Constraining the Nature of Dark Matter and Reionization with the Lyman-Alpha Forest

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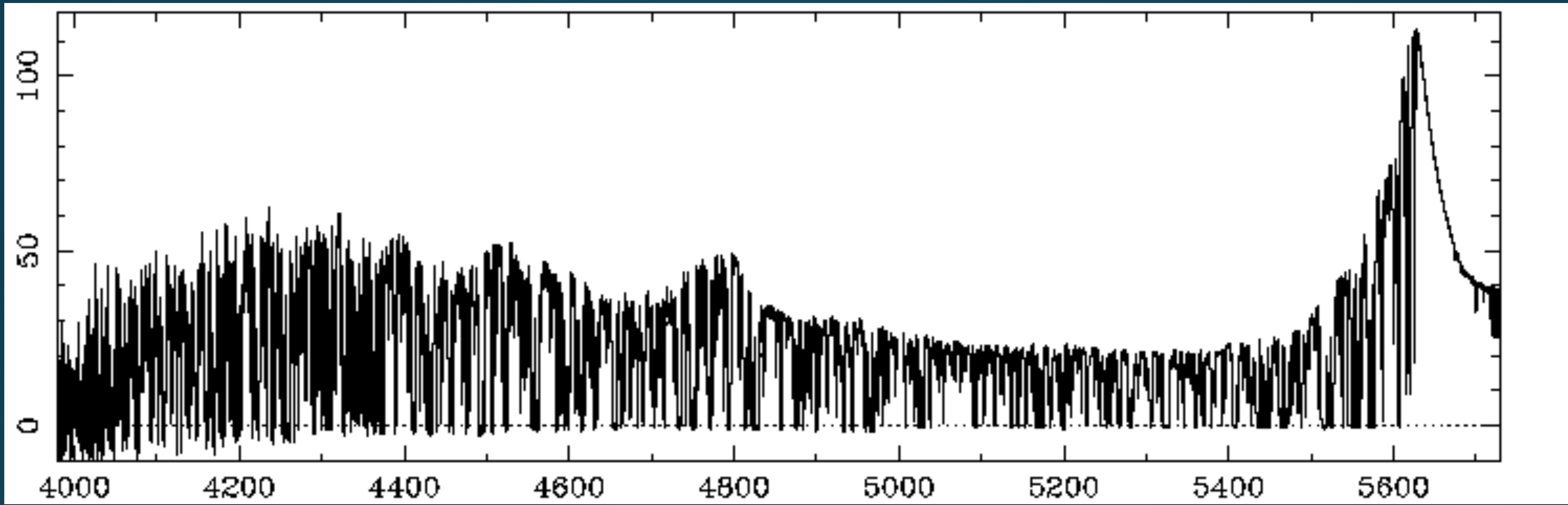
Matteo Viel

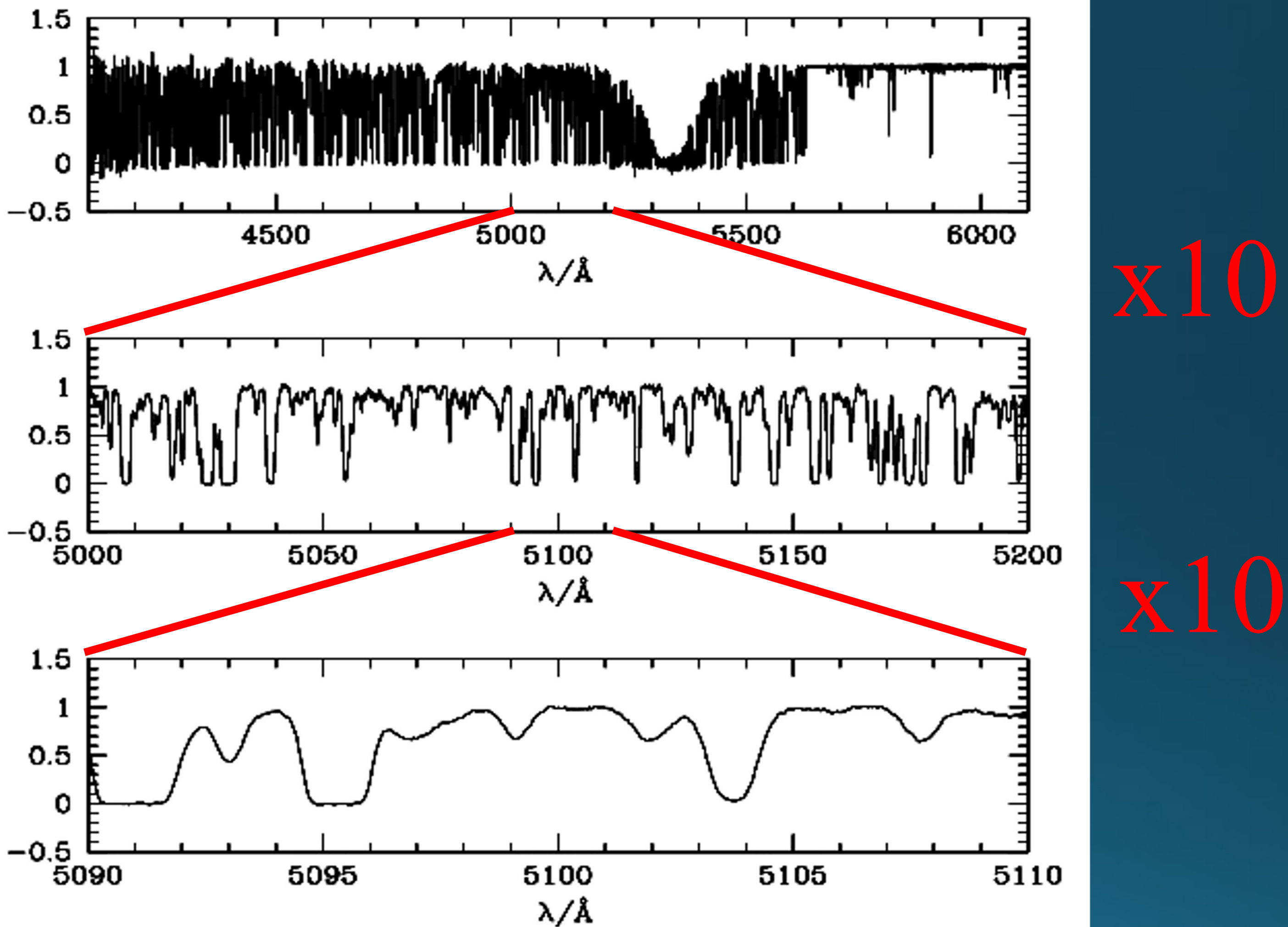
KITP, 9 March 2023

The Lyα forest

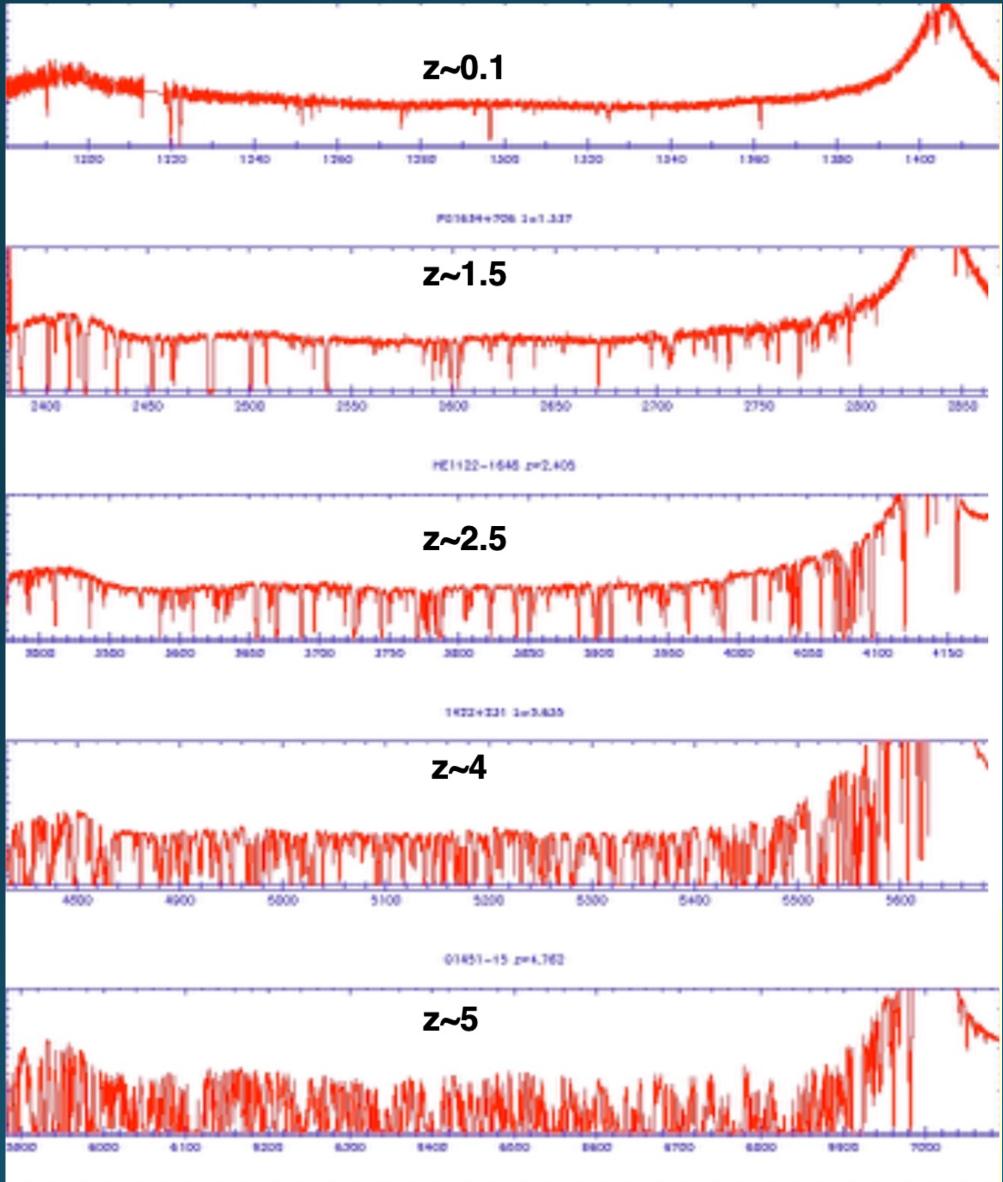


$\lambda_{Ly\alpha} = 1215.67\ (1+z)\ \text{Å}$

High resolution – High S/N!



A treasure trove of information!



The Lyα forest evolves rapidly

from Xiaohui Fan's Sao Paolo lectures

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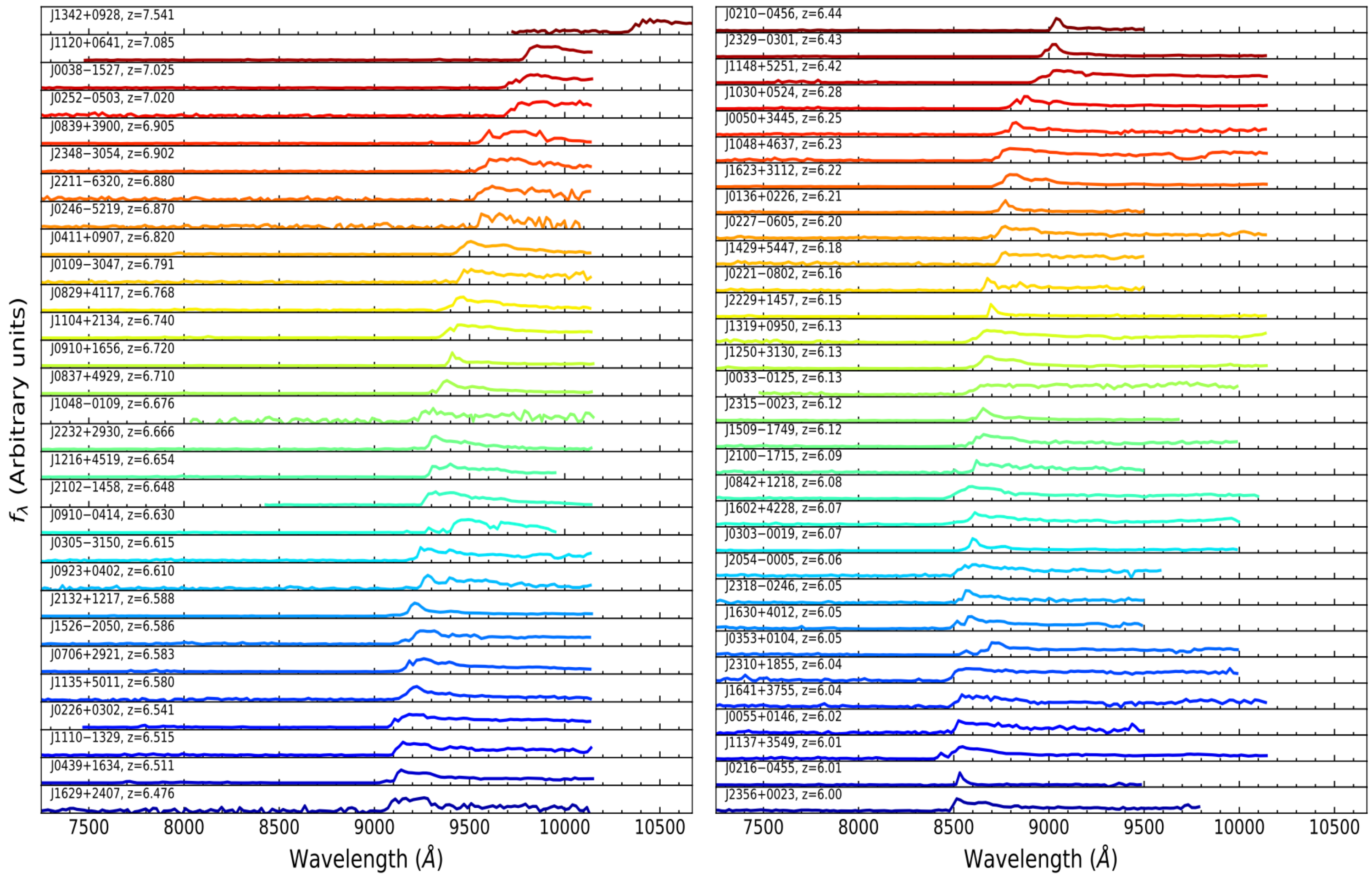


from Xiaohui Fan's Sao Paolo lectures

There are now large numbers of QSOs at z>6.

photoionization equilibrium:

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

↑ recombination coefficient ↑ photoionization rate

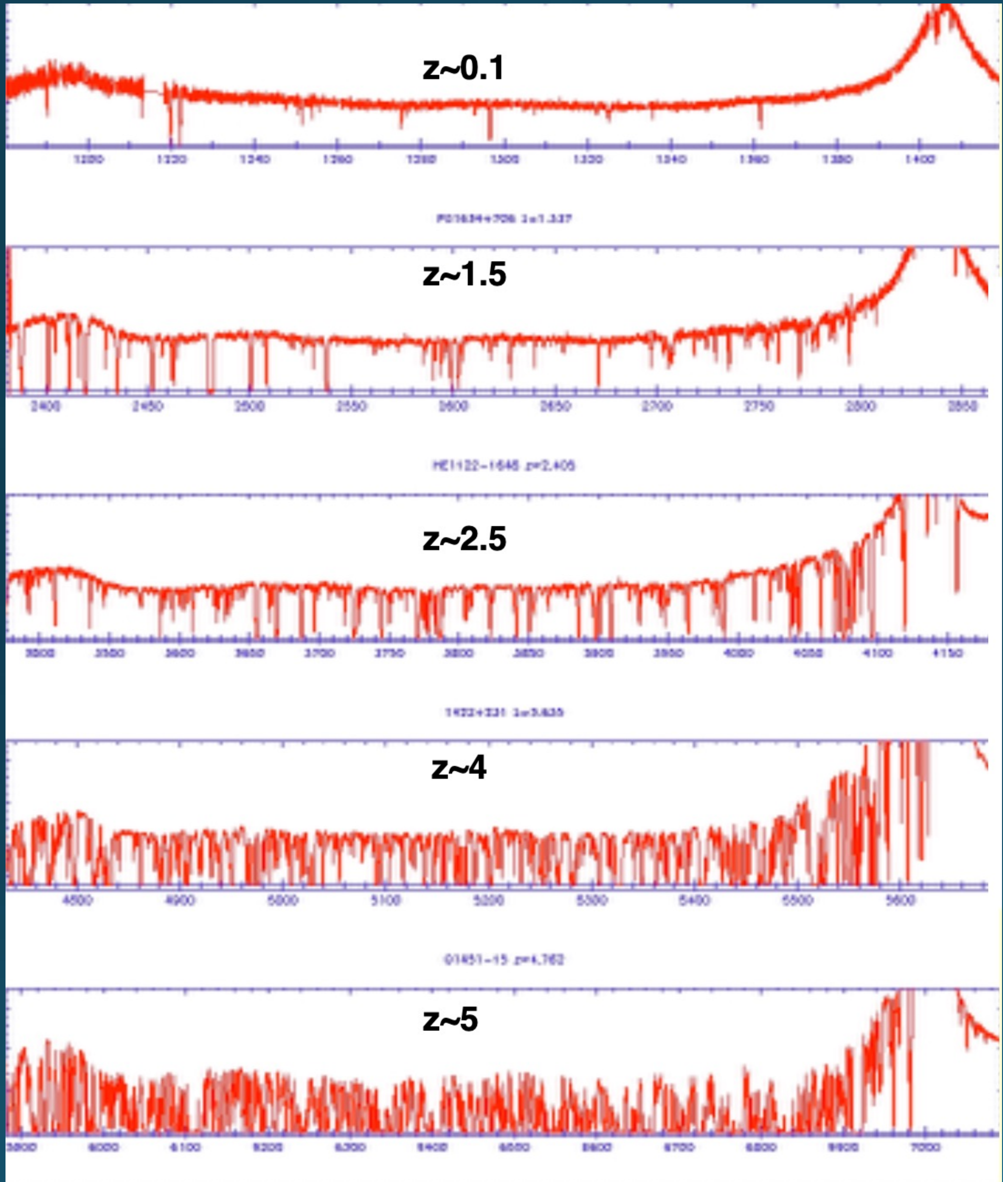
$$\frac{n_{HI}}{n_H} \sim 5 \cdot 10^{-6} \frac{\rho}{\hat{\rho}} \left(\frac{\Gamma}{10^{-12}\,s^{-1}}\right)^{-1} \left(\frac{T}{10^4\,K}\right)^{-0.7}$$

photoheating vs adiabatic cooling:

T indep. of density $\longrightarrow$ $T = T_0 \cdot \left(\frac{\rho}{\hat{\rho}}\right)^{\gamma - 1}$ $\quad \gamma \approx 1.3 - 1.4$

Fluctuating Gunn-Peterson approximation:

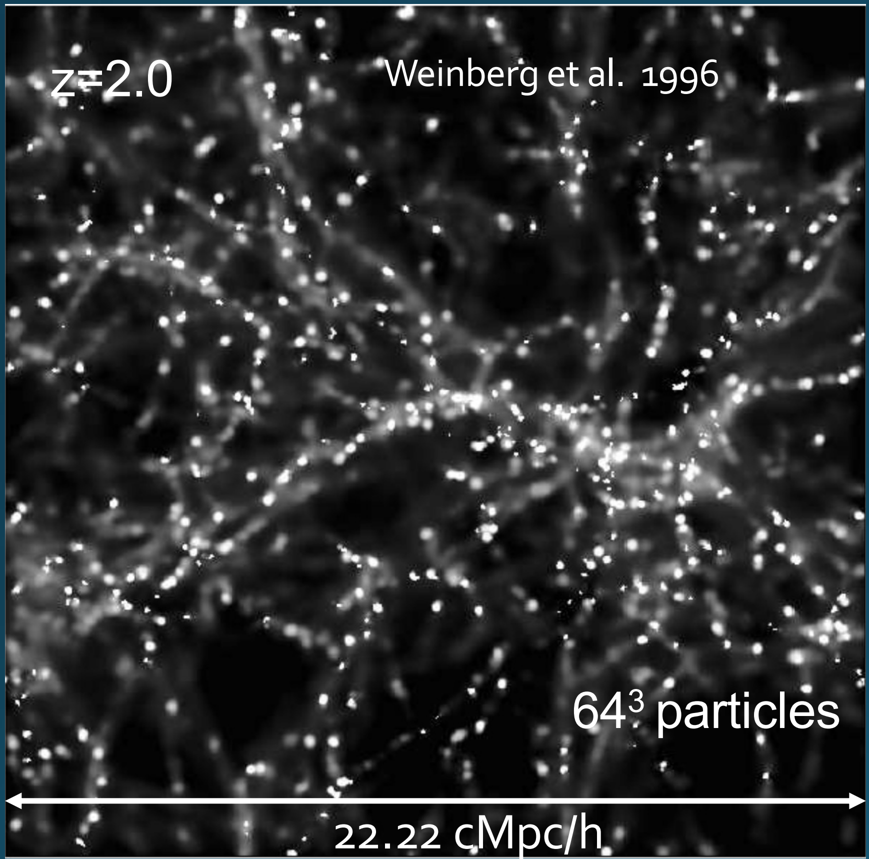
$$\tau_{HI}(z) = \int_0^z n_{HI}\, \sigma(\nu)\, \frac{dl}{dz}\, dz \sim 0.8 \frac{\rho}{\hat{\rho}} \left(\frac{1+z}{4}\right)^{4.5} \left(\frac{\Gamma}{10^{-12}\,s^{-1}}\right)^{-1} \left(\frac{T}{10^4\,K}\right)^{-0.7}$$

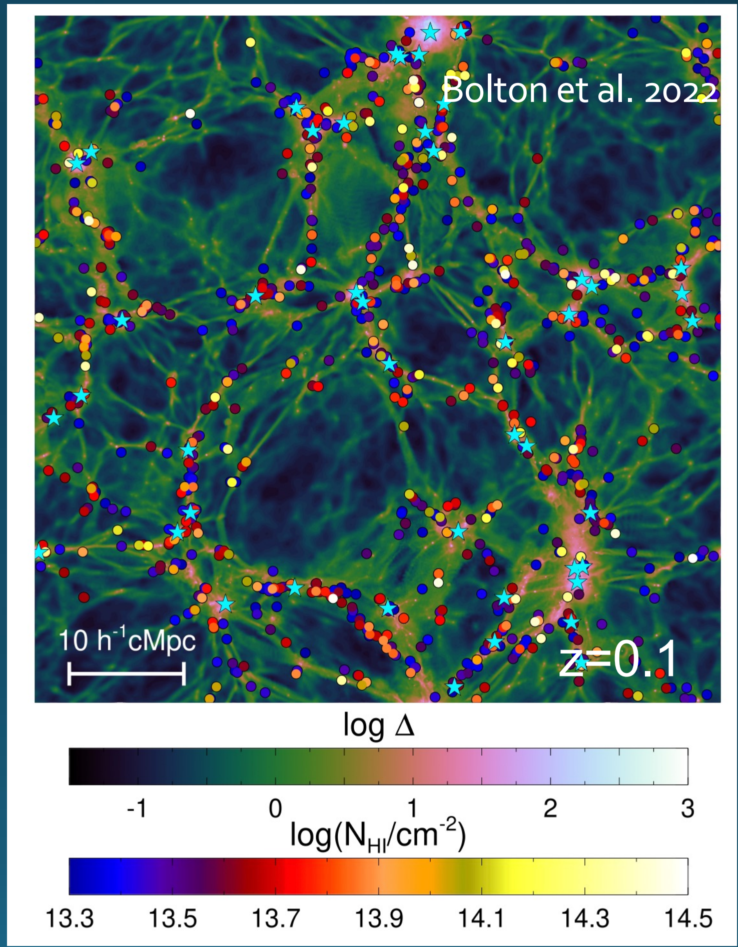


The Lyα forest evolves rapidly

from Xiaohui Fan's Sao Paolo lectures

A bit of history and connection to the cosmic web





Cen et al. 1994
Hernquist et al. 1996
Miralda-Escude et al. 1996
Rauch et al. 1997

cf Ikeuchi & Ostriker 1986
Rees 1986
Bond, Szalay & Silk 1988
Bi, Boerner & Chu 1992

Lyα forest ~~clouds~~

The Astrophysical Journal, 632:58–80, 2005 October 10
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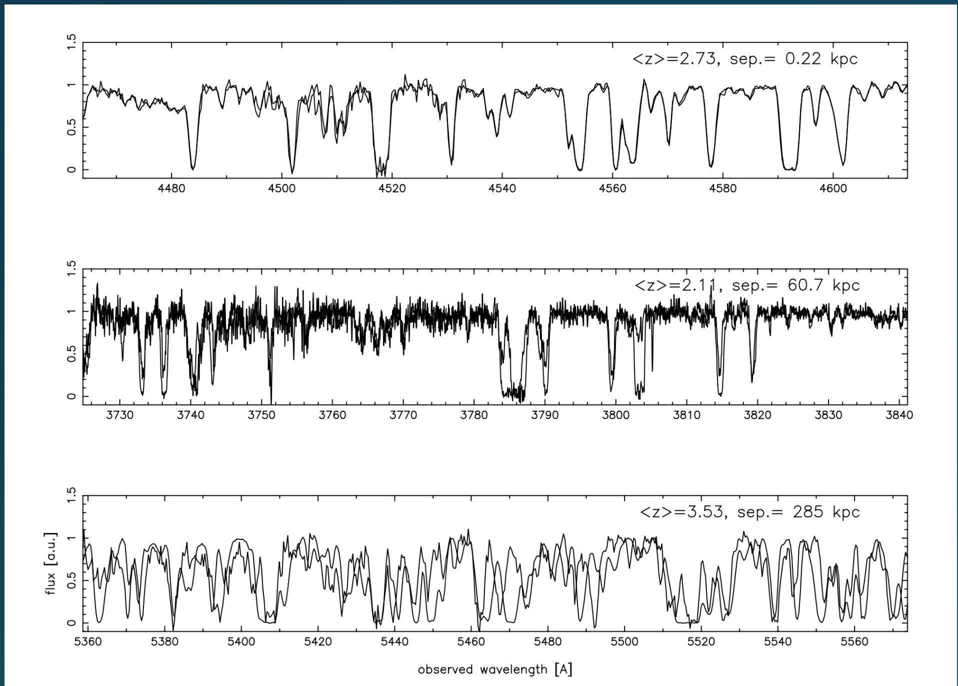
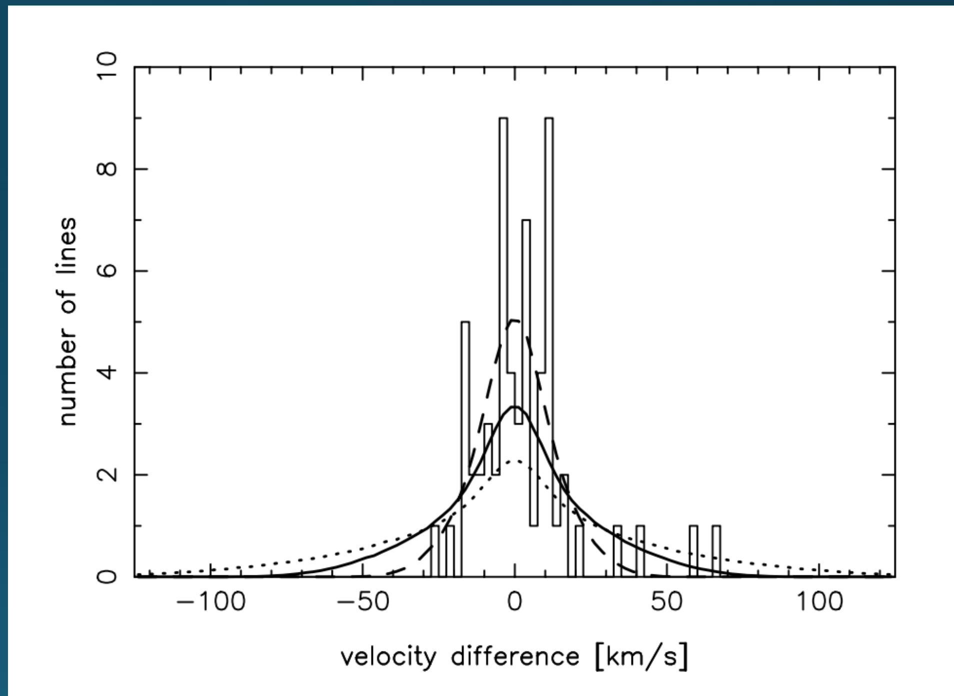
EXPANSION AND COLLAPSE IN THE COSMIC WEB[1,2]

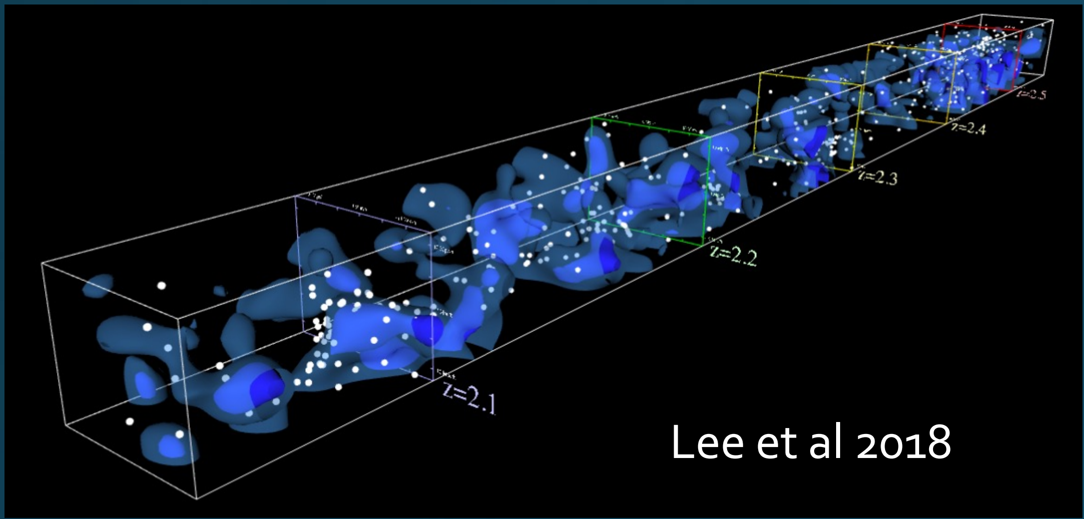
Michael Rauch,[3] George D. Becker,[4] Matteo Viel,[5] Wallace L. W. Sargent,[4] Alain Smette,[6,7]
Robert A. Simcoe,[8] Thomas A. Barlow,[4] and Martin G. Haehnelt[5]
Received 2005 April 2; accepted 2005 May 26





Velocity “shear” consistent with randomly orientated pancakes at z=2 expanding with 0.8 × v_{Hubble}

Lyman-alpha forest tomography of the cosmic web



Nusser & Haehnelt 1999
Pichon et al 2001
Caucci et al. 2008
Stark et al. 2015
.....
Kraljic, Laigle, Pichon et al. 2022
cf talk by Nick Gnedin in this program

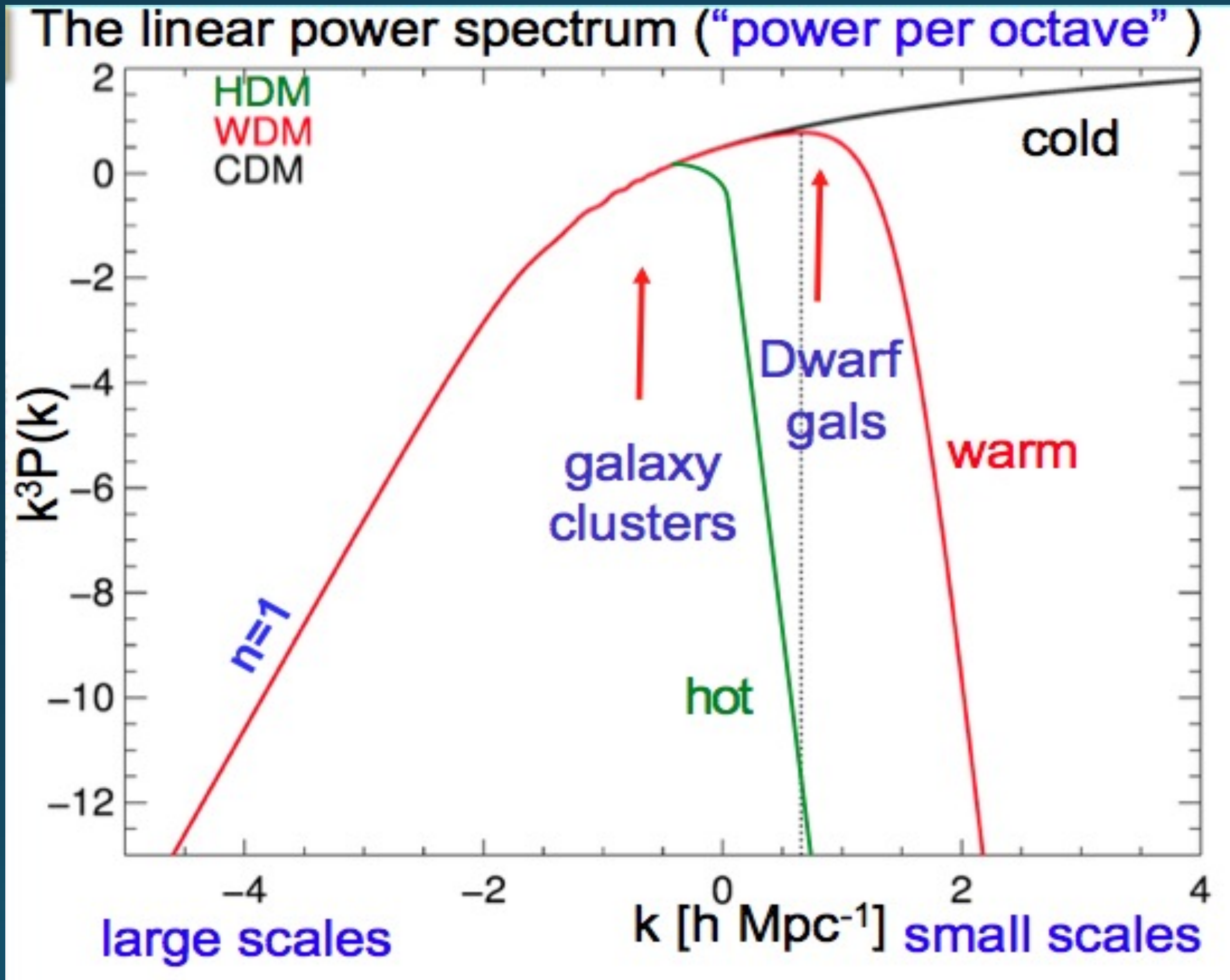
"Inverting" the flux distribution to obtain the density distribution using the fluctuating Gunn-Peterson approximation.
Cross-correlating with galaxies.

Major science case for WEAVE , DESI, Subaru, ELT's ....

Probing dark matter with the Lyα forest

KITP, 9 March 2023

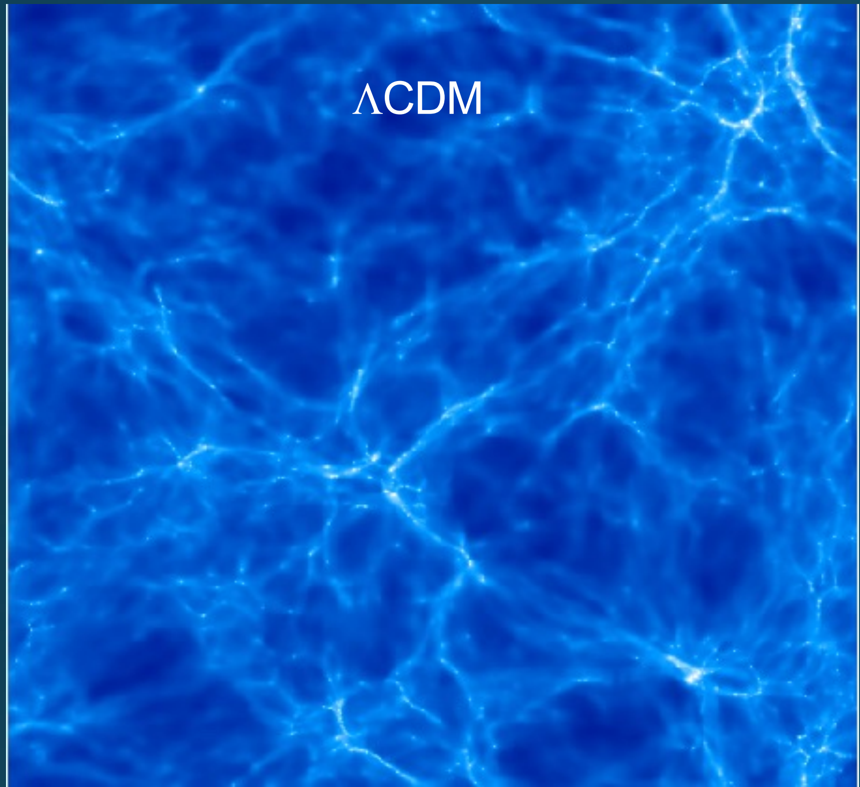
Cut-off in the matter power spectrum on astrophysically interesting scales due to free-streaming or FDM.

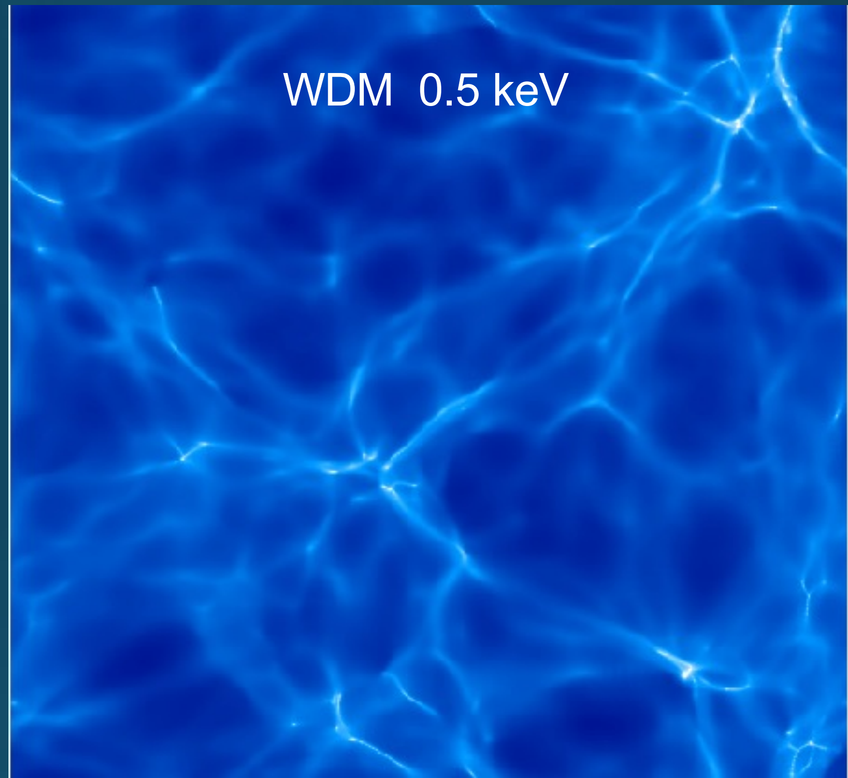


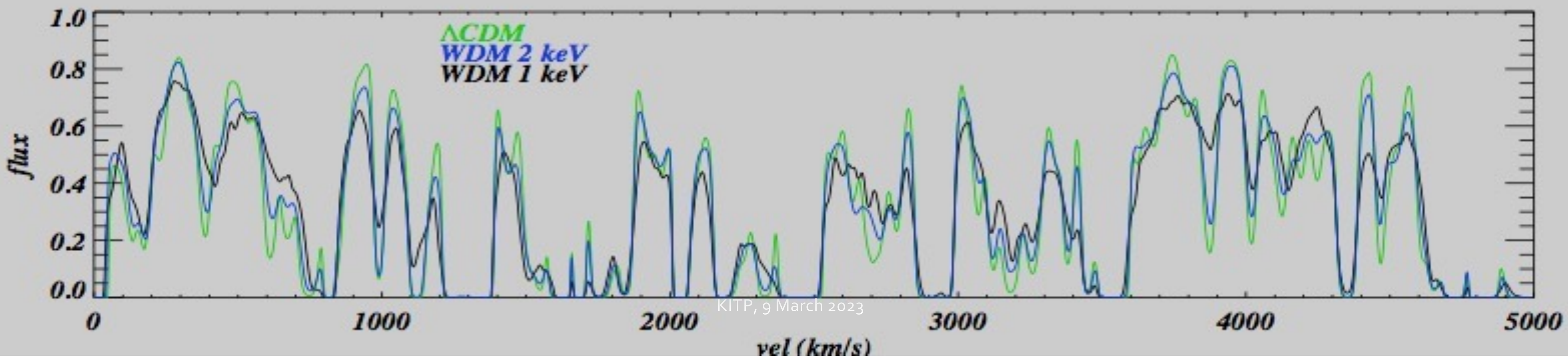
- early decoupling thermal relics
- sterile neutrinos
- ultralight axions
- gravitinos
- ….

courtesy of Carlos Frenk

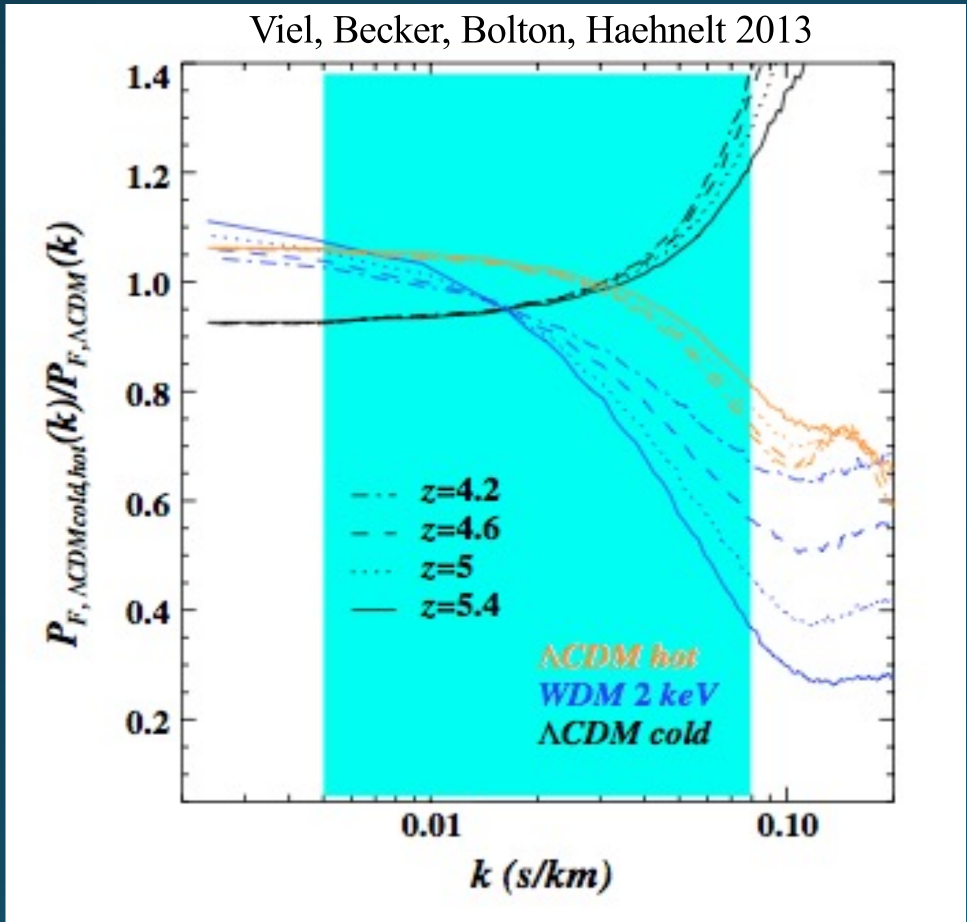
Free-streaming erases structure







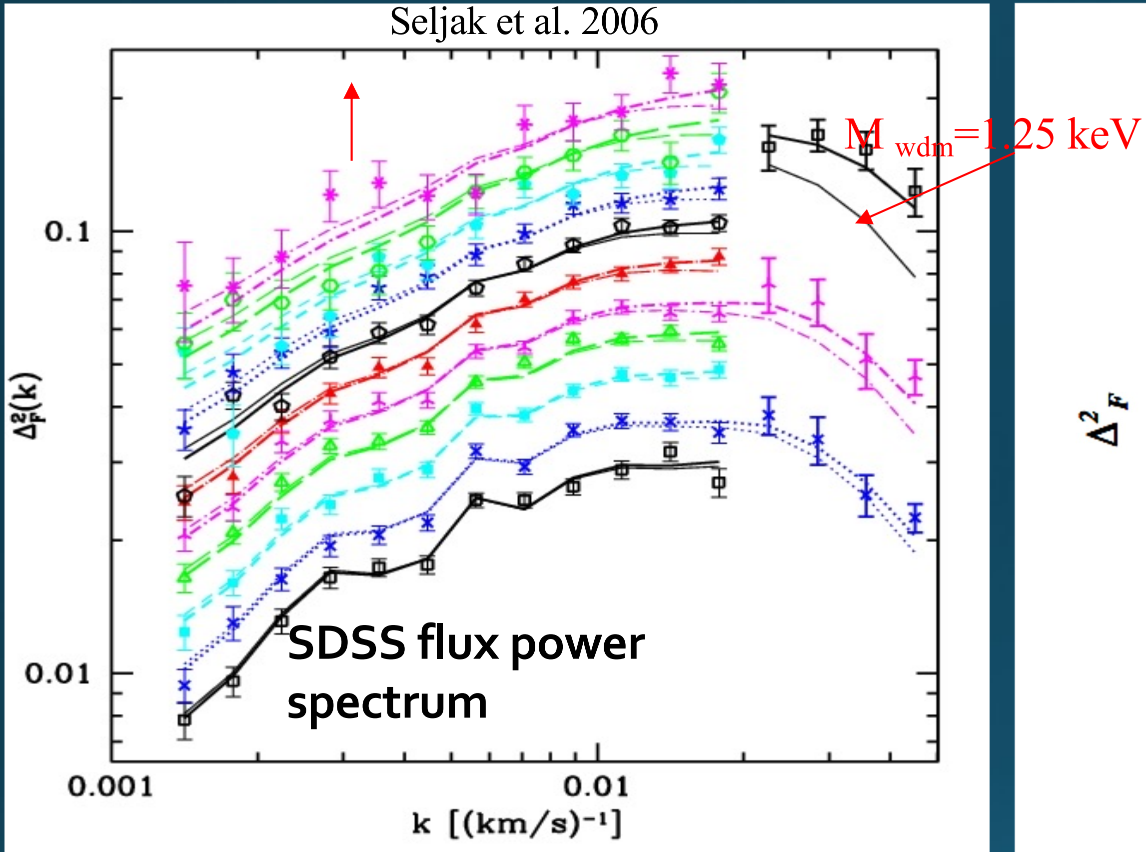
The effects of temperature and free streaming are not degenerate



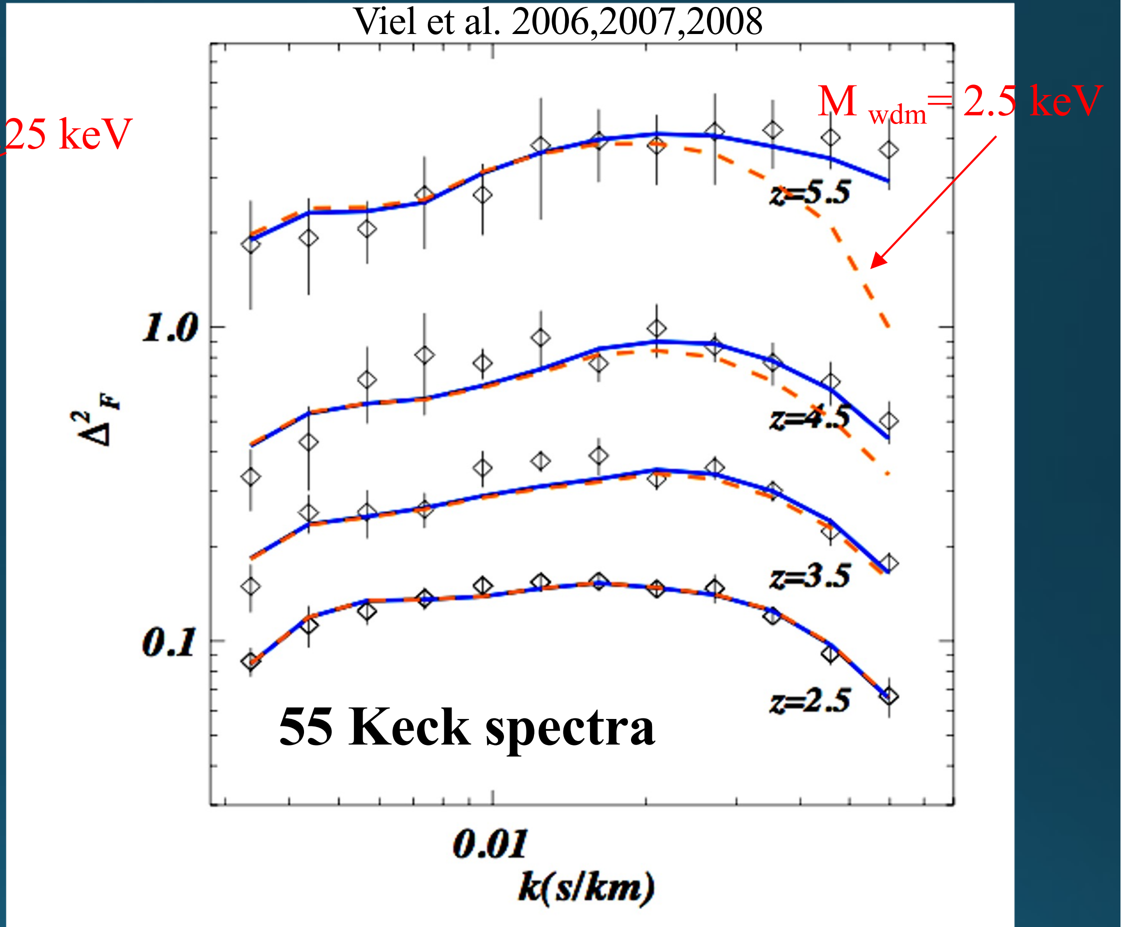
For fixed comoving free-streaming length the cut-off in velocity space is at larger scales/smaller k at higher redshift, and thus in principle easier to detect.

I will focus on constraints from high-resolution data. All limits are quoted as masses of a thermal relic.

Observational results



large scales small scales

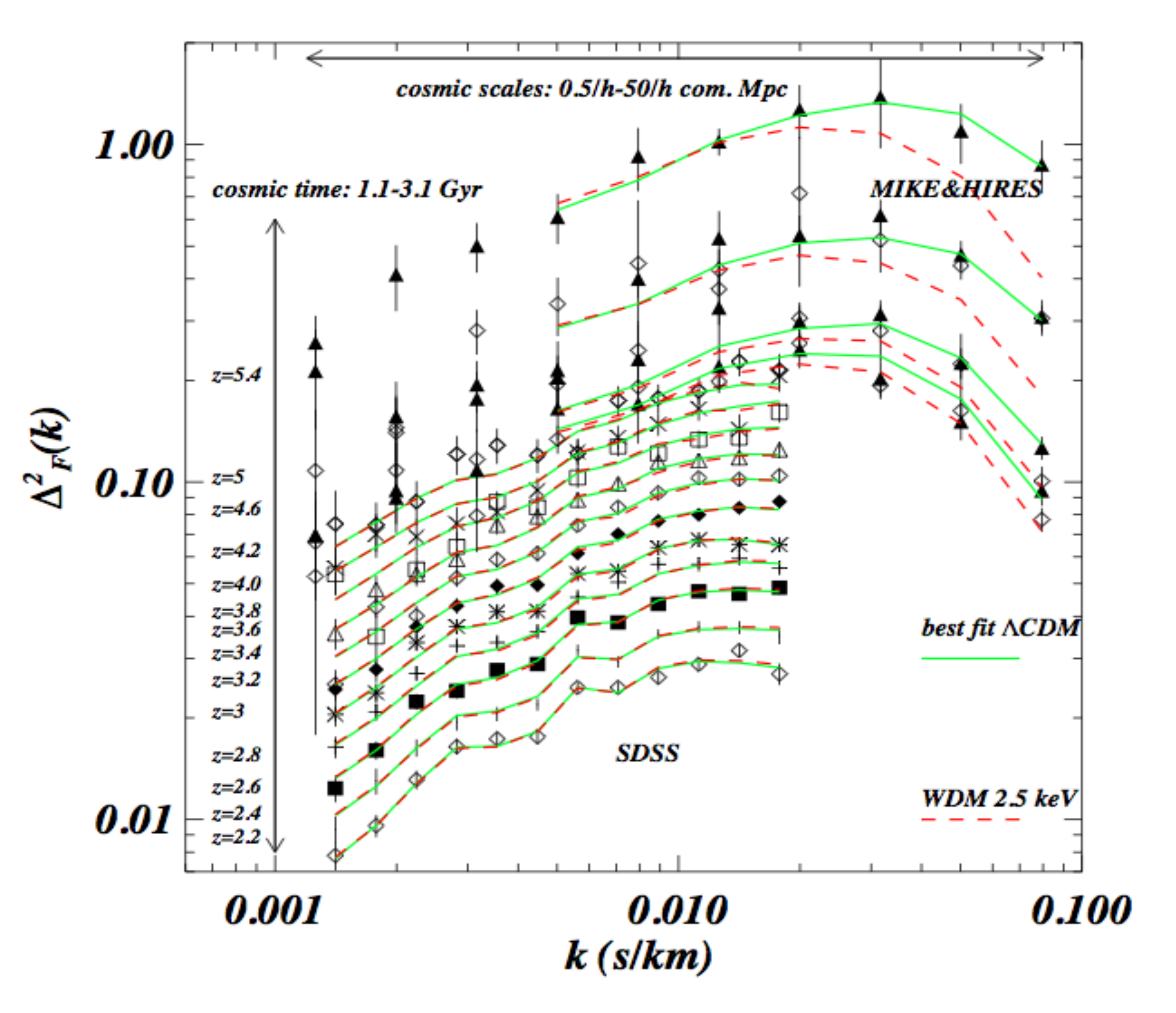


M_{wdm} >2.4 keV

M_{wdm} > 4 keV

These are the limits for thermal relics. For sterile neutrinos the story is more complicated.

Our "best" WDM results in 2013



- 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)

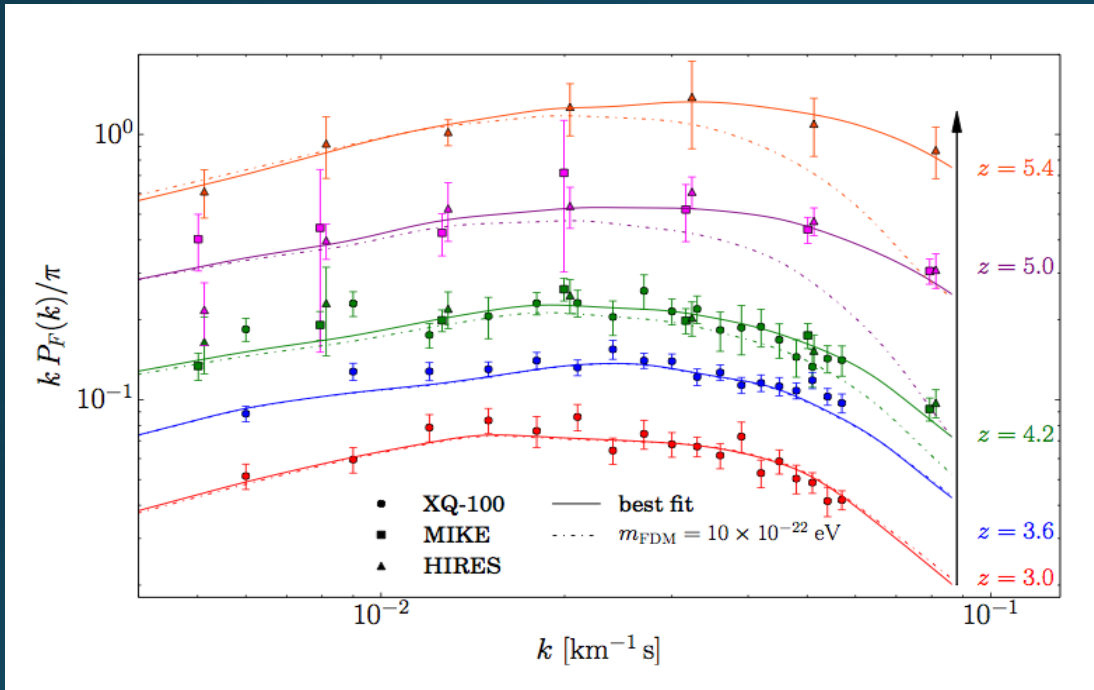
2 keV WDM disfavoured at about 4σ!

Viel, Becker, Bolton, Haehnelt 2013

PRL **119,** 031302 (2017) PHYSICAL REVIEW LETTERS week ending 21 JULY 2017

First Constraints on Fuzzy Dark Matter from Lyman-α Forest Data and Hydrodynamical Simulations

Vid Iršič,[1,2,3,*] Matteo Viel,[4,5,6,†] Martin G. Haehnelt,[7] James S. Bolton,[8] and George D. Becker[7,9]



- New intermediadiate resolution X-Shooter data(XQ 100 sample)
- Improved analysis

For reasonable prior on thermal history:

m_{FDM}>37.5 x 10^{-22} eV (2 σ C.L.)

m_{WDM}>5.3 keV (2σ C.L.)

This leaves very little/no room for resolving the "small scale crisis" of CDM
→ baryonic solution is favoured

PHYSICAL REVIEW D **96,** 023522 (2017)

New constraints on the free-streaming of warm dark matter from intermediate and small scale Lyman-α forest data

Vid Iršič,[1,2,3,*] Matteo Viel,[4,5,6,†] Martin G. Haehnelt,[7] James S. Bolton,[8] Stefano Cristiani,[5,6] George D. Becker,[7,9] Valentina D'Odorico,[5] Guido Cupani,[5] Tae-Sun Kim,[5] Trystyn A. M. Berg,[10] Sebastian López,[11] Sara Ellison,[10] Lise Christensen,[12] Kelly D. Denney,[13] and Gábor Worseck[14]

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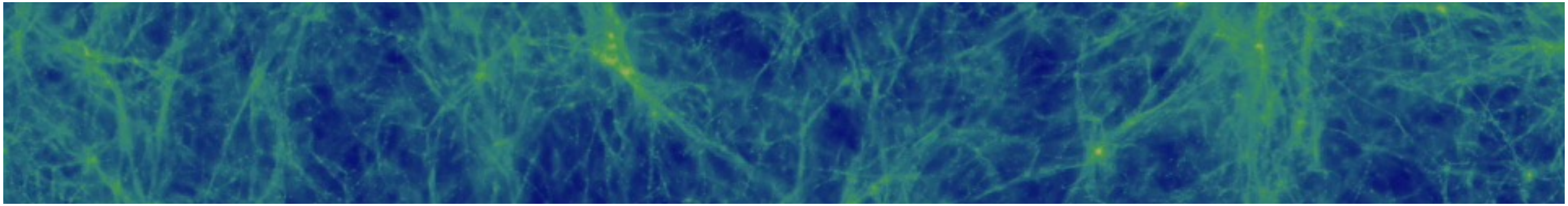
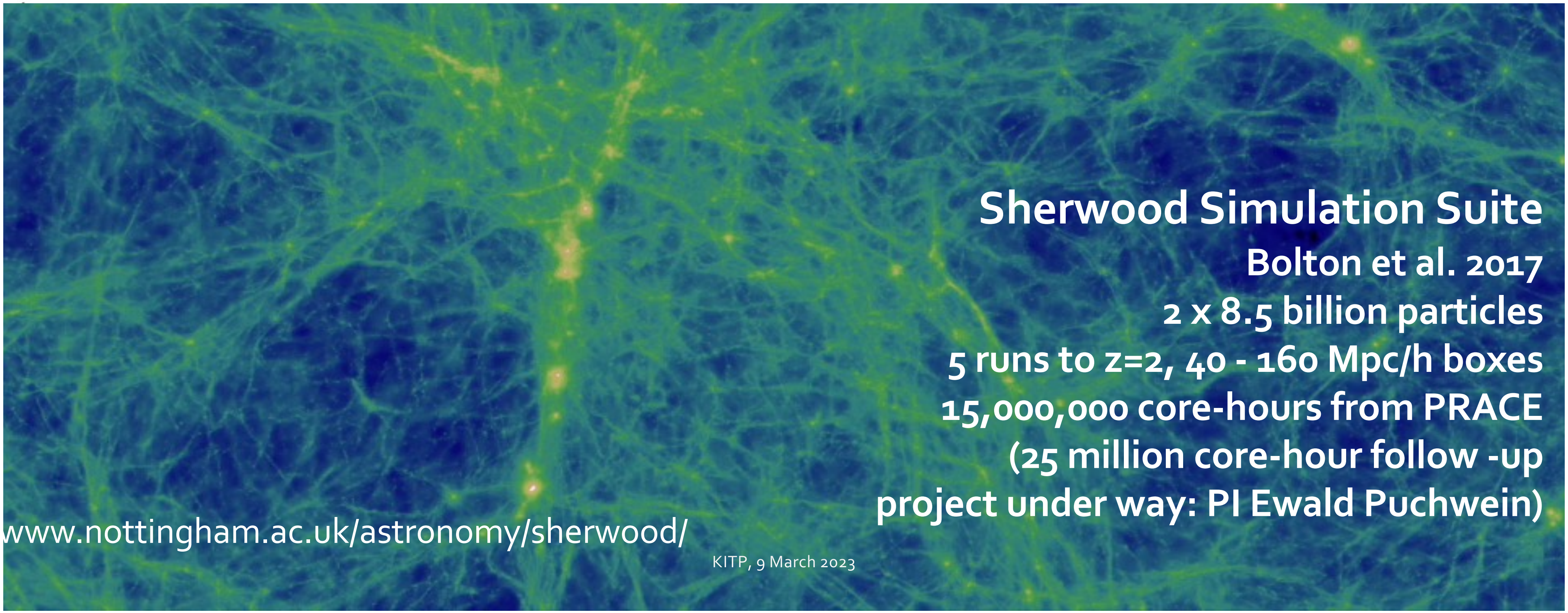


The Sherwood simulation suite: overview and data comparisons with the Lyman α forest at redshifts $2 \leq z \leq 5$

James S. Bolton,[1★] Ewald Puchwein,[2] Debora Sijacki,[2] Martin G. Haehnelt,[2] Tae-Sun Kim,[3] Avery Meiksin,[4] John A. Regan[5] and Matteo Viel[3,6]



Nuisance effects /parameters

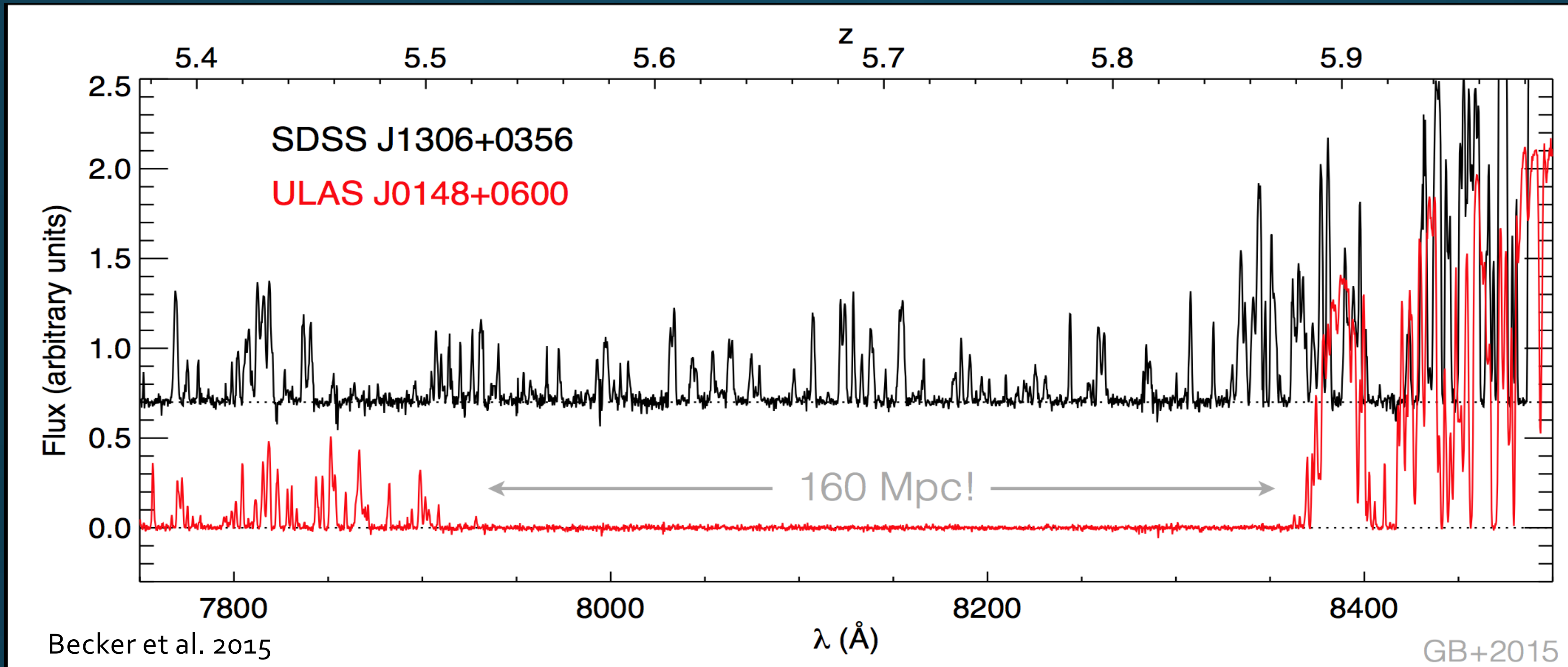
- instrumental resolution
- instrumental noise
- "continuum" fitting
- strong absorbers
- metal absorbers

- mean flux has to be measured/assumed
  alternatively photoionization rate has to be measured/assumed
- thermal broadening (instantaneous temperature)
- Jeans smoothing (integrated energy input)
- **spatial variations of the above**

- **anchoring at large scales**
- cosmological parameters
- shape of cut-off in DM transfer function is not generic

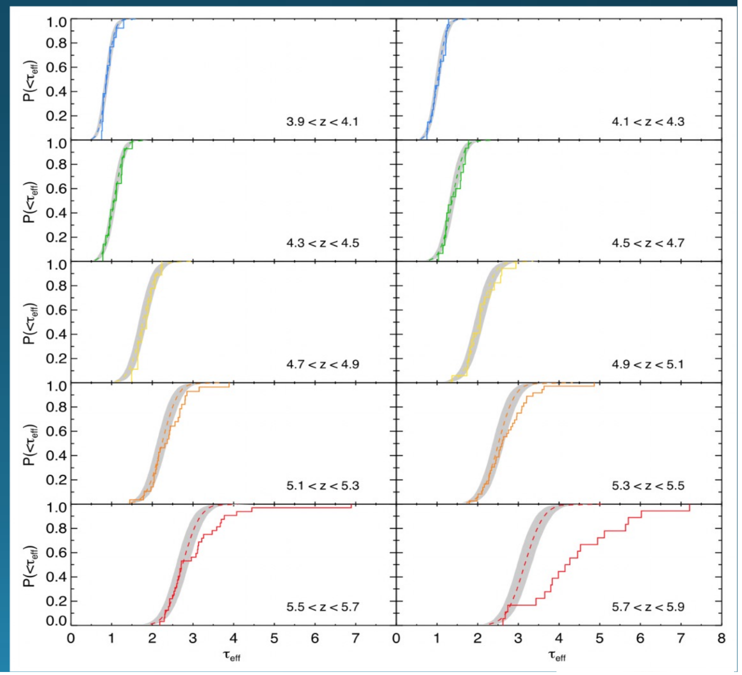
- corrections for box size and resolution
- missing physics in the simulations
- interpolation errors in sparsely sampled parameter space

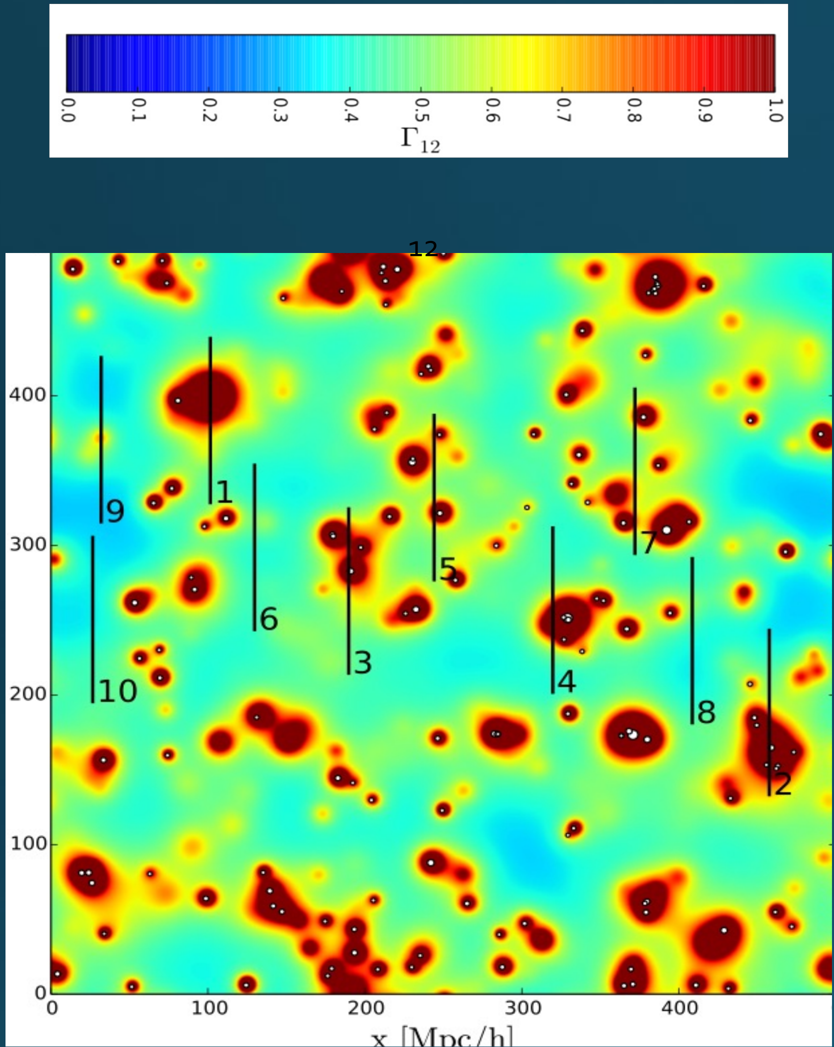
Reionization – later than thought

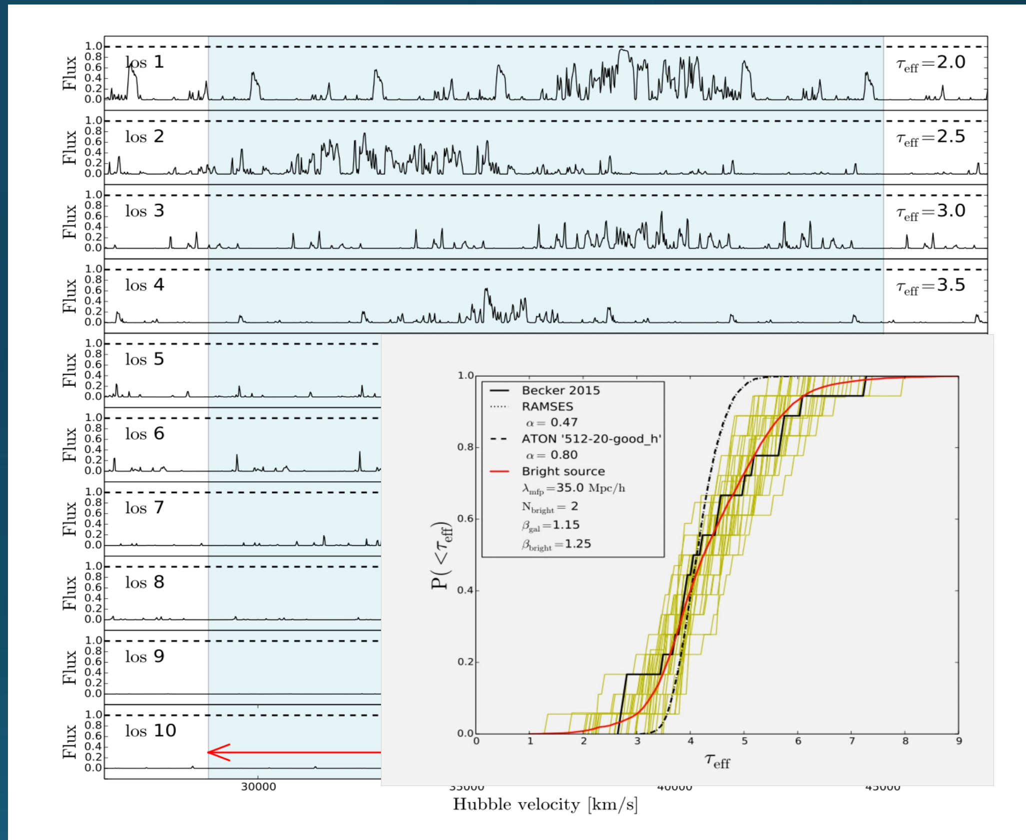


The large fluctuations of the optical depth extend to surprisingly large scales.

Are there still large completely neutral regions even at z~5.5?







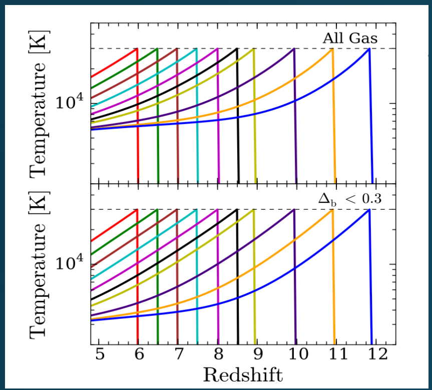
Chardin et al. 17

Opacity fluctuation on large scales → QSOs?
Are there enough QSOs? Helium reionization too early?

LARGE OPACITY VARIATIONS IN THE HIGH-REDSHIFT LYα FOREST: THE SIGNATURE OF RELIC TEMPERATURE FLUCTUATIONS FROM PATCHY REIONIZATION

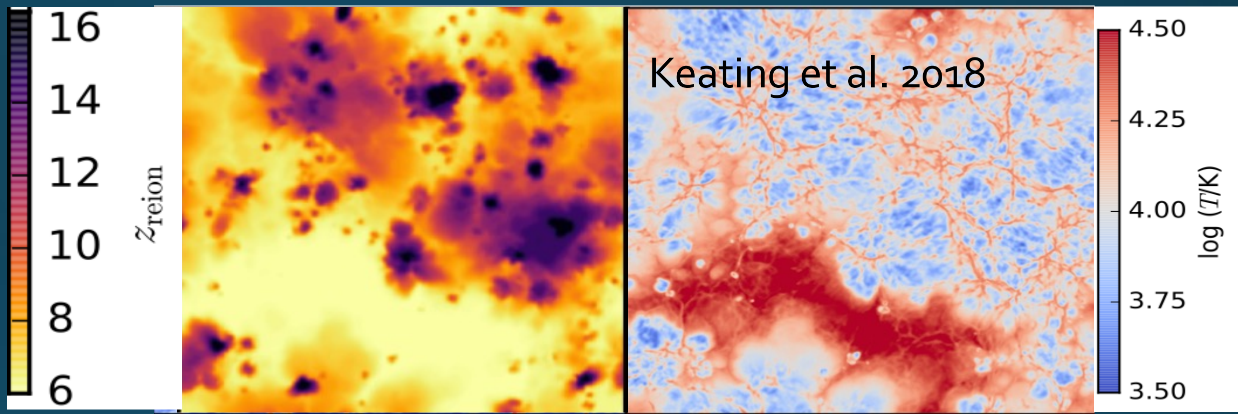
ANSON D'ALOISIO[1†], MATTHEW MCQUINN[1], & HY TRAC[2]

Draft version December 2, 2015



Temperature dependence of recombinations

$n_{HI} \propto T^{-0.7}$



Adiabatic cooling following very high initial temperatures

+

extended reionization with wide spread of reionization redshifts

=

large opacity fluctuations

For realistic assumptions temperature fluctuations are not large enough for this to work.

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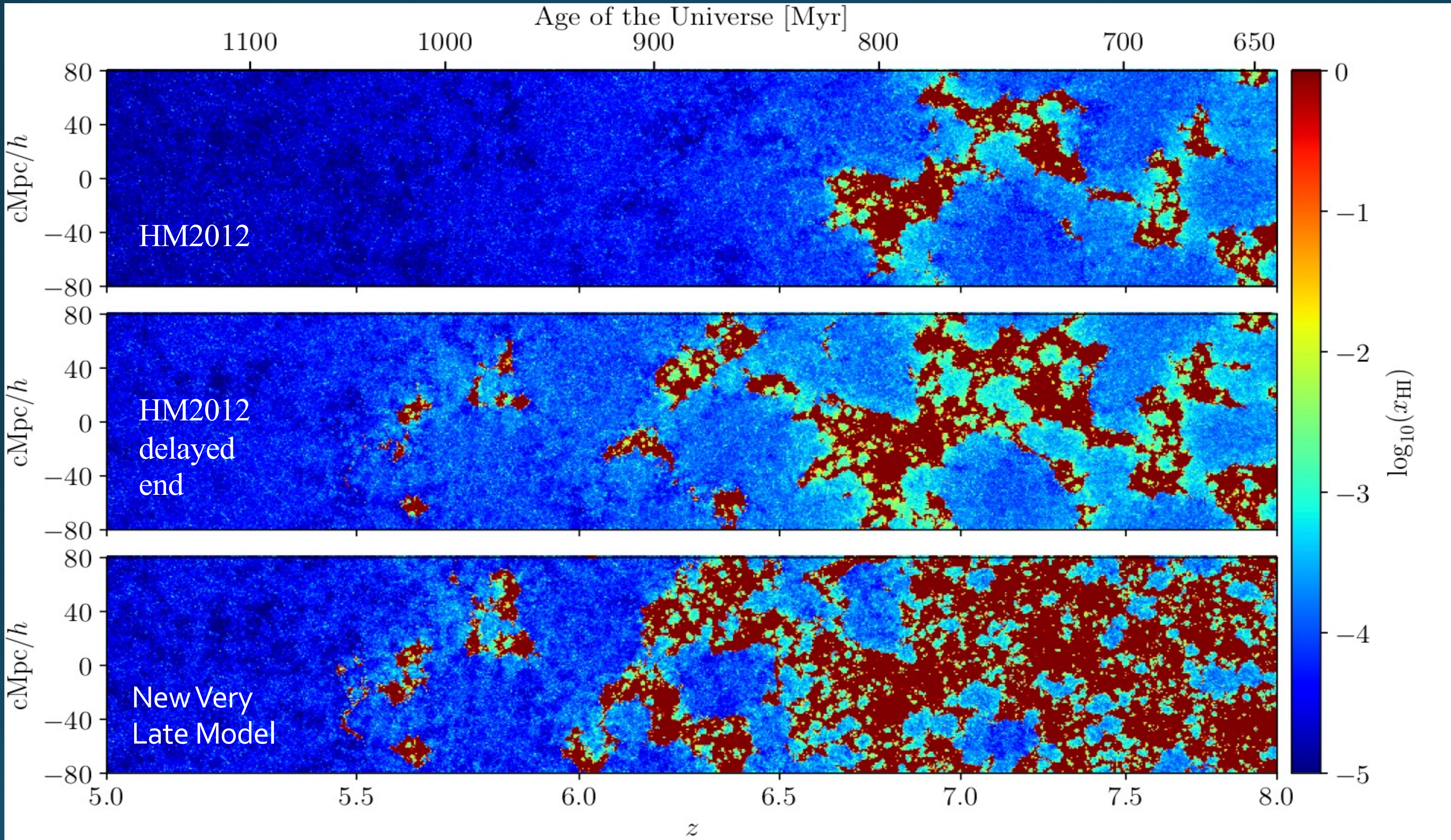
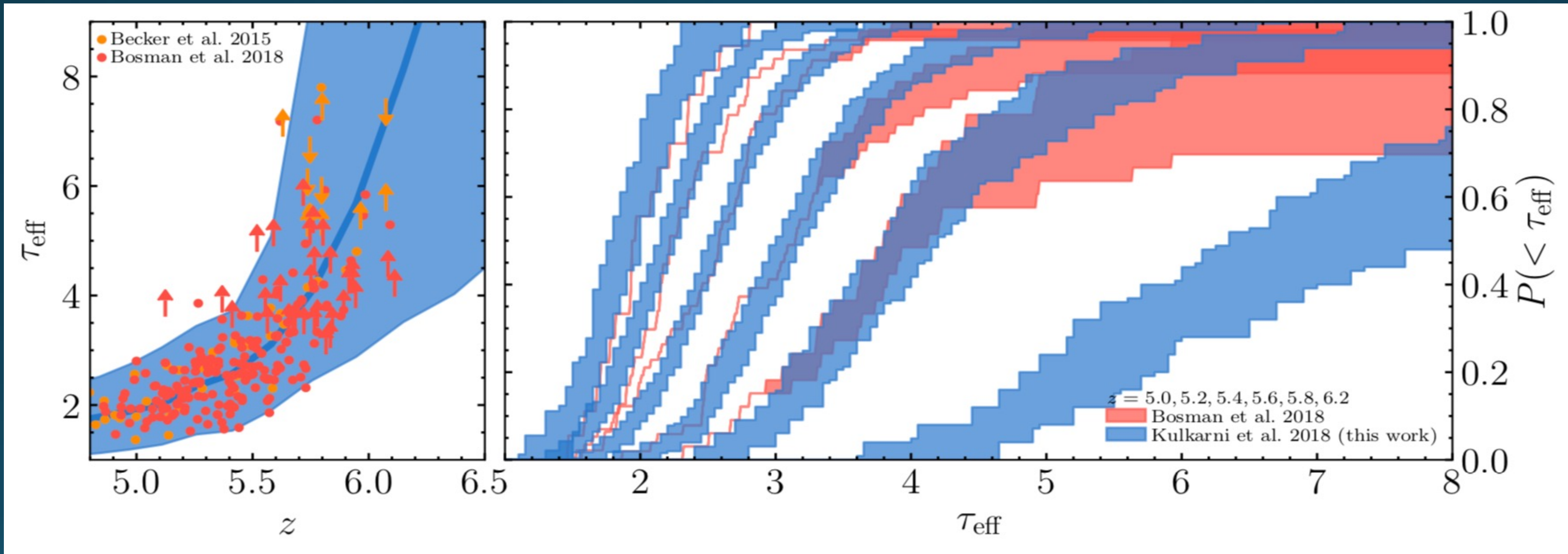
Later than thought



The end of reionization in our new simulation is significantly later than z~6, with large islands of neutral hydrogen persisting until z≤ 5.5.

Large Lyman-α opacity fluctuations and low CMB τ in models of late reionization with large islands of neutral hydrogen extending to $z < 5.5$

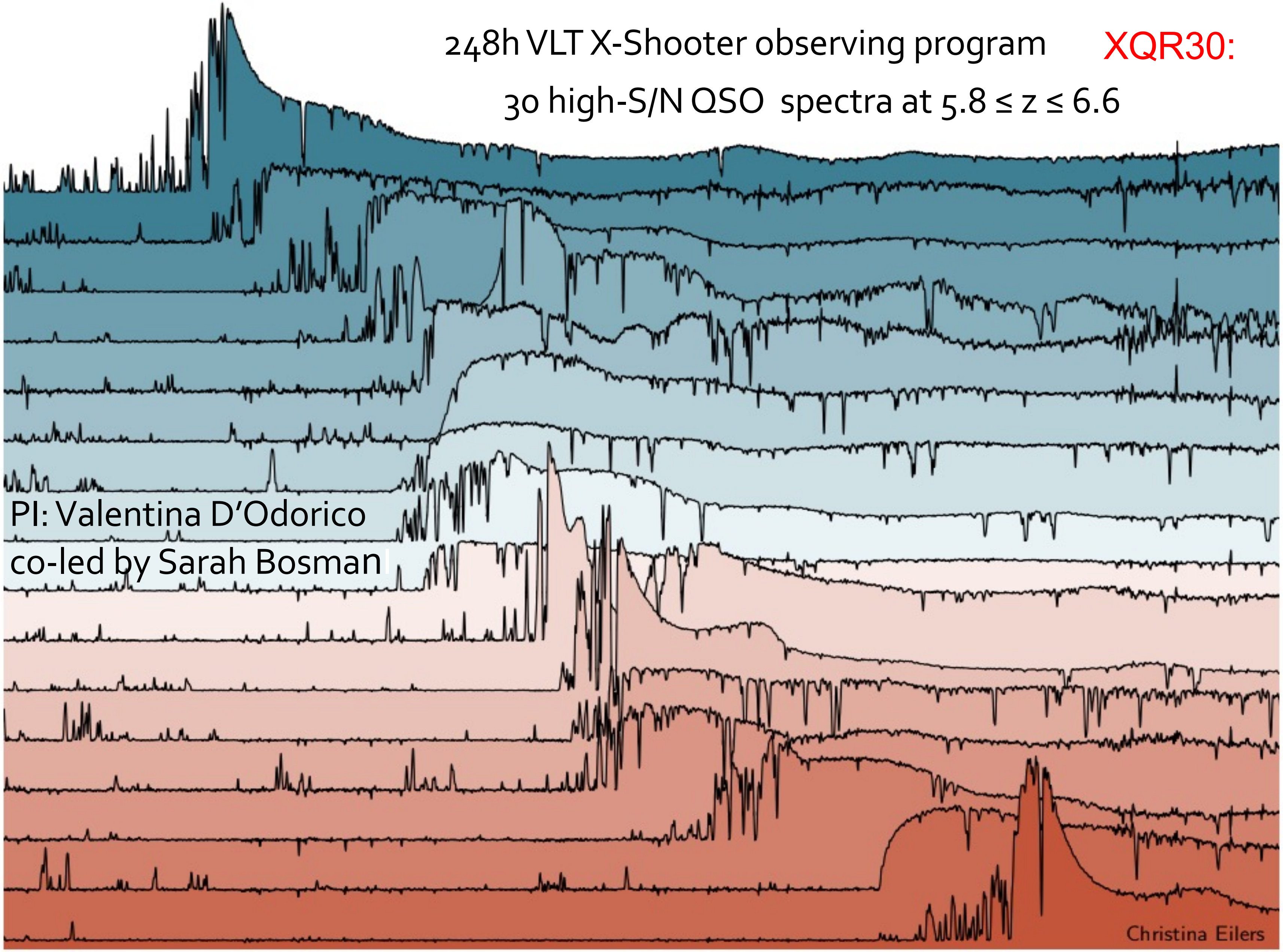
Girish Kulkarni[1,2★], Laura C. Keating[3], Martin G. Haehnelt[1,2], Sarah E. I. Bosman[4], Ewald Puchwein[1,2], Jonathan Chardin[5] and Dominique Aubert[5]



The new simulation agrees with the Lyα forest opacity data very well.

XQR30: 248h VLT X-Shooter observing program

30 high-S/N QSO spectra at $5.8 \leq z \leq 6.6$



PI: Valentina D'Odorico

co-led by Sarah Bosman

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **514,** 55–76 (2022) https://doi.org/10.1093/mnras/stac1046

Hydrogen reionization ends by $z = 5.3$: Lyman-α optical depth measured by the XQR-30 sample

Sarah E. I. Bosman ,[1★] Frederick B. Davies ,[1] George D. Becker ,[2] Laura C. Keating ,[3] Rebecca L. Davies,[4,5] Yongda Zhu ,[2] Anna-Christina Eilers ,[6†] Valentina D'Odorico ,[7,8] Fuyan Bian,[9] Manuela Bischetti,[7,10] Stefano V. Cristiani ,[7] Xiaohui Fan,[11] Emanuele P. Farina ,[12] Martin G. Haehnelt,[13,14] Joseph F. Hennawi ,[15,16] Girish Kulkarni ,[17] Andrei Mesinger ,[8] Romain A. Meyer,[1] Masafusa Onoue,[1] Andrea Pallottini ,[7] Yuxiang Qin ,[18,5] Emma Ryan-Weber ,[4,5] Jan-Torge Schindler ,[1,16] Fabian Walter ,[1] Feige Wang [11†] and Jinyi Yang [11]

The Astrophysical Journal, 923:223 (23pp), 2021 December 20 https://doi.org/10.3847/1538-4357/ac26c2
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Chasing the Tail of Cosmic Reionization with Dark Gap Statistics in the Lyα Forest over $5 < z < 6$

Yongda Zhu[1], George D. Becker[1], Sarah E. I. Bosman[2], Laura C. Keating[3], Holly M. Christenson[1], Eduardo Bañados[2], Fuyan Bian[4], Frederick B. Davies[2], Valentina D'Odorico[5,6,7], Anna-Christina Eilers[8,14], Xiaohui Fan[9], Martin G. Haehnelt[10], Girish Kulkarni[11], Andrea Pallottini[6], Yuxiang Qin[12,13], Feige Wang[9,14], and Jinyi Yang[9,15]

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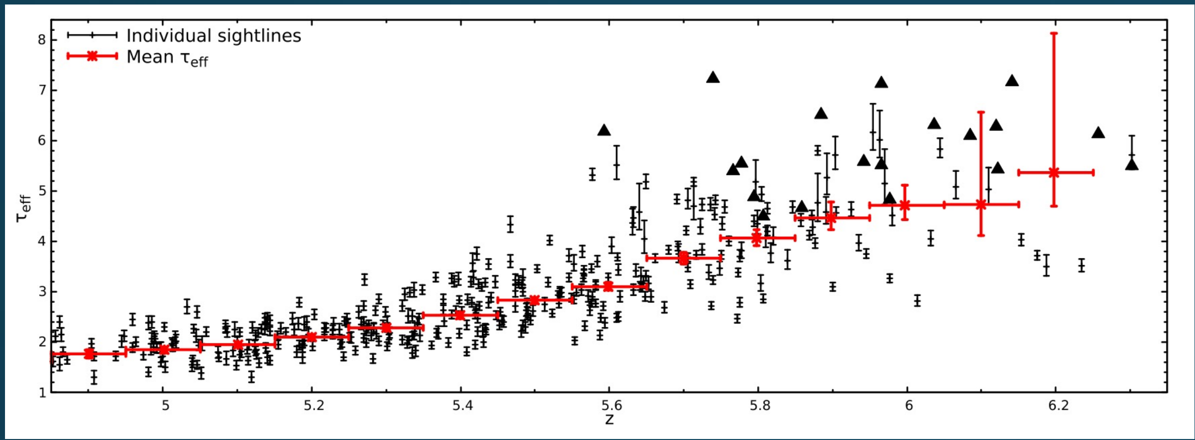
Long Dark Gaps in the Lyβ Forest at $z < 6$: Evidence of Ultra-late Reionization from XQR-30 Spectra

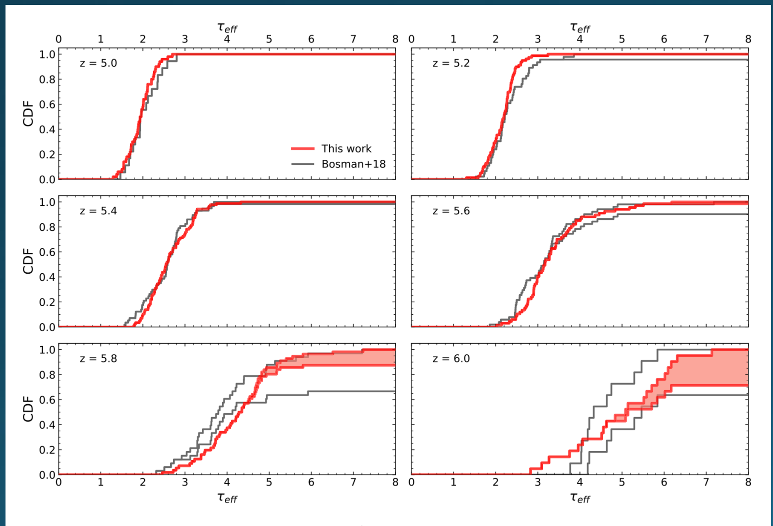
Yongda Zhu[1], George D. Becker[1], Sarah E. I. Bosman[2], Laura C. Keating[3], Valentina D'Odorico[4,5,6], Rebecca L. Davies[7,8], Holly M. Christenson[1], Eduardo Bañados[2], Fuyan Bian[9], Manuela Bischetti[4], Huanqing Chen[10], Frederick B. Davies[2], Anna-Christina Eilers[11,17], Xiaohui Fan[12], Prakash Gaikwad[2], Bradley Greig[8,13], Martin G. Haehnelt[14], Girish Kulkarni[15], Samuel Lai[16], Andrea Pallottini[5], Yuxiang Qin[8,13], Emma V. Ryan-Weber[7,8], Fabian Walter[2], Feige Wang[12,17], and Jinyi Yang[12,18]

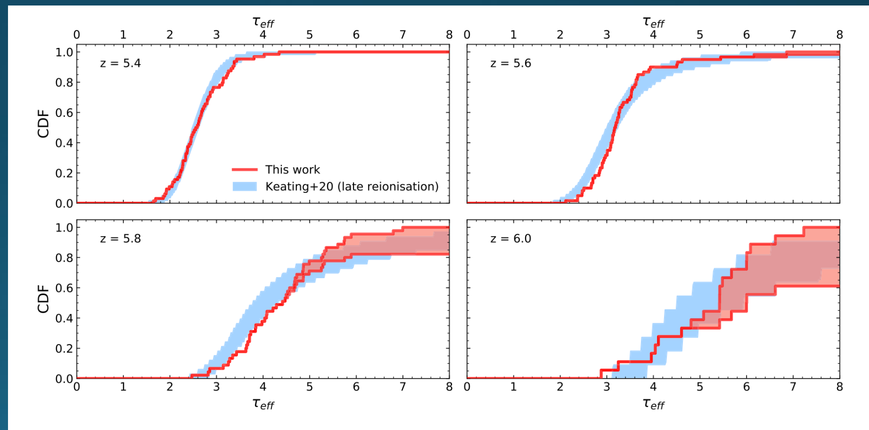
XQR30: a new measurement of the Lyman-alpha opacity



Improved data quality and analysis

Bosman et al 2022

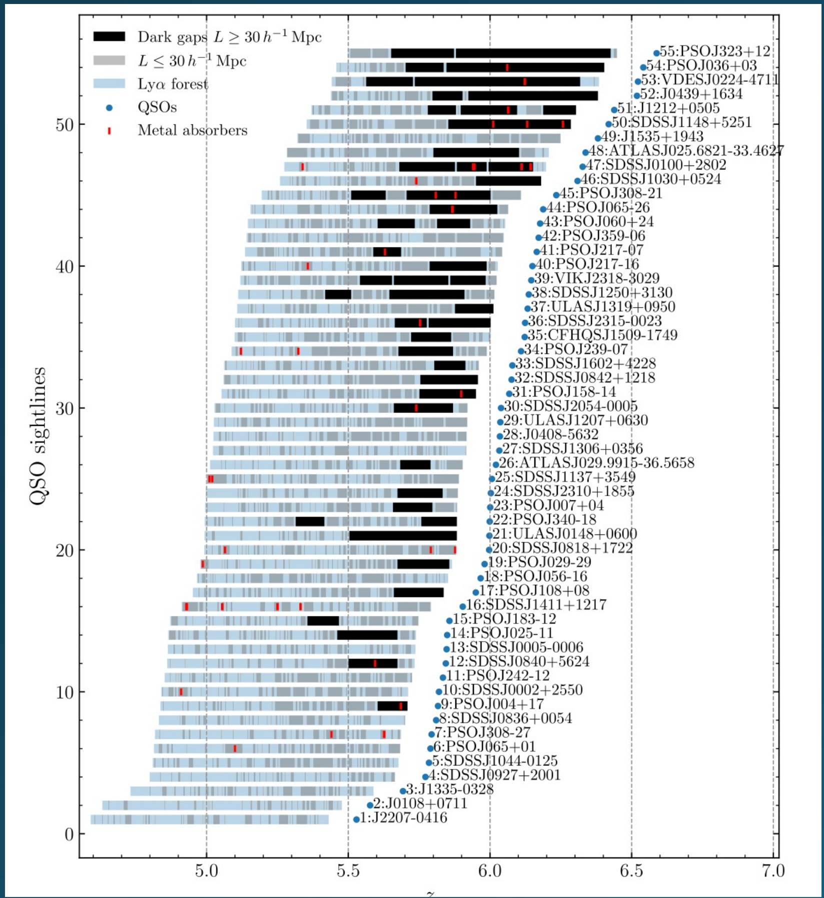


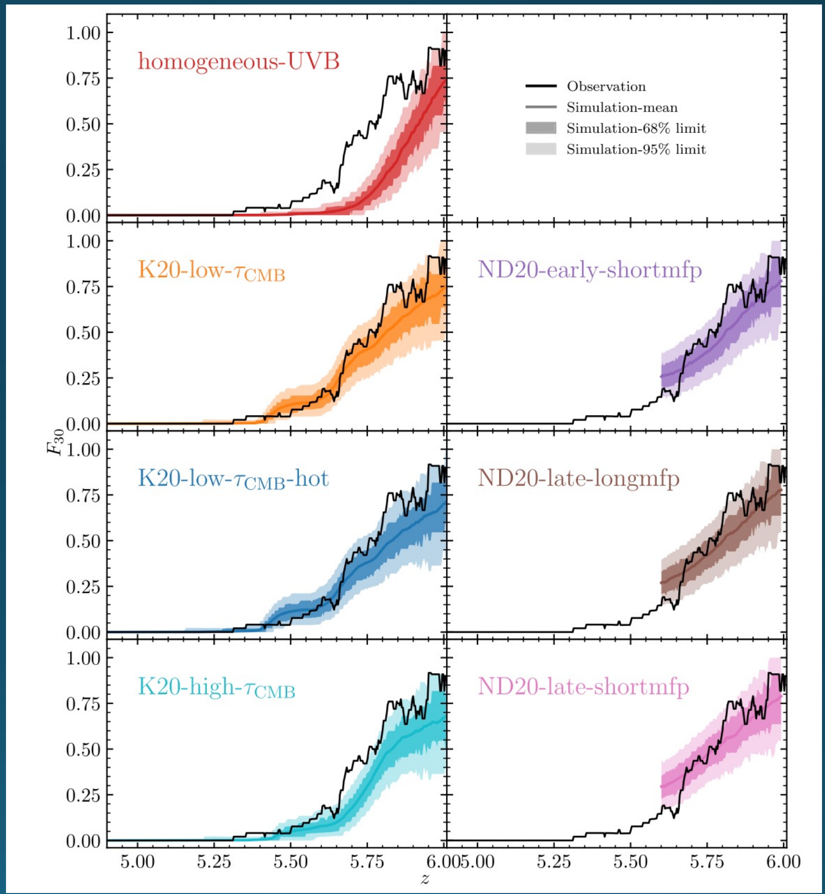


Good agreement with data from Bosman et al. 2018 and modelling from Keating et al. 2020

XQR30: a new measurement of the dark gap statistics

Zhu et al 2021,2022





Good agreement with late-end reionization models

The Sherwood-Relics simulations: overview and impact of patchy reionization and pressure smoothing on the intergalactic medium

Ewald Puchwein[1⋆], James S. Bolton[2], Laura C. Keating[1], Margherita Molaro[2], Prakash Gaikwad[3], Girish Kulkarni[4], Martin G. Haehnelt[5], Vid Iršič[5], Tomáš Šoltinský[2], Matteo Viel[6,7,8,9], Dominique Aubert[10], George D. Becker[11] and Avery Meiksin[12]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

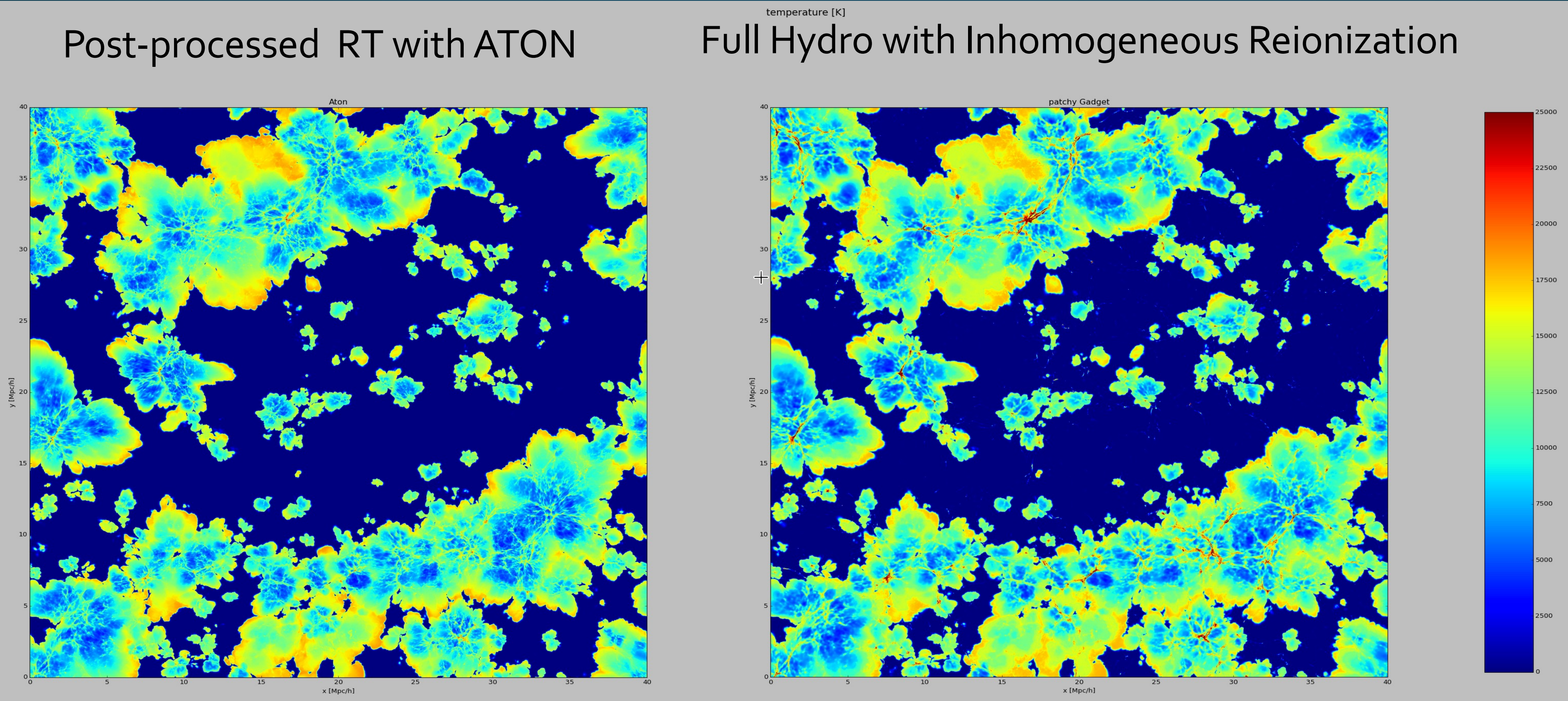
MNRAS **509,** 6119–6137 (2022) https://doi.org/10.1093/mnras/stab3416
Advance Access publication 2021 November 26

The effect of inhomogeneous reionization on the Lyman α forest power spectrum at redshift $z > 4$: implications for thermal parameter recovery

Margherita Molaro,[1⋆] Vid Iršič,[2] James S. Bolton,[1] Laura C. Keating,[3] Ewald Puchwein,[3] Prakash Gaikwad,[2] Martin G. Haehnelt,[2] Girish Kulkarni[4] and Matteo Viel[5,6,7,8]

Full hydro-simulations incorporating reionization:

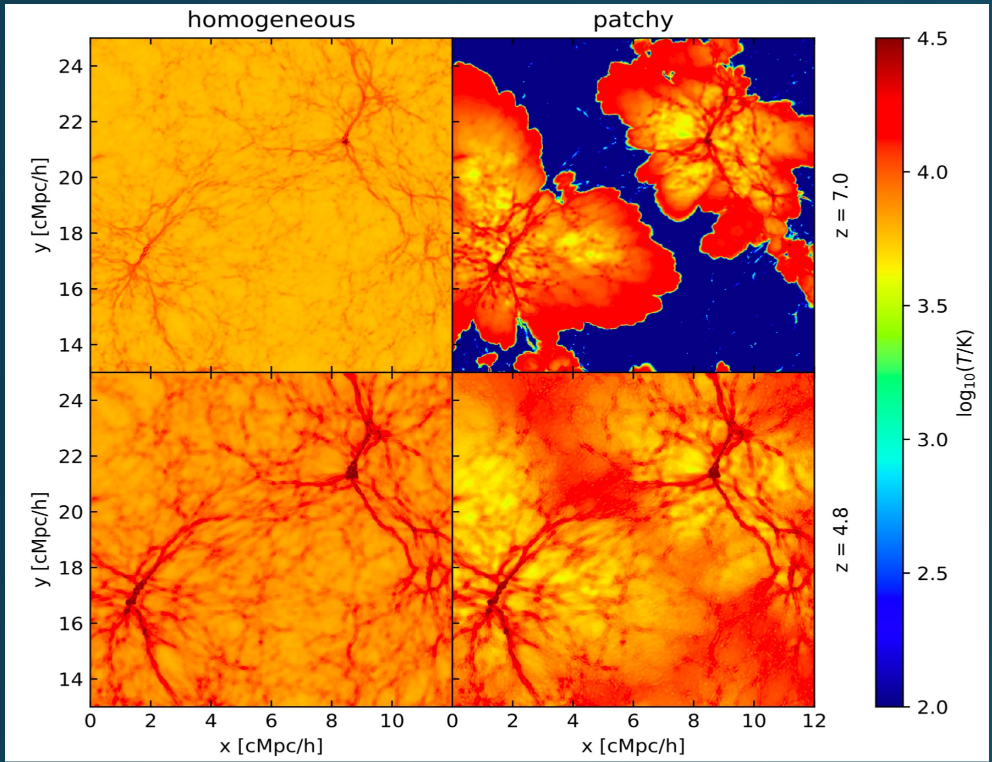
Post-processed RT with ATON | Full Hydro with Inhomogeneous Reionization

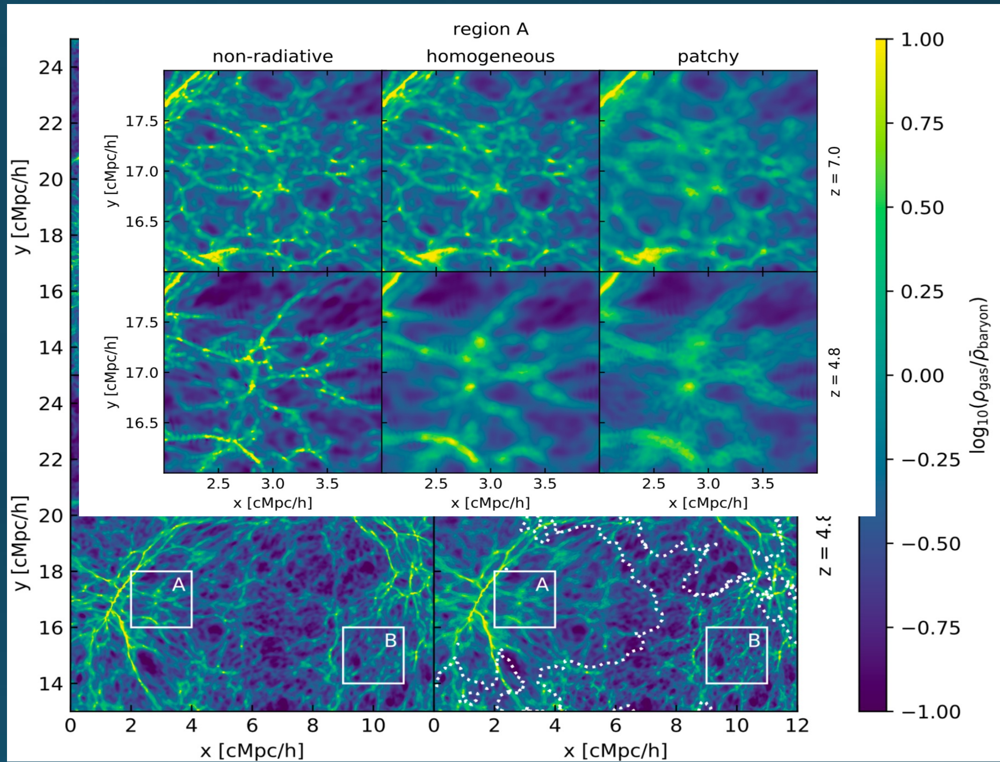


Puchwein et al. 2023

The Sherwood-Relics simulations suite

The Sherwood-Relics simulation suite





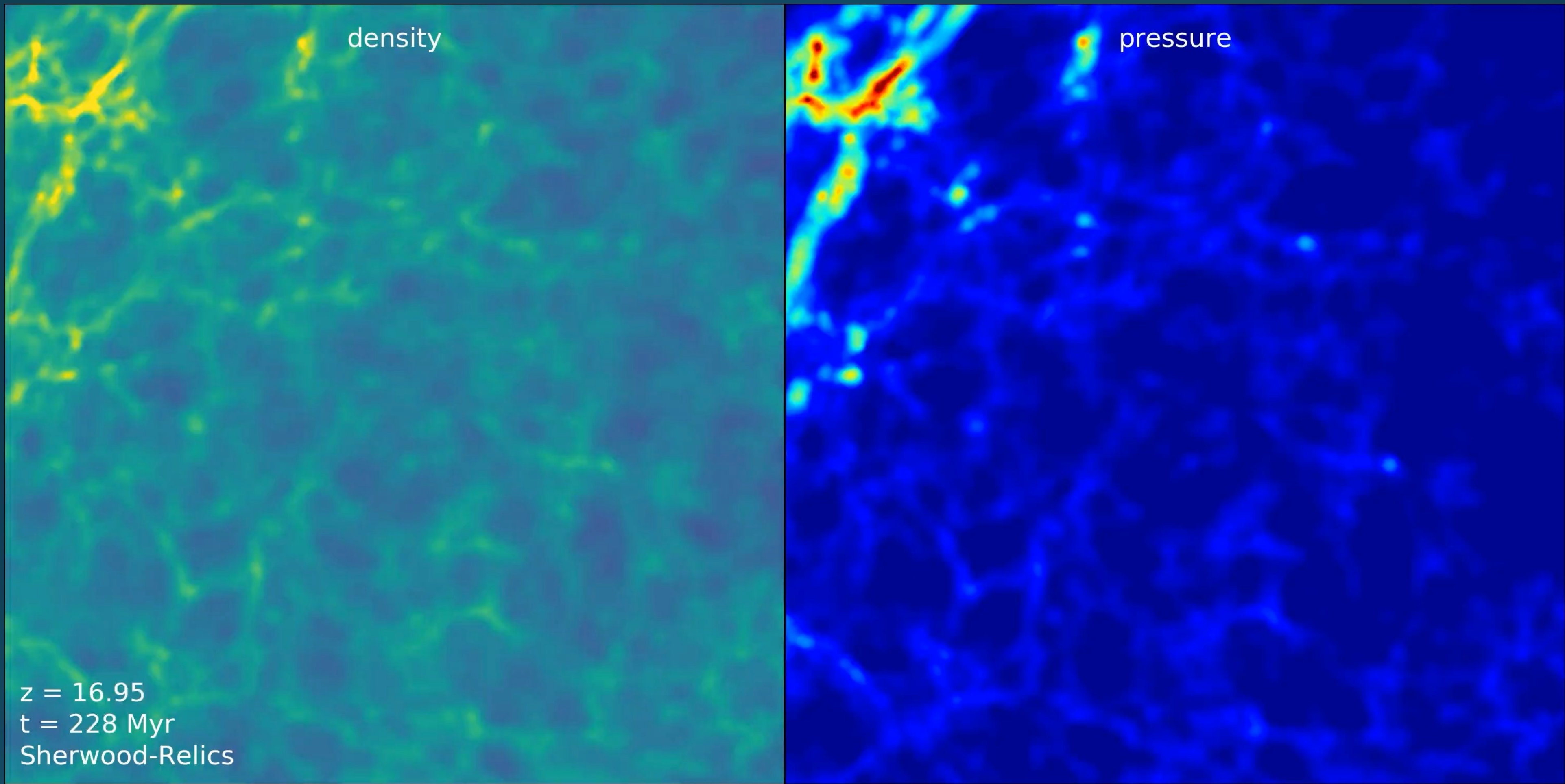
Puchwein et al. 2023, Molaro et al. 2022

Fluctuations of the temperature density relation on rather large scales
→ increased flux power on large scales

Jeans smoothing on small scales due to integrated energy input which depends on reionization history. Complex interplay with thermal broadening which depends on instantaneous temperature.

c.f. Keating et al. 2018
Wu et al. 2020

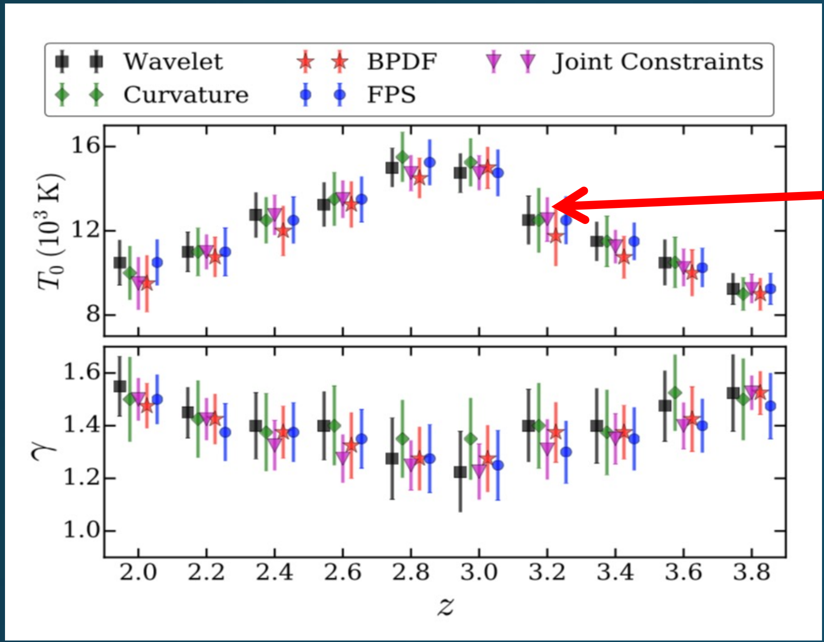
Pressure smoothing in action

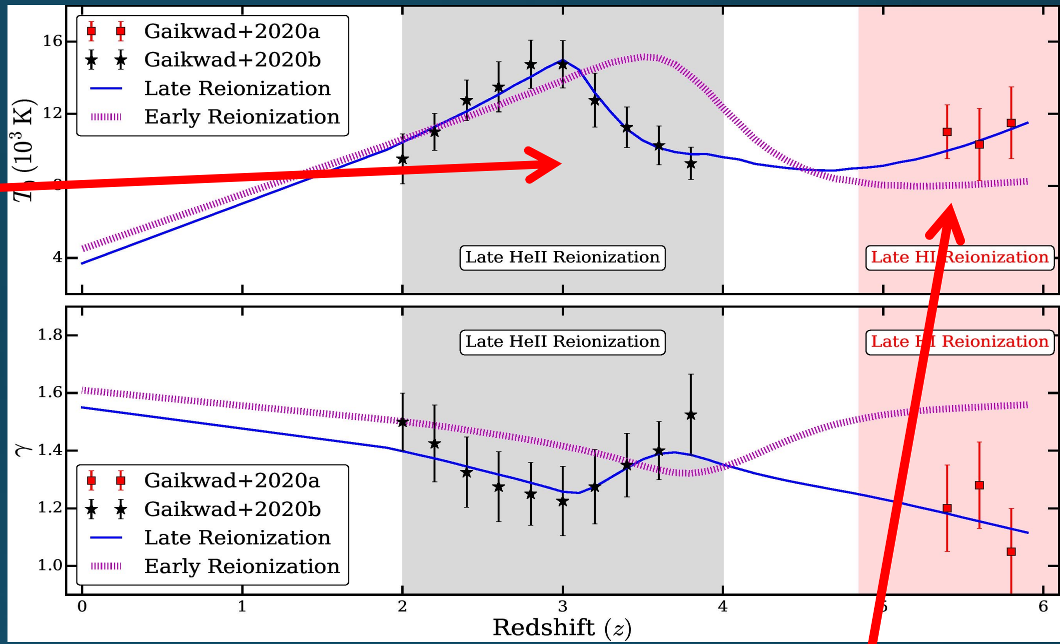


Puchwein et al. submitted

Overdense regions become overpressured and expand when they become ionized.

IGM Temperature measurements are getting accurate (and consistent)





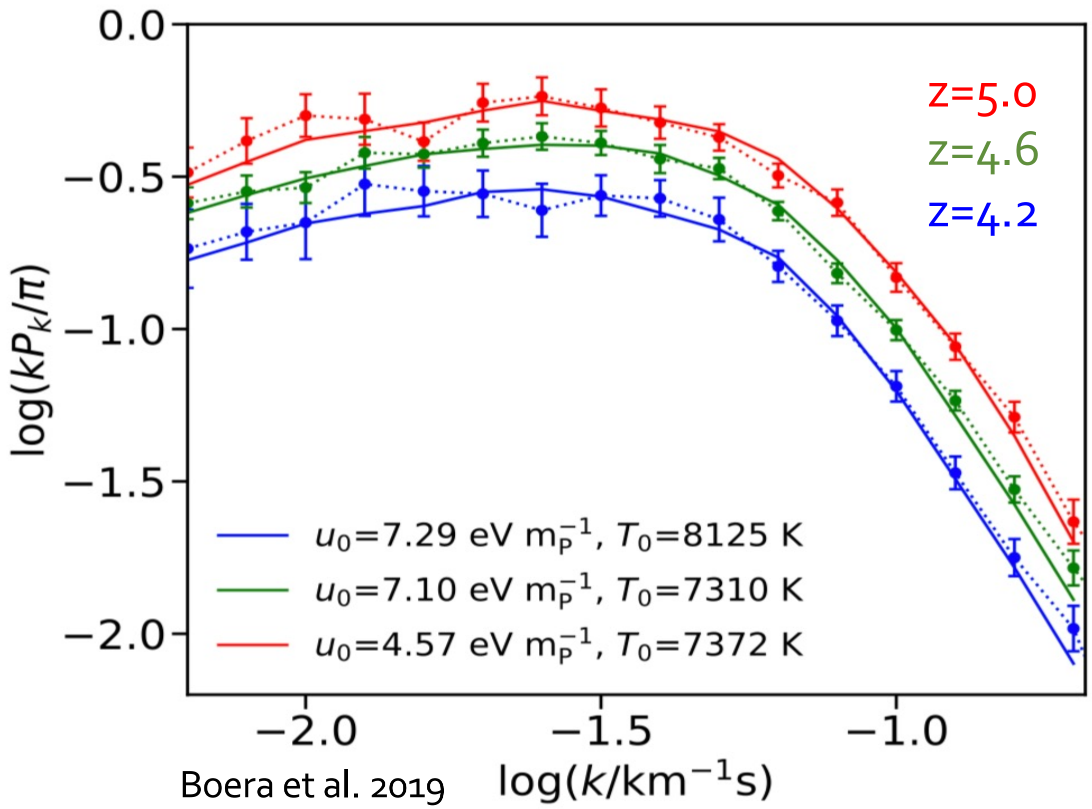
Gaikwad et al. 2021:

- 4 different flux statistics agree well
- based on 103/296 Keck/HIRES spectra from the KODIAQ sample
- careful modeling of the observed sample for finely spaced parameter grid in T_0 and γ

Gaikwad et al. 2020:

new consistent measurement of IGM temperature at 5.3<z<5.9 by characterising width of transmission spikes in high S/N high resolution spectra with novel technique

A new measurement of the high-redshift flux power spectrum



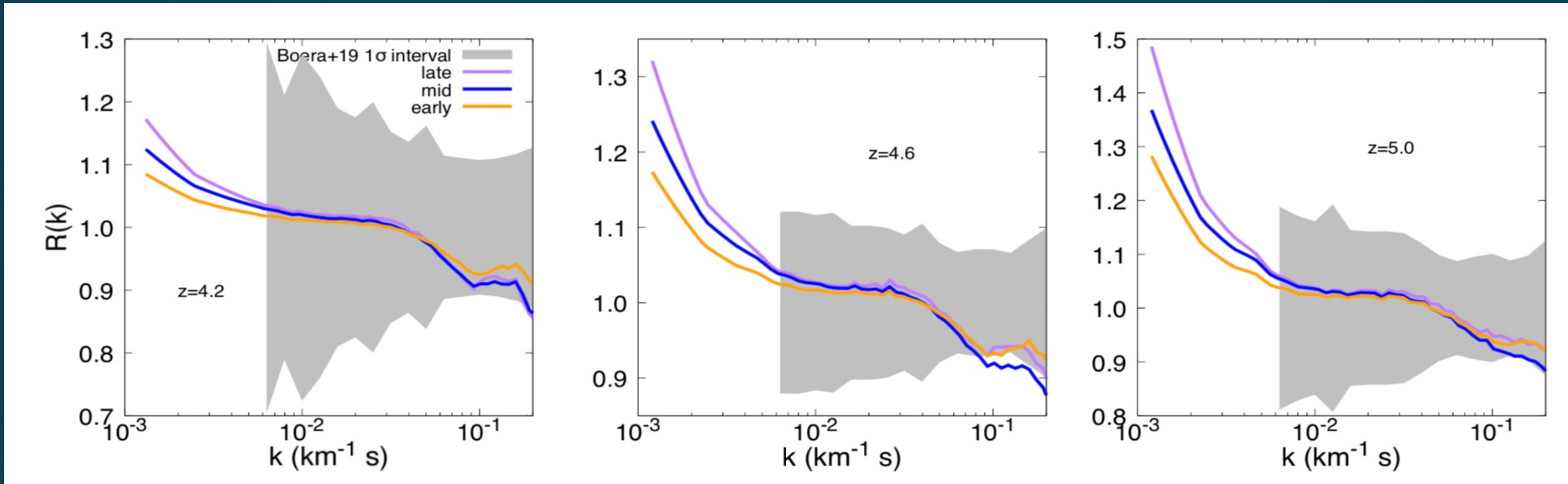
Boera et al. 2019

15 high-quality spectra

extends to higher redshift and to smaller scales

A piece of art

Spatial variations of the temperature-density relation



Noticable effect on the flux power spectrum, but well within the errors.

Effects of Photoionization and Photoheating on Lyman-α Forest Properties from *Cholla* Cosmological Simulations

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[2] *Department of Physics and Astronomy & Pittsburgh Particle Physics, Astrophysics, and Cosmology Center (PITT PACC), University of Pittsburgh, Pittsburgh, PA 15260, USA*

Inferring the Thermal History of the Intergalactic Medium from the Properties of the Hydrogen and Helium Lyman-α Forest

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New Constraints on Warm Dark Matter from the Lyman-α Forest Power Spectrum

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(Dated: September 29, 2022)

KICC

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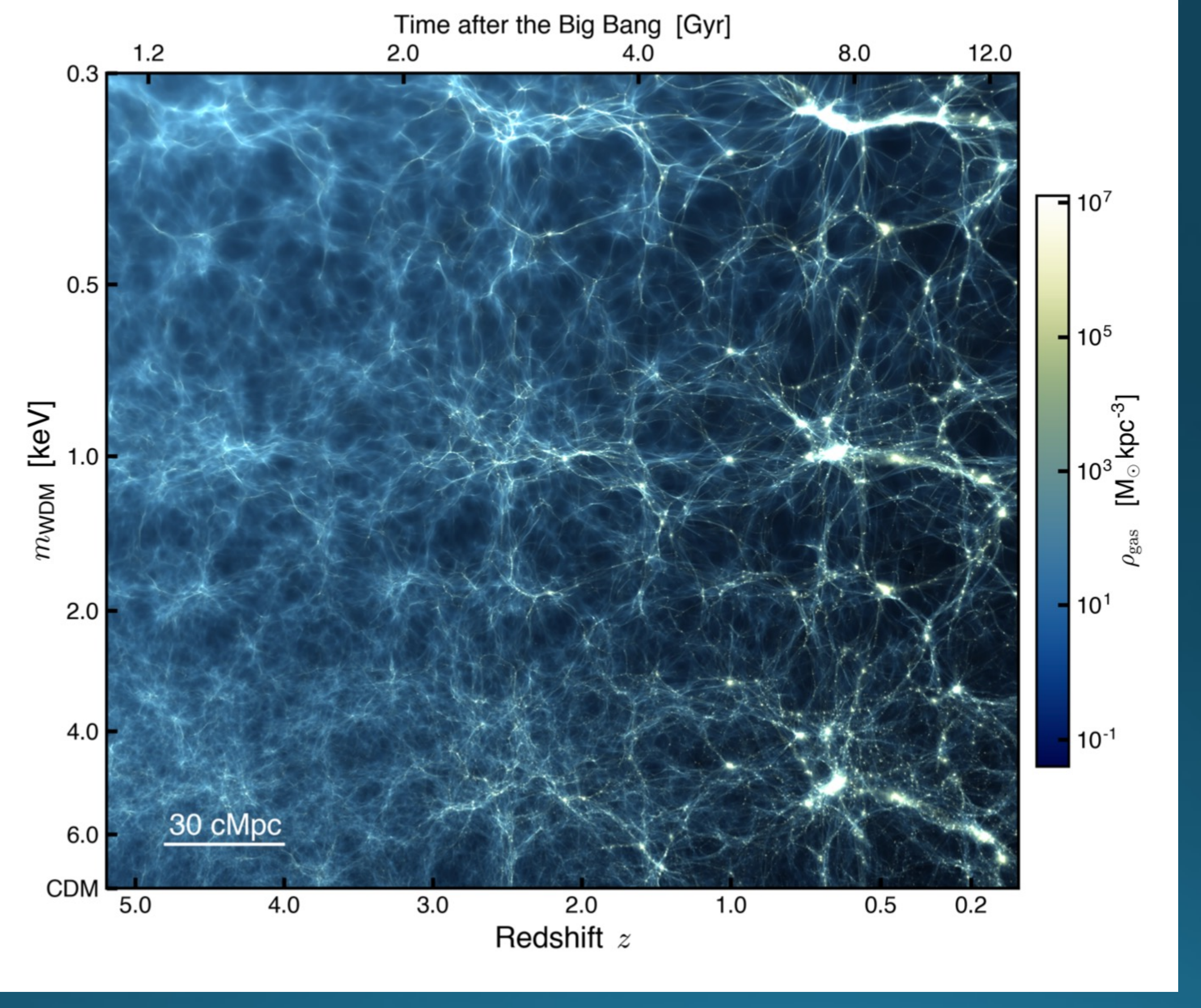
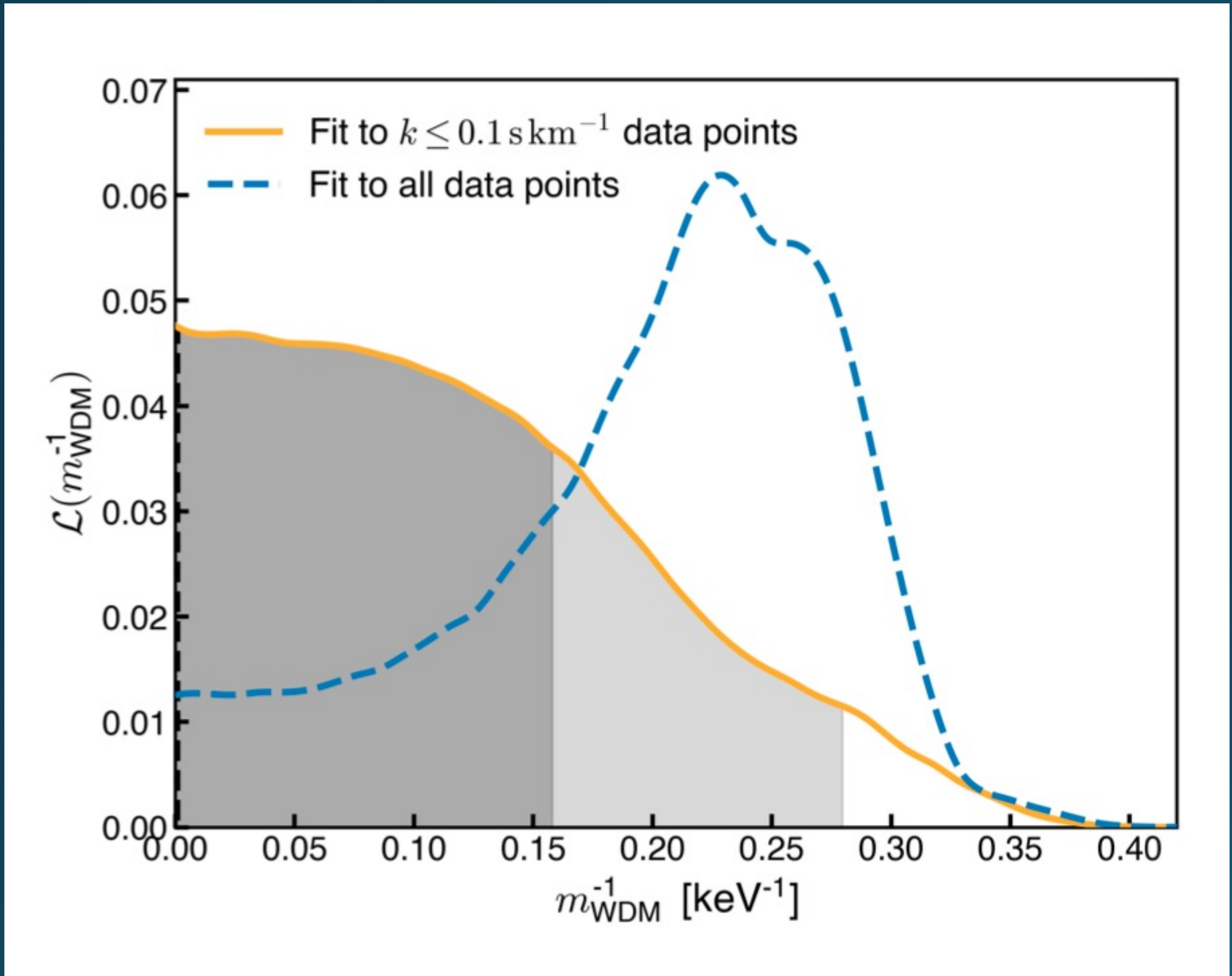
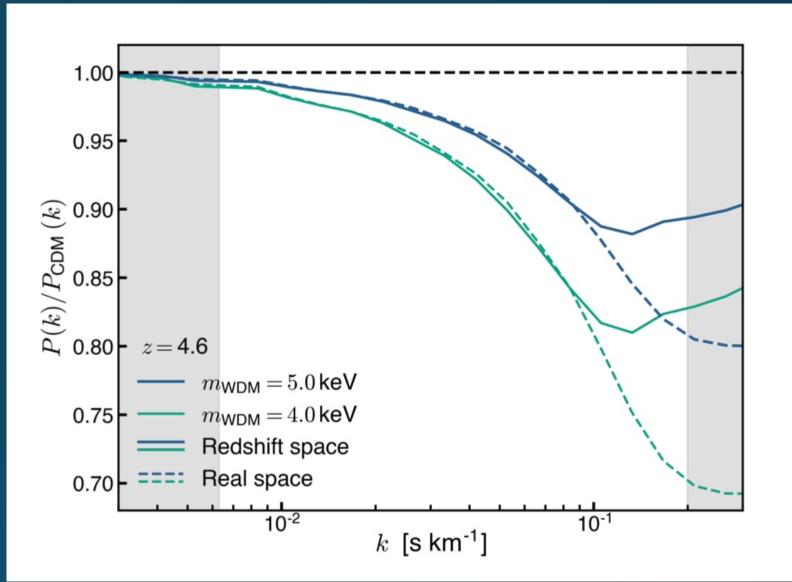
Visualising the free-streaming of dark matter



Villasenor et al. 2022



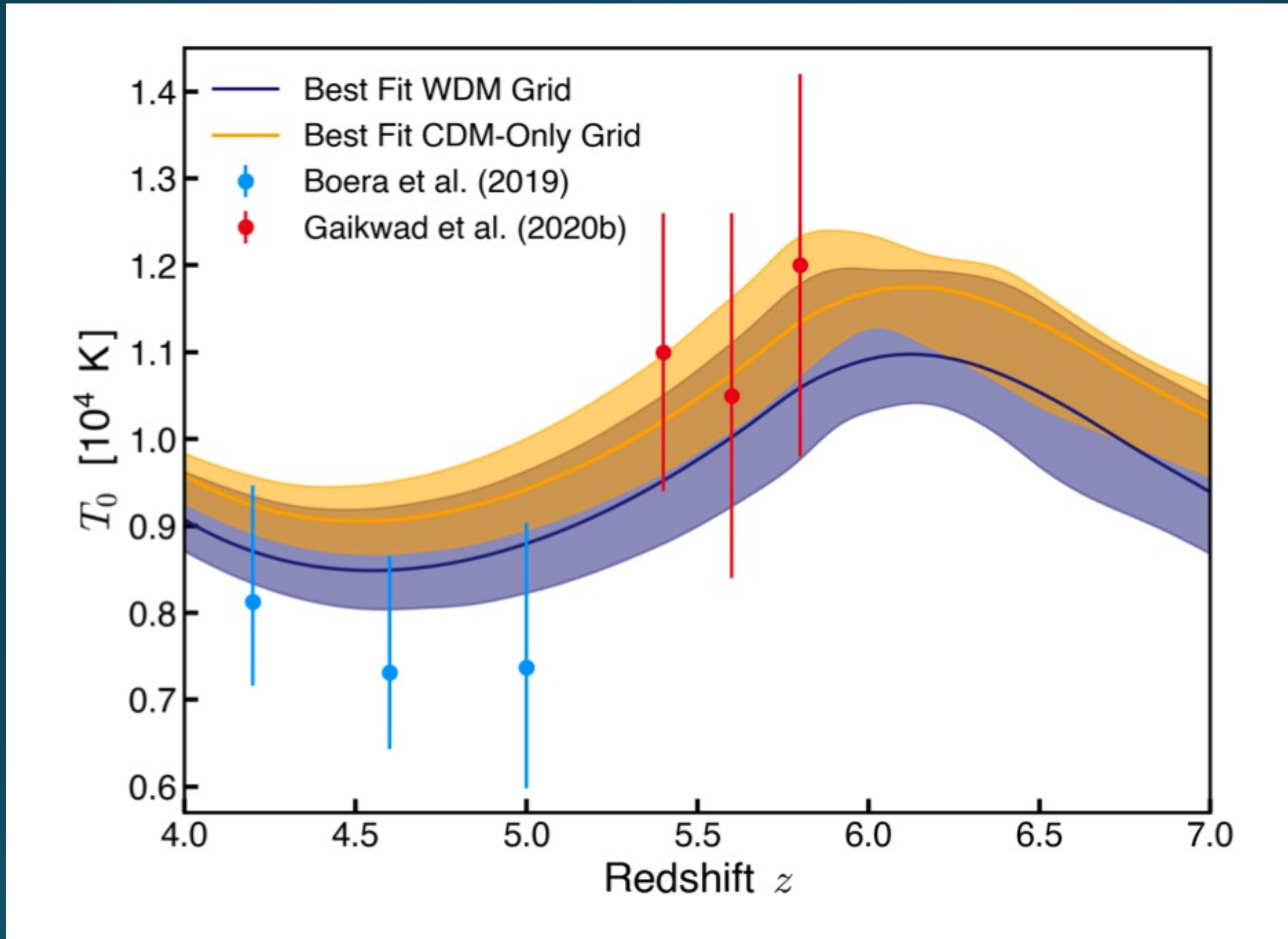
Villasenor et al. 2022



Signature of gas peculiar velocities?

An intriguing peak in the likelihood for the WDM mass if the smallest scales are included.

Villasenor et al. 2022



The data prefers a reasonable thermal history

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Strong Bound on Canonical Ultralight Axion Dark Matter from the Lyman-Alpha Forest

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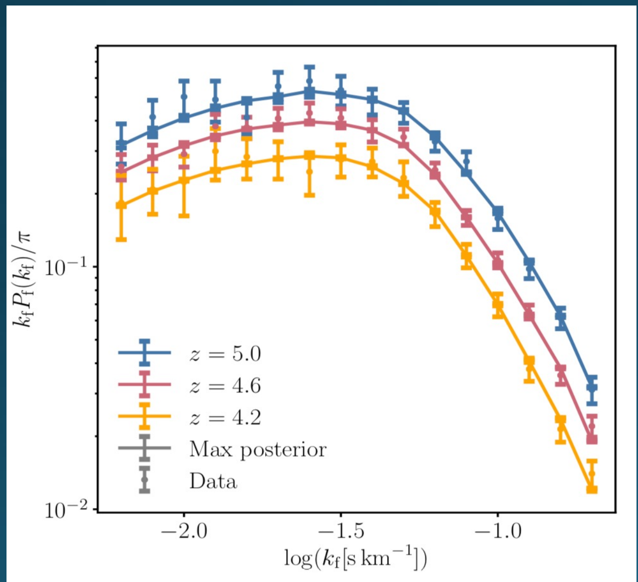
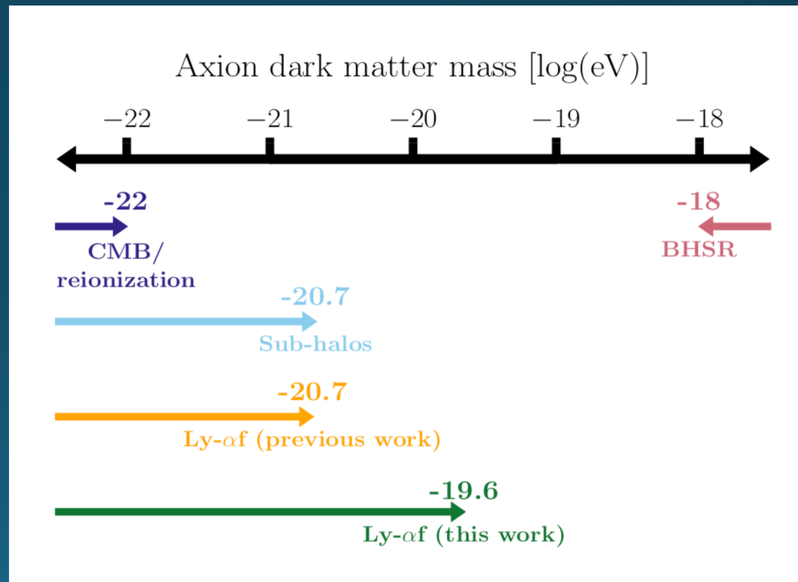
(Received 7 August 2020; revised 18 November 2020; accepted 22 December 2020; published 19 February 2021)





The axion limit corresponds to about 10keV for a thermal relic, but shape of transfer function is different and that matters.

Nuisance effects /parameters

- instrumental resolution
- instrumental noise
- "continuum" fitting
- strong absorbers
- metal absorbers

- mean flux has to be measured/assumed
  alternatively photoionization rate has to be measured/assumed
- thermal broadening (instantaneous temperature)
- Jeans smoothing (integrated energy input)
- **spatial variations of the above**

- **anchoring at large scales**
- cosmological parameters
- shape of cut-off in DM transfer function is not generic

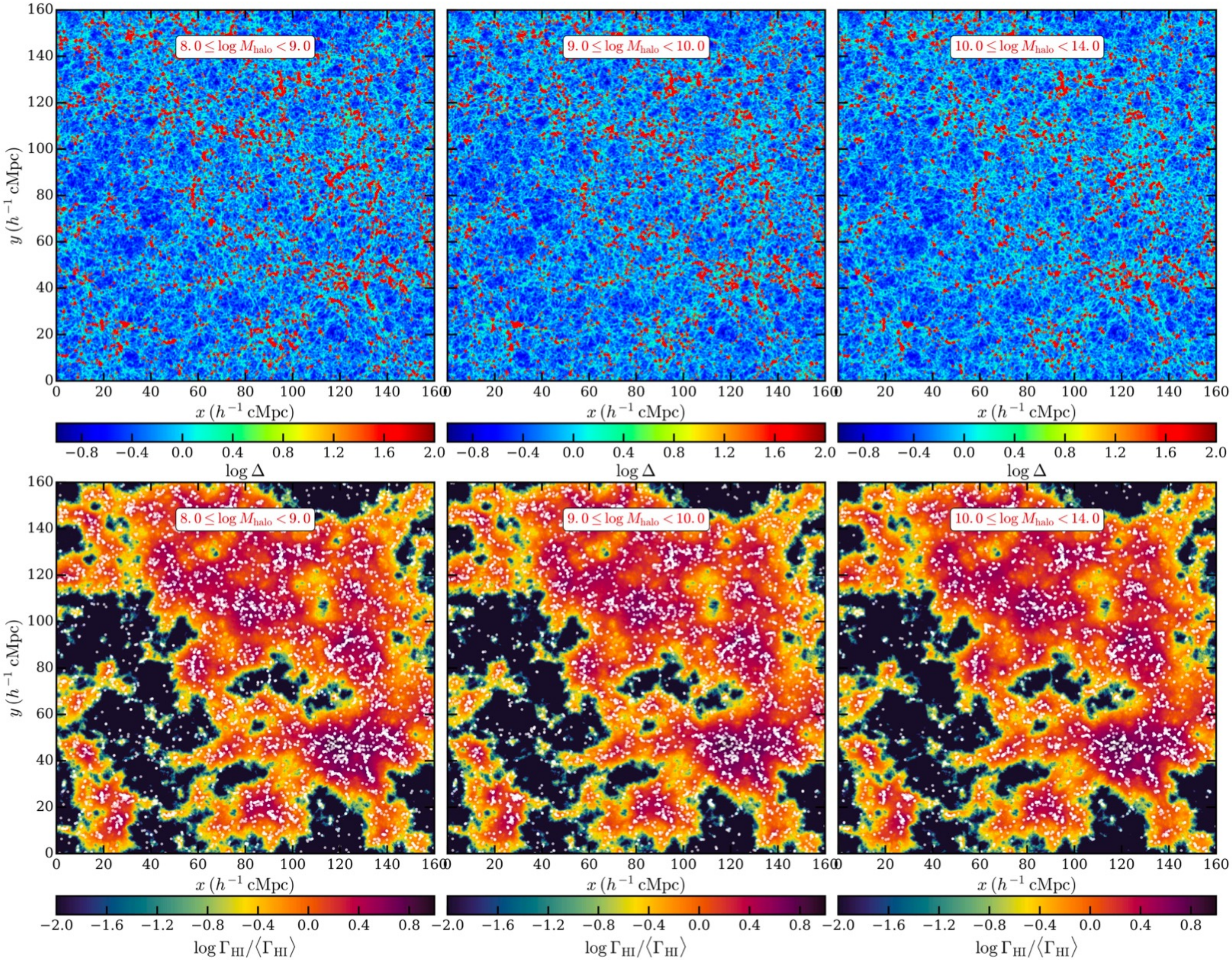
- corrections for box size and resolution
- missing physics in the simulations
- interpolation errors in sparsely sampled parameter space

Summary

- Good progress with characterising thermal evolution of IGM. Quantitative modelling of the effect of helium reionization still on to do list.
- Evidence is building for rather late reionization
  → spatial fluctuations of temperature-density relation and photoionization rate more pronounced.
- Exciting new data and more to come. Lyman-alpha forest data and its analysis is (rapidly) improving.
- Modeling of systematic uncertainties is lagging behind improvement of the data.

ANDES @ ELT

Wavelength	0.40—1.80 µm (baseline), 0.35—2.40 µm (goal)
Spectral resolution	100,000
Wavelength precision	1 m/s (baseline), 0.1 m/s (goal)
Wavelength calibration stability	1 m/s over 24 hours (baseline), 0.02 m/s over 10 years (goal)



Gaikwad et al. in preparation