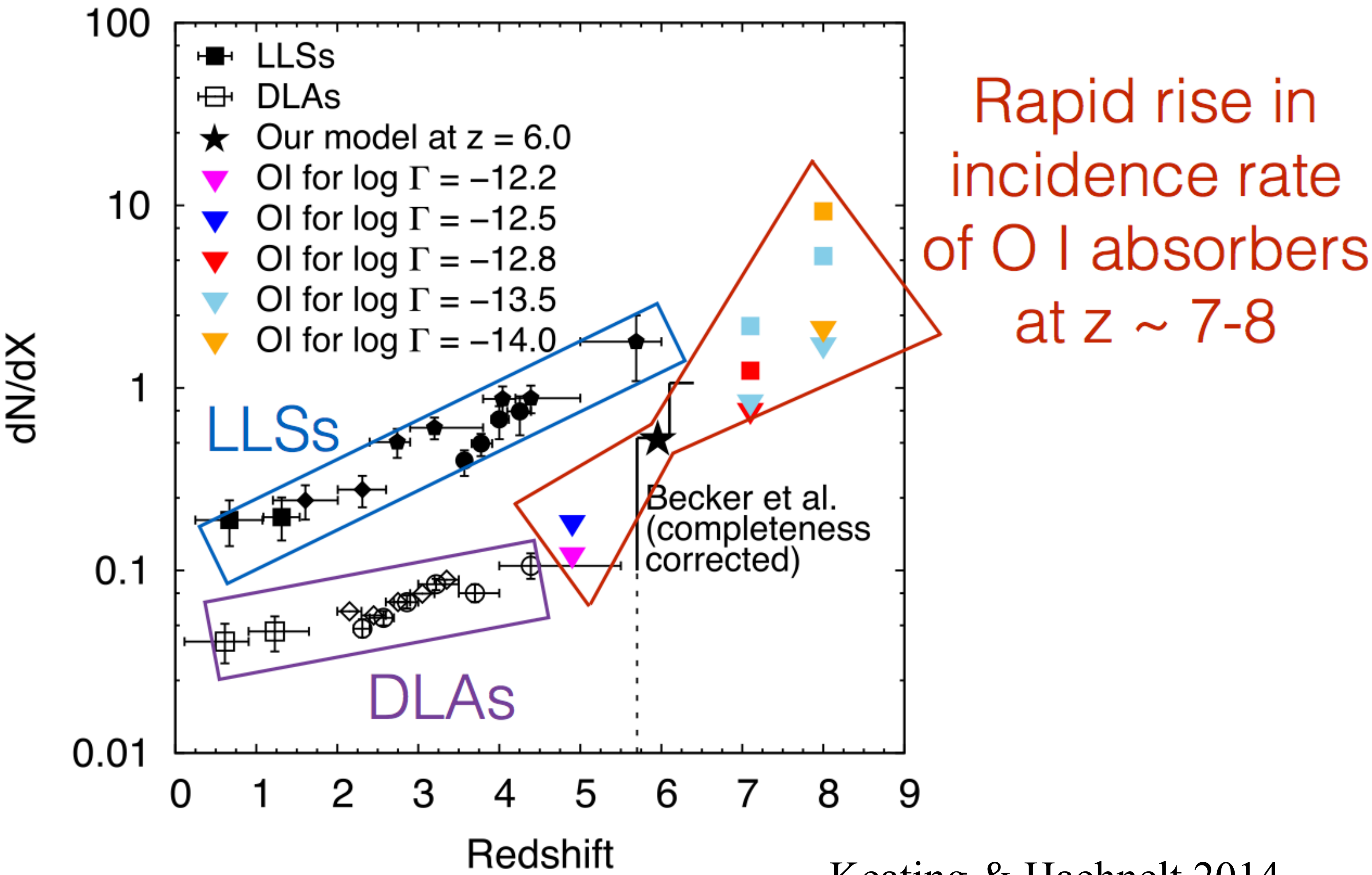


Becker+2011

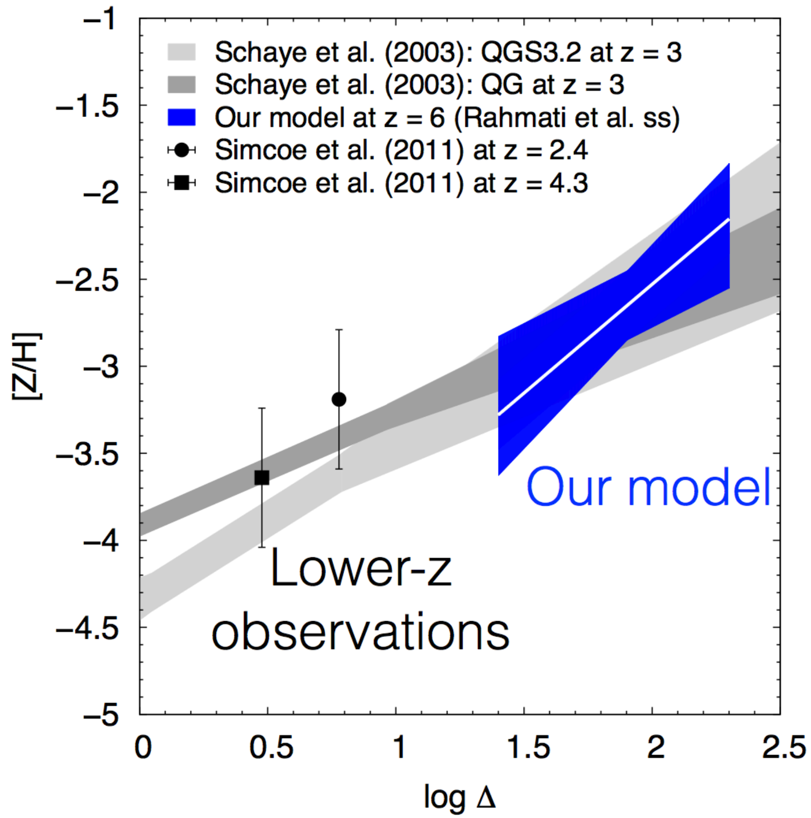
- When did the IGM become enriched with metals?
- Where are these absorbers found?

Keating & Haehnelt 2014.

The O I absorber incidence rate lies between lower redshift LLSs and DLAs



Keating & Haehnelt 2014.



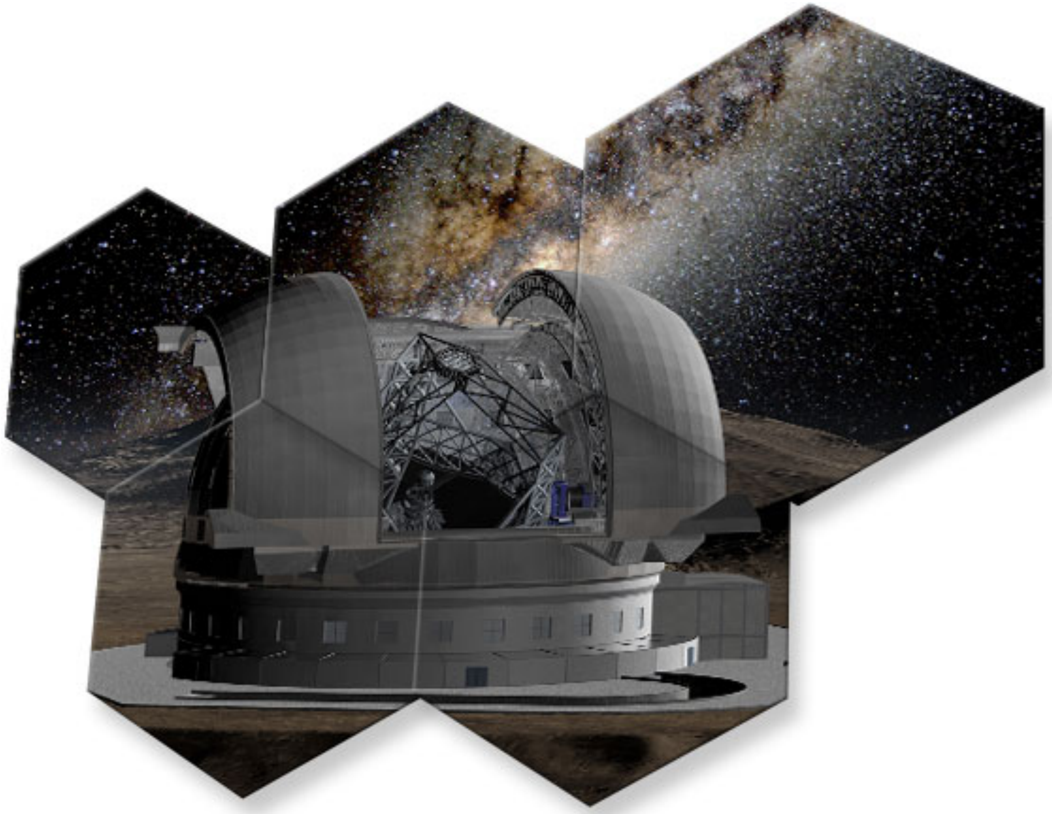
Model that fits:

$$Z = 10^{-2.65}\, Z_{\odot} \left(\frac{\Delta}{80}\right)^{1.3}$$

Surprisingly, little evidence for evolution between z = 3 and z = 6

Keating & Haehnelt 2014.

The End



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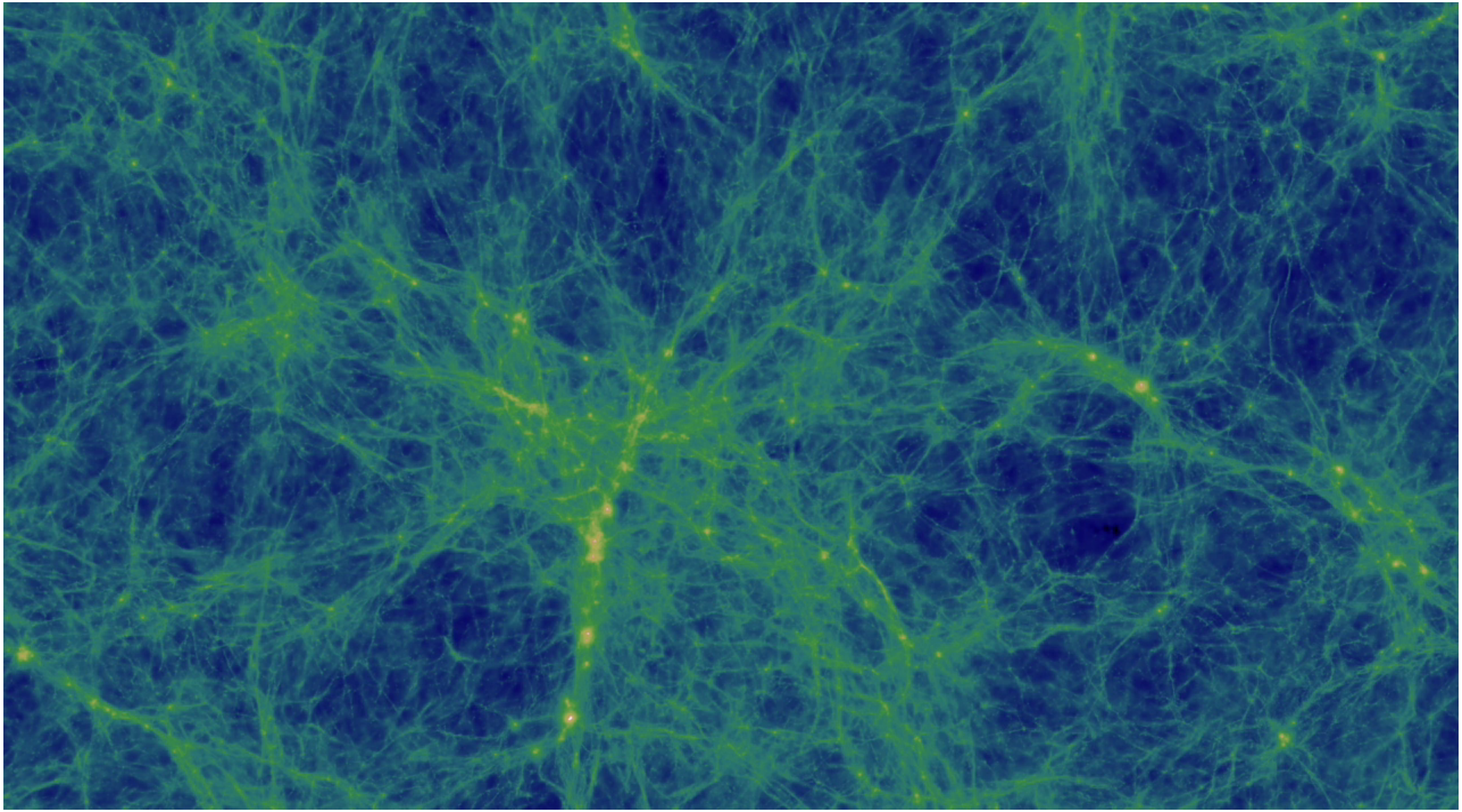

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