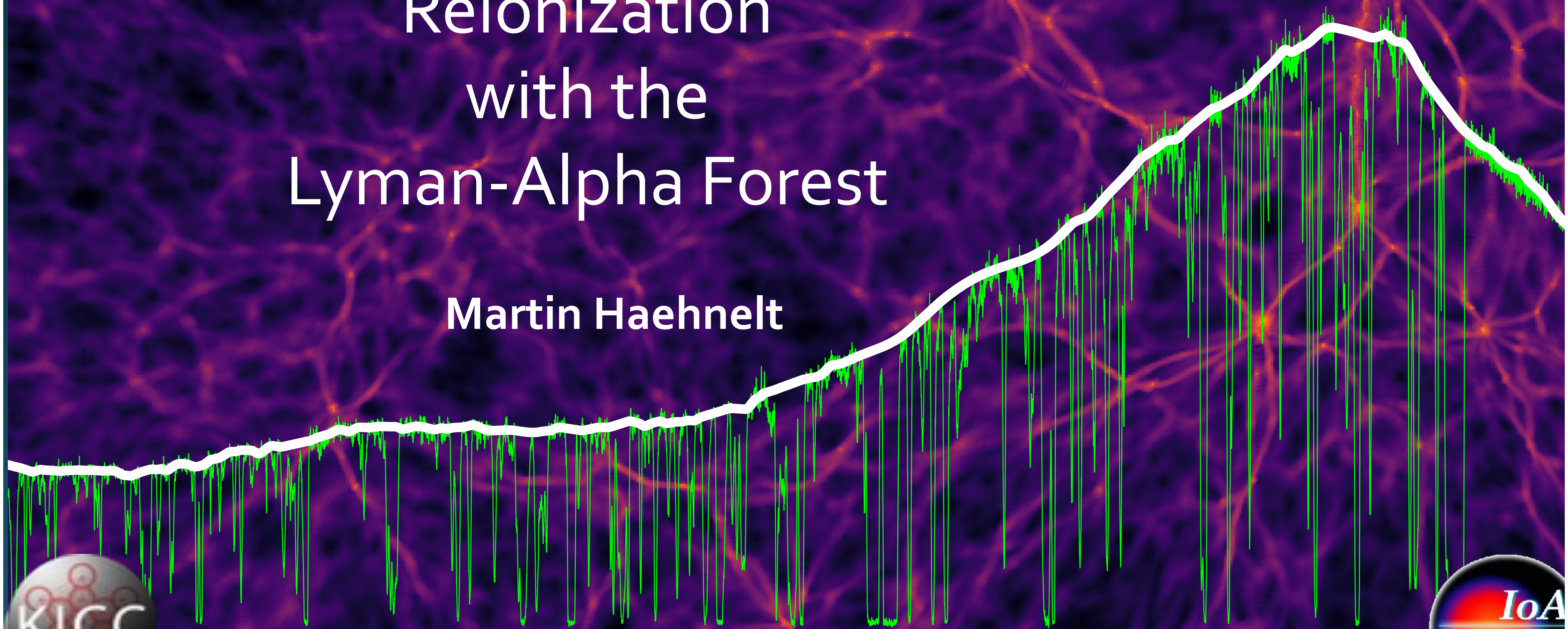
# Constraining the Nature of Dark Matter and Reionization with the Lyman-Alpha Forest

**Martin Haehnelt**

Shikhar Asthana
George Becker
Elisa Boera
James Bolton
Sarah Bosman
Prakash Gaikwad
Olga Garcia Galleg
Vid Irsic
Laura Keating
Girish Kulkarni
Margherita Molaro
Ewald Puchwein
Matteo Viel



KICC

Cambridge-LMU, 16 September 2025

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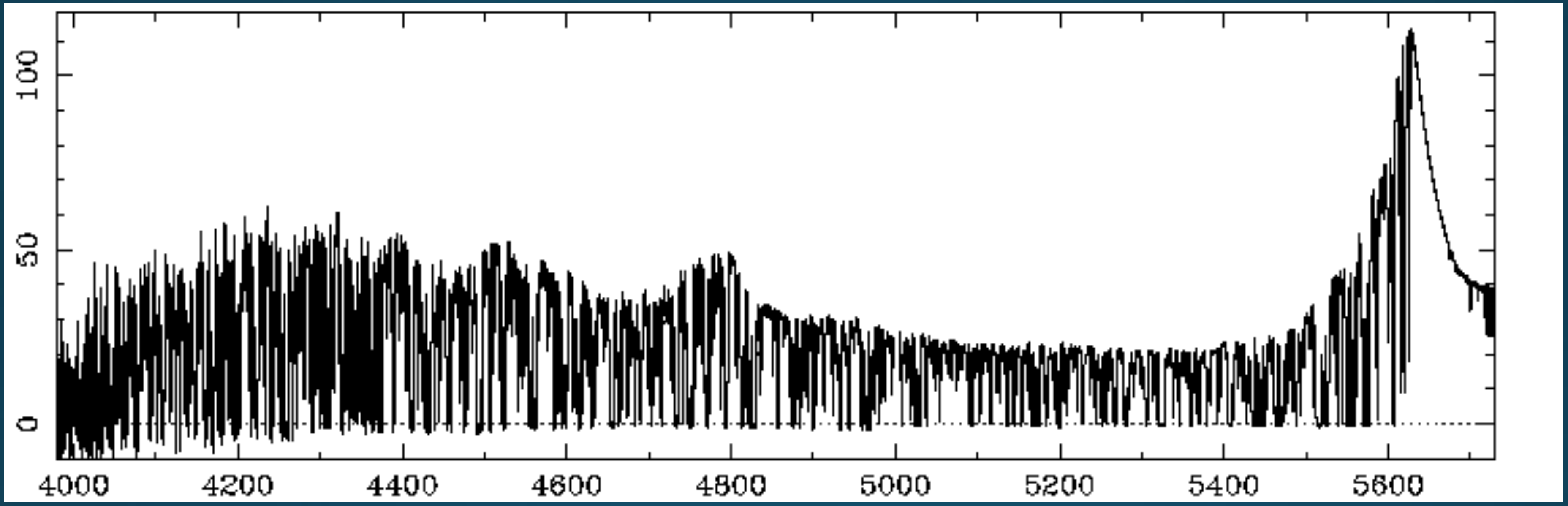
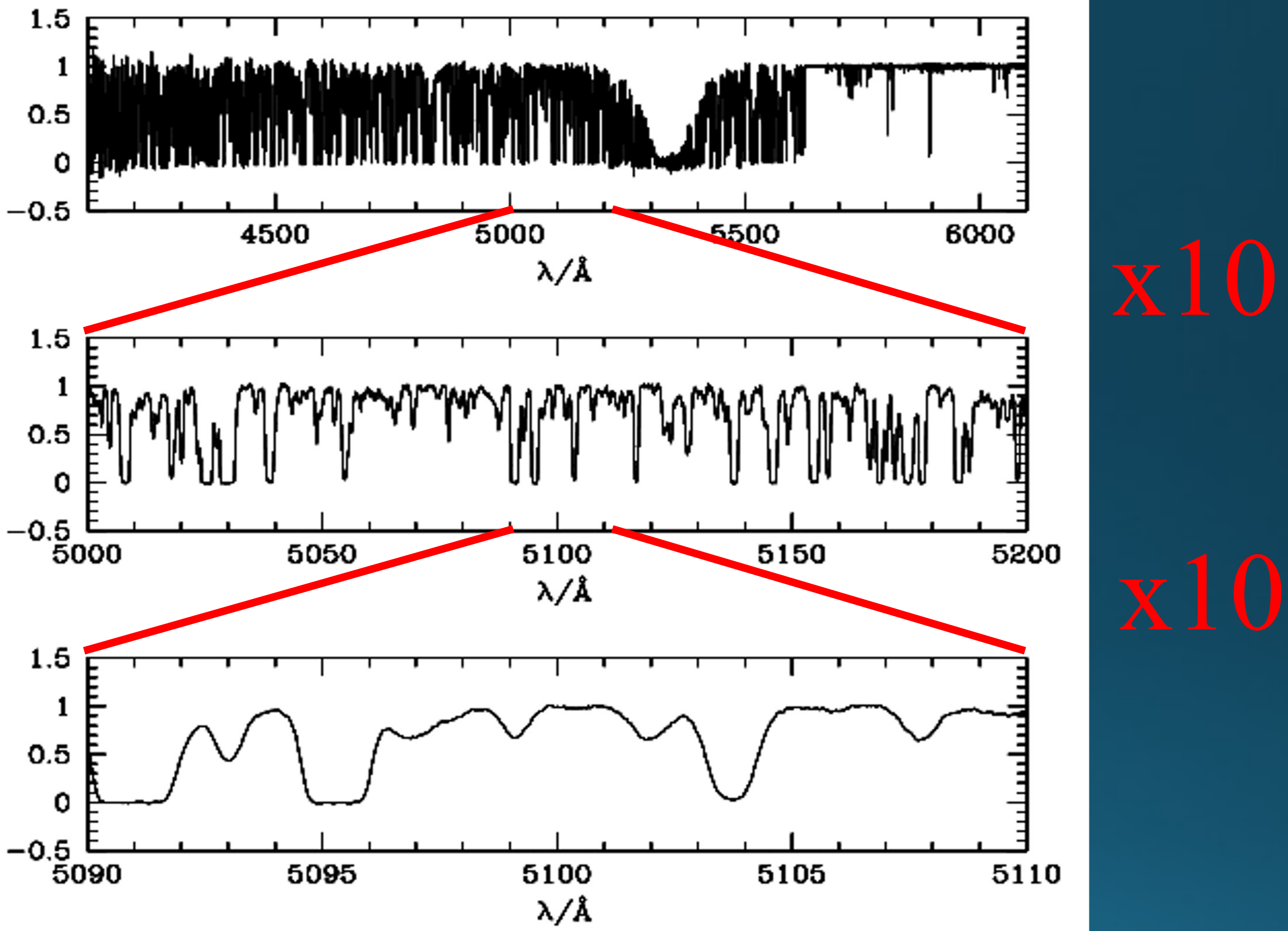
# The Lyα forest

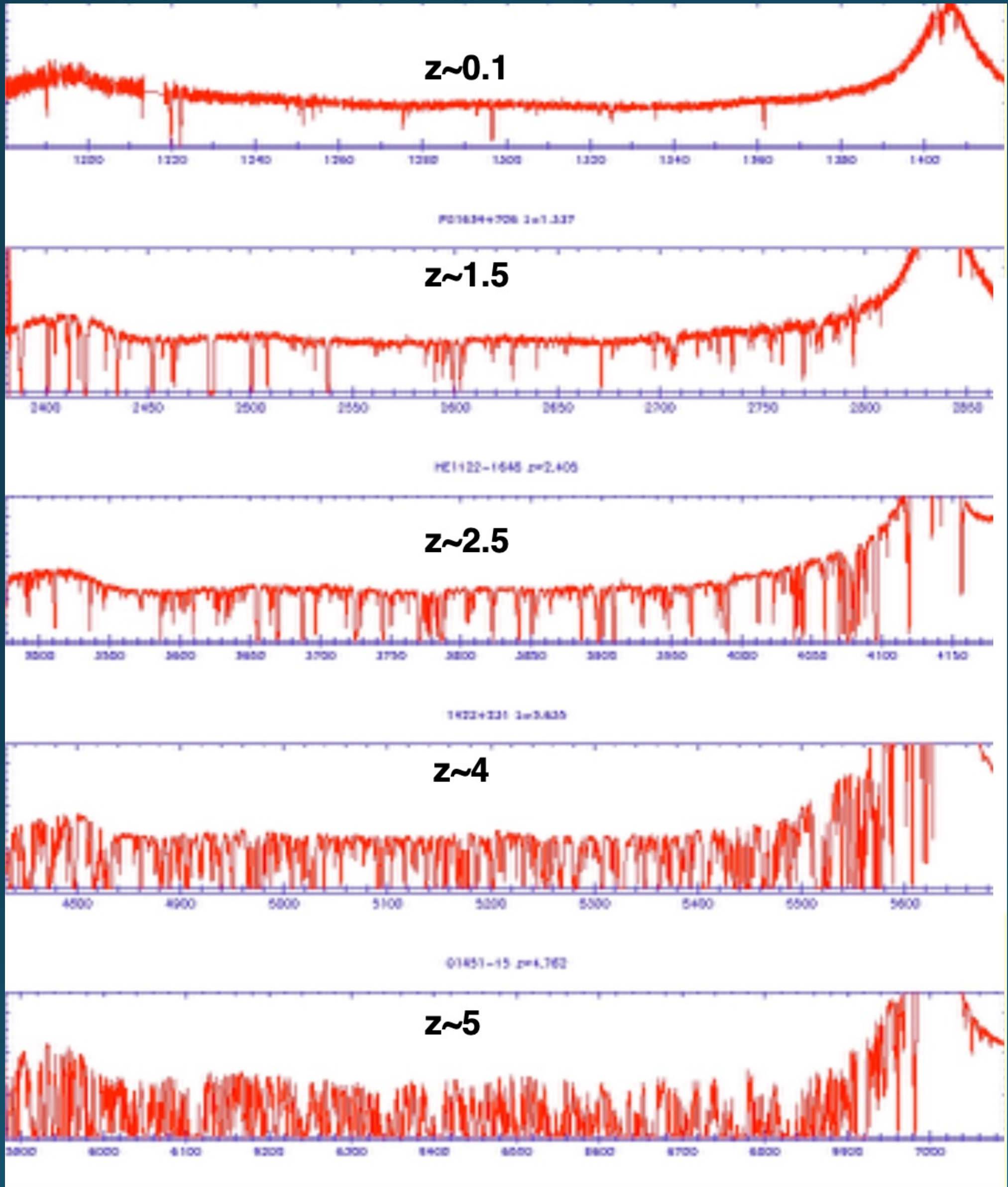



$\lambda_{Ly\alpha} = 1215.67\ (1+z)\ Å$

# High resolution – High S/N!

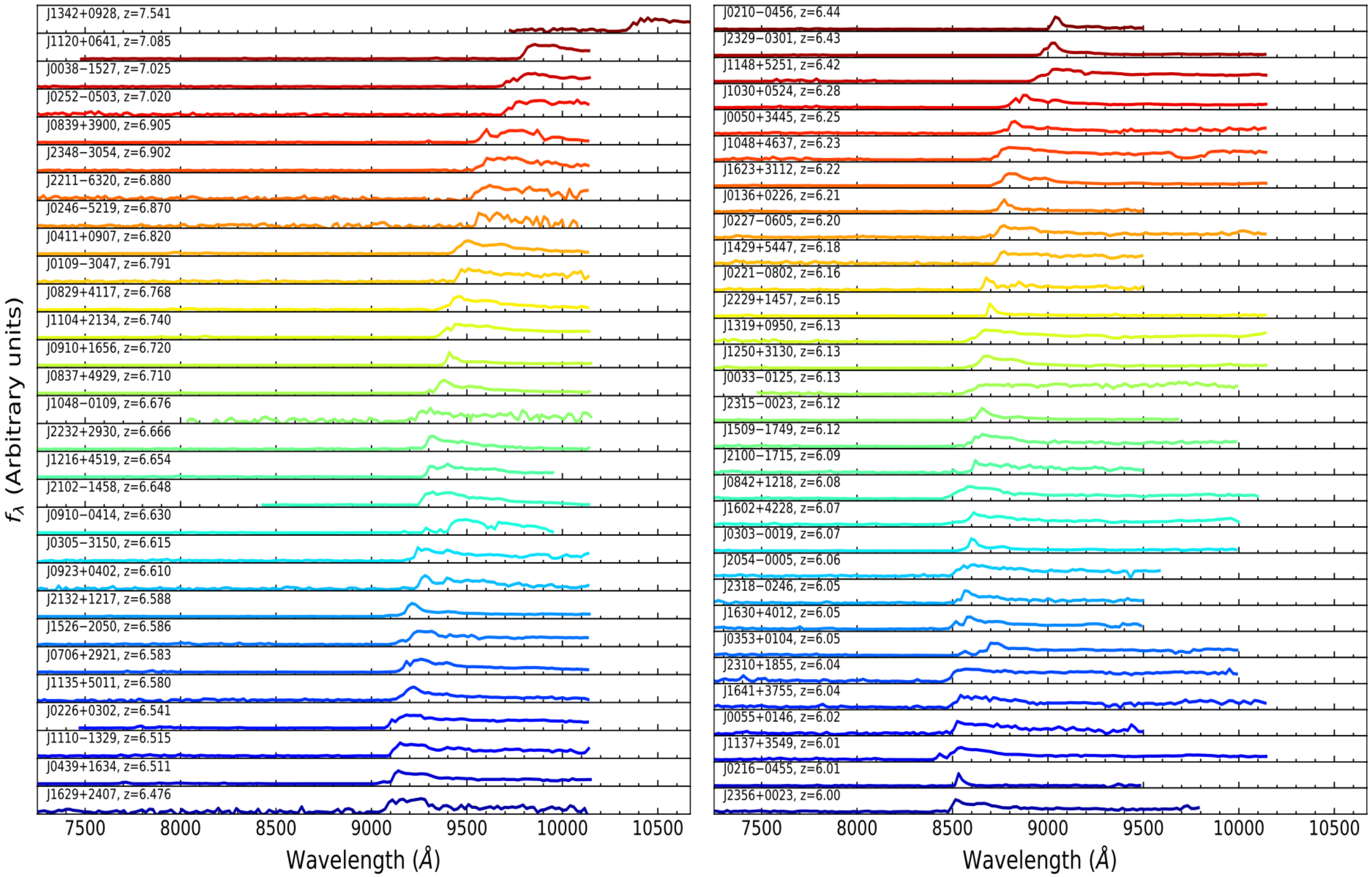



A treasure trove of information!




# The Lyα forest evolves rapidly

from Xiaohui Fan's Sao Paolo lectures




from Xiaohui Fan's Sao Paolo lectures

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

photoionization equilibrium:

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

$\uparrow$ recombination coefficient $\qquad$ $\uparrow$ photoionization rate

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

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photoheating vs adiabatic cooling:

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

photoionization equilibrium:

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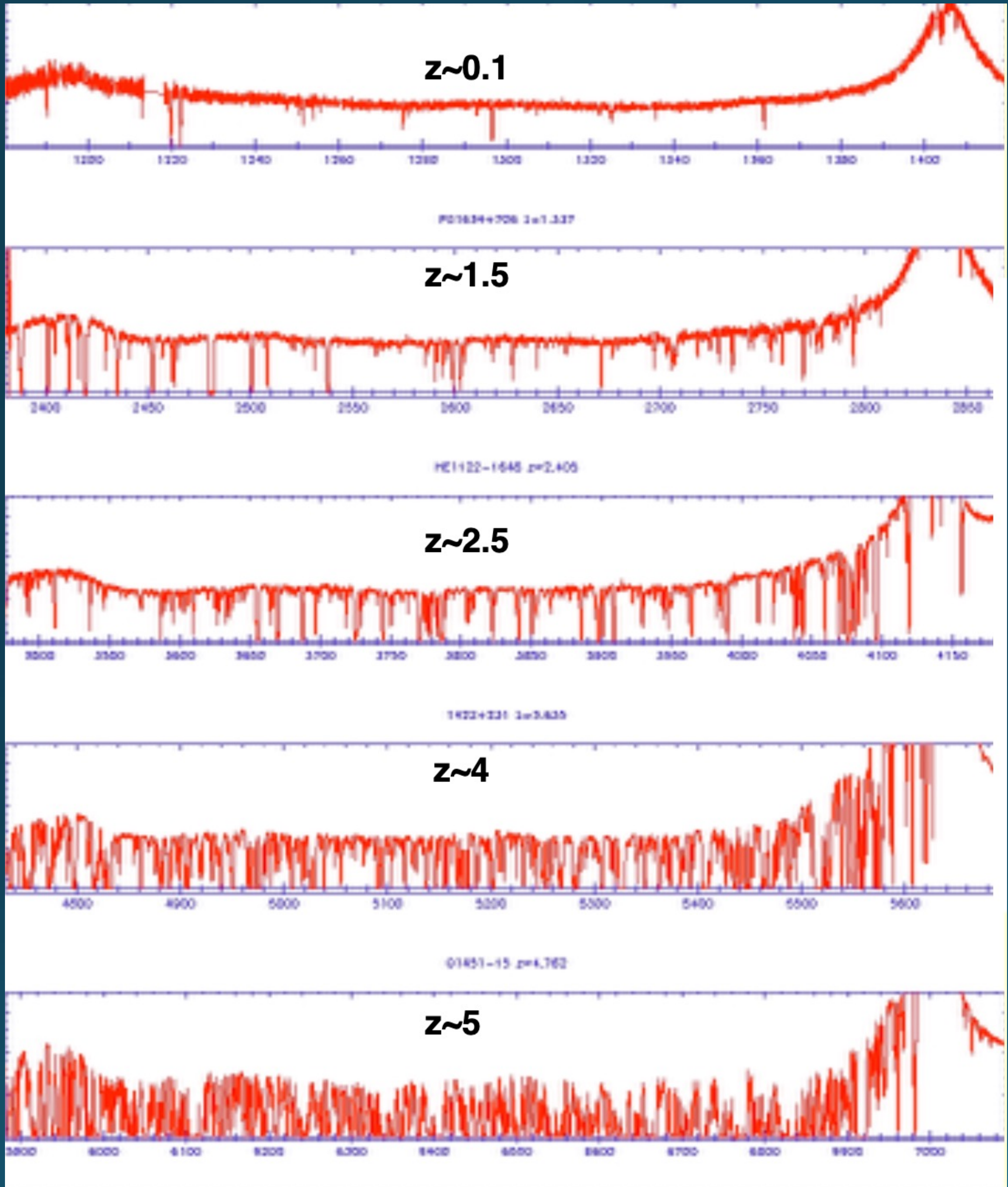
photoheating vs adiabatic cooling:

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

Fluctuating Gunn-Peterson approximation:

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

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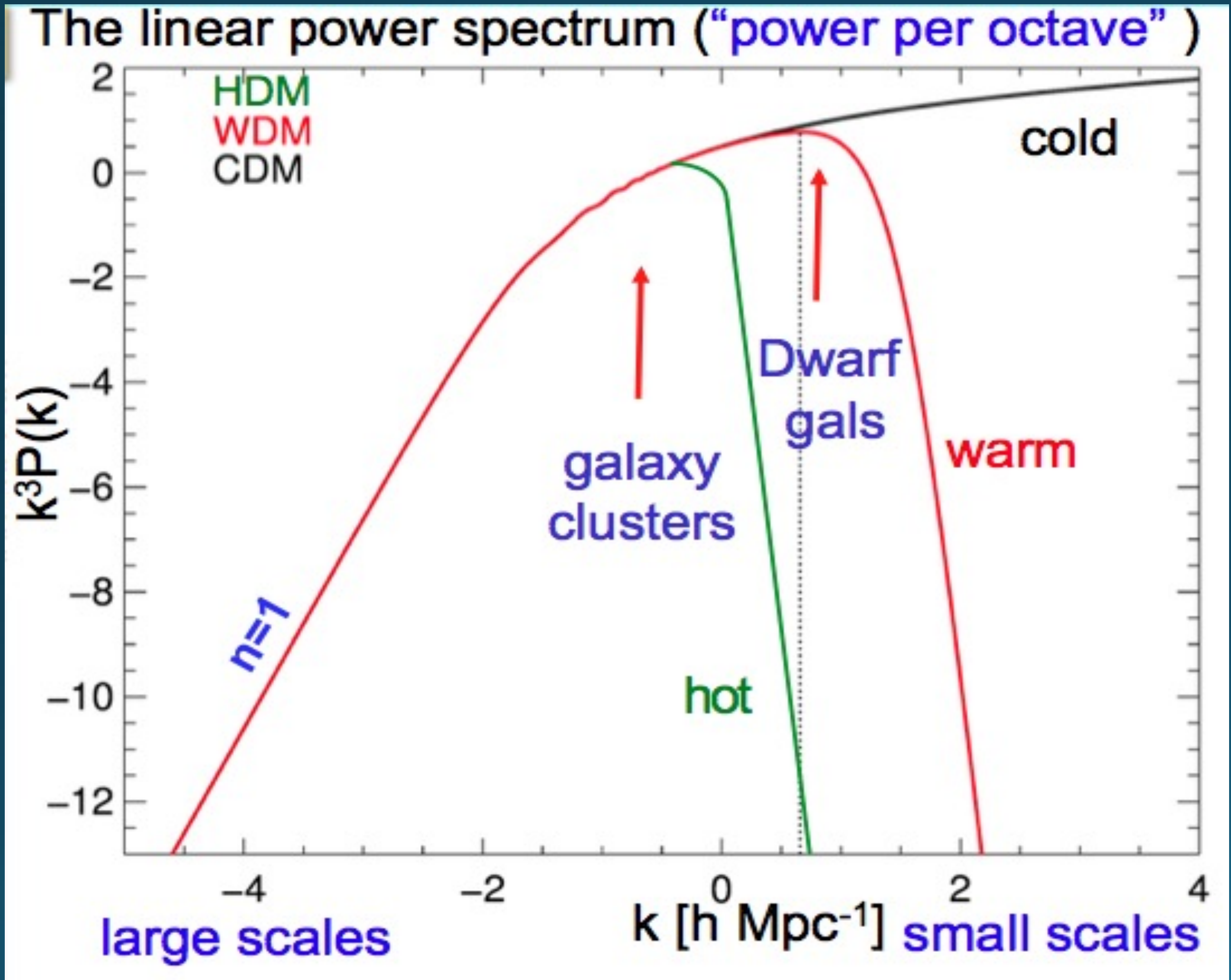
# The Lyα forest evolves rapidly

# Probing dark matter with the Lyα forest

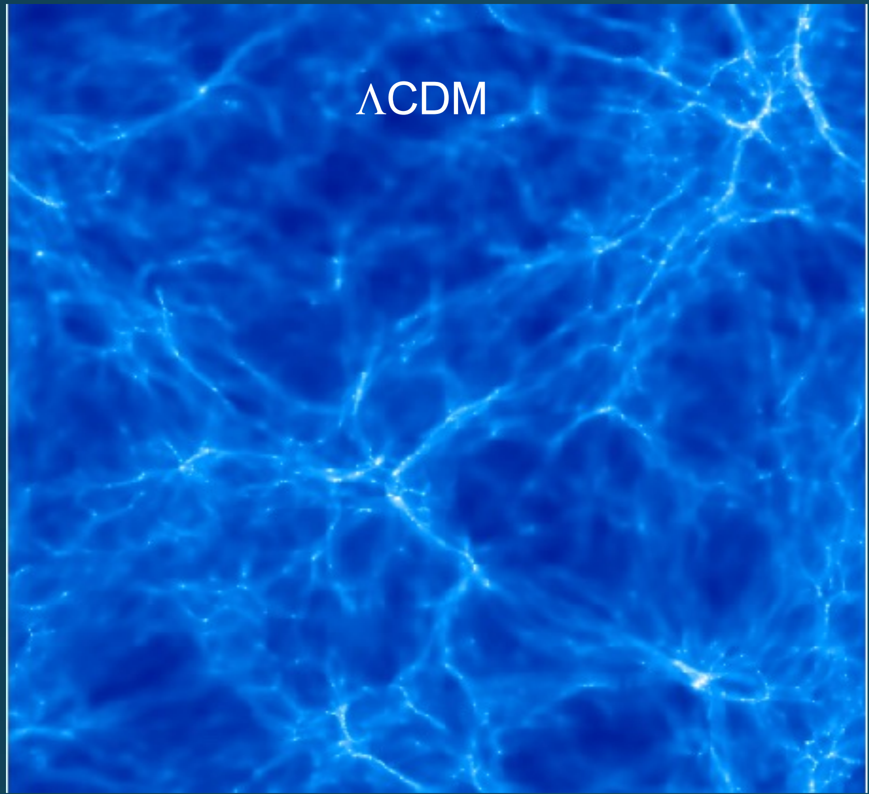
Cut-off in the matter power spectrum on astrophysically interesting scales due to free-streaming or FDM.

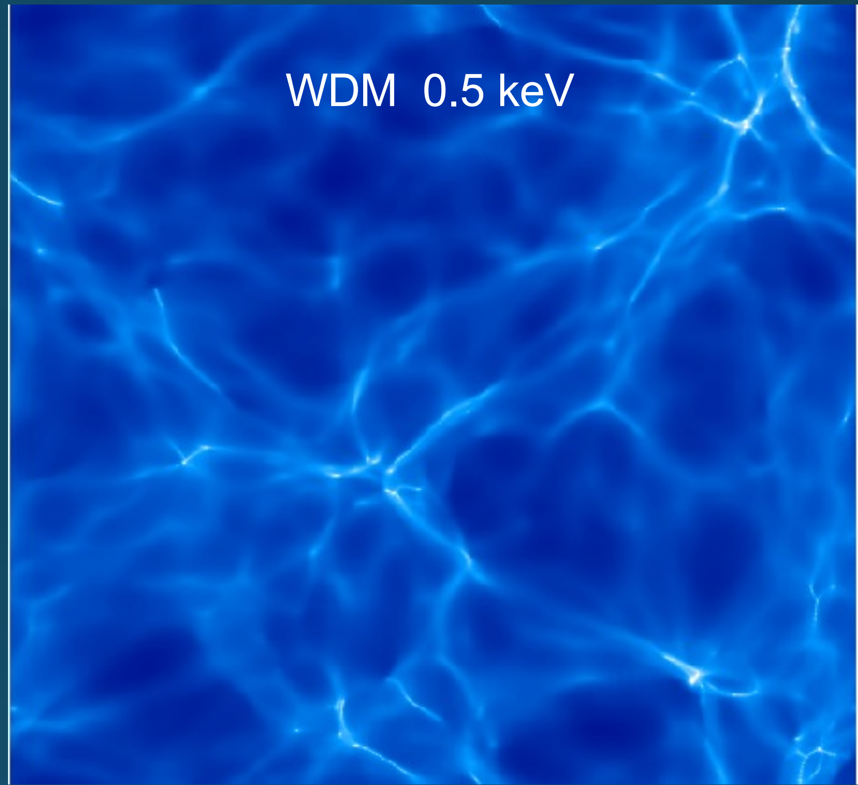


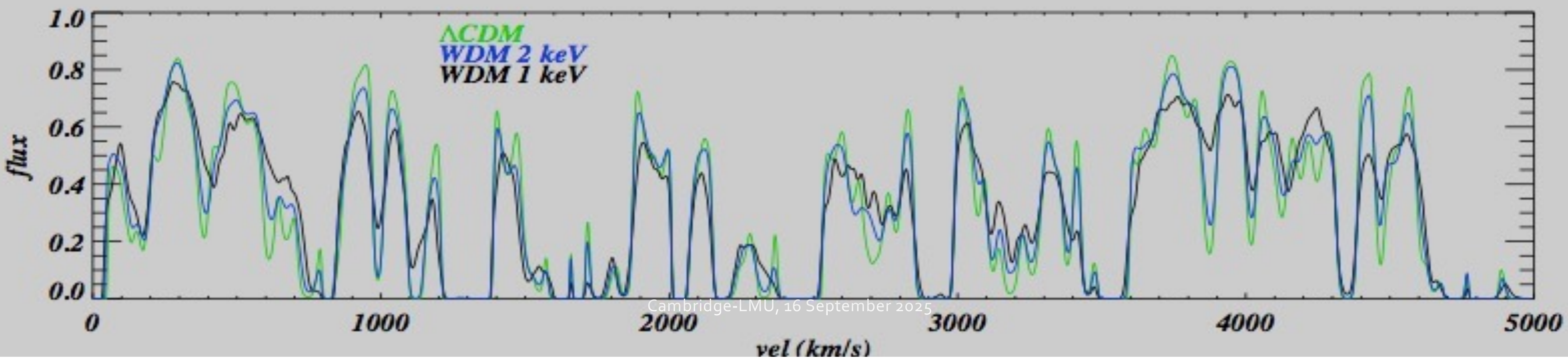

- early decoupling thermal relics
- sterile neutrinos
- ultralight axions
- gravitinos
- ….

courtesy of Carlos Frenk

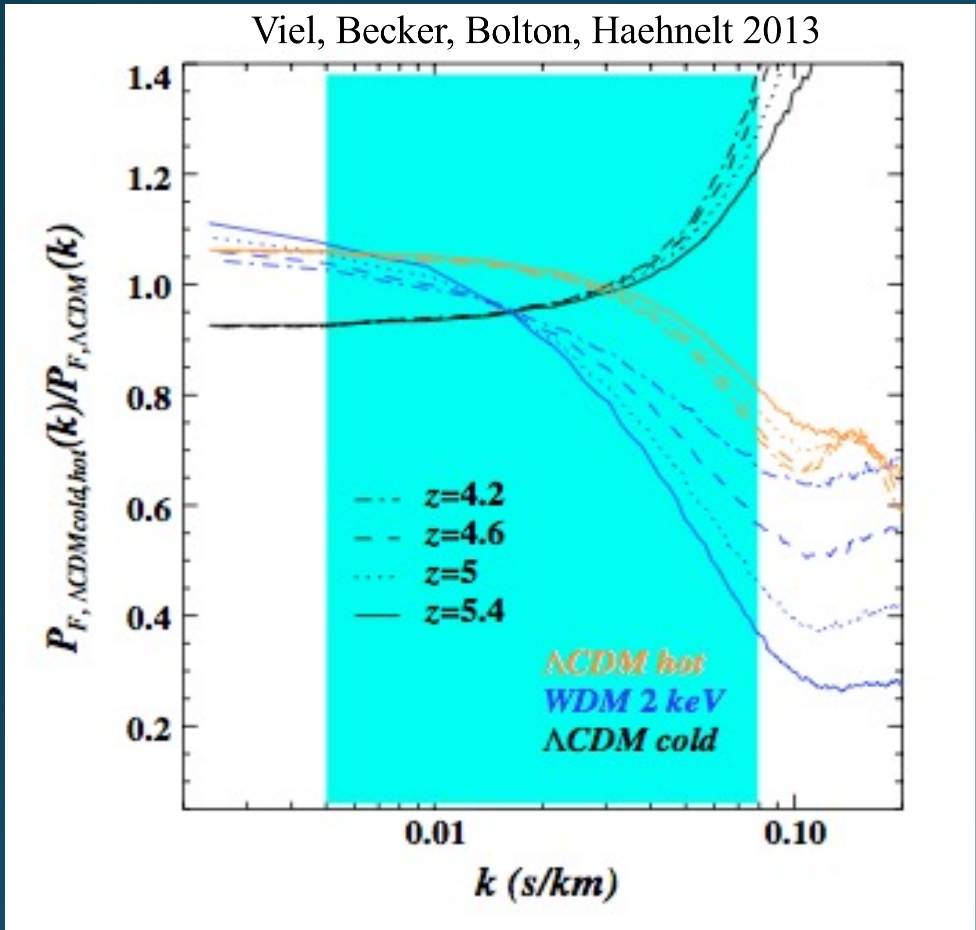
# Free-streaming erases structure



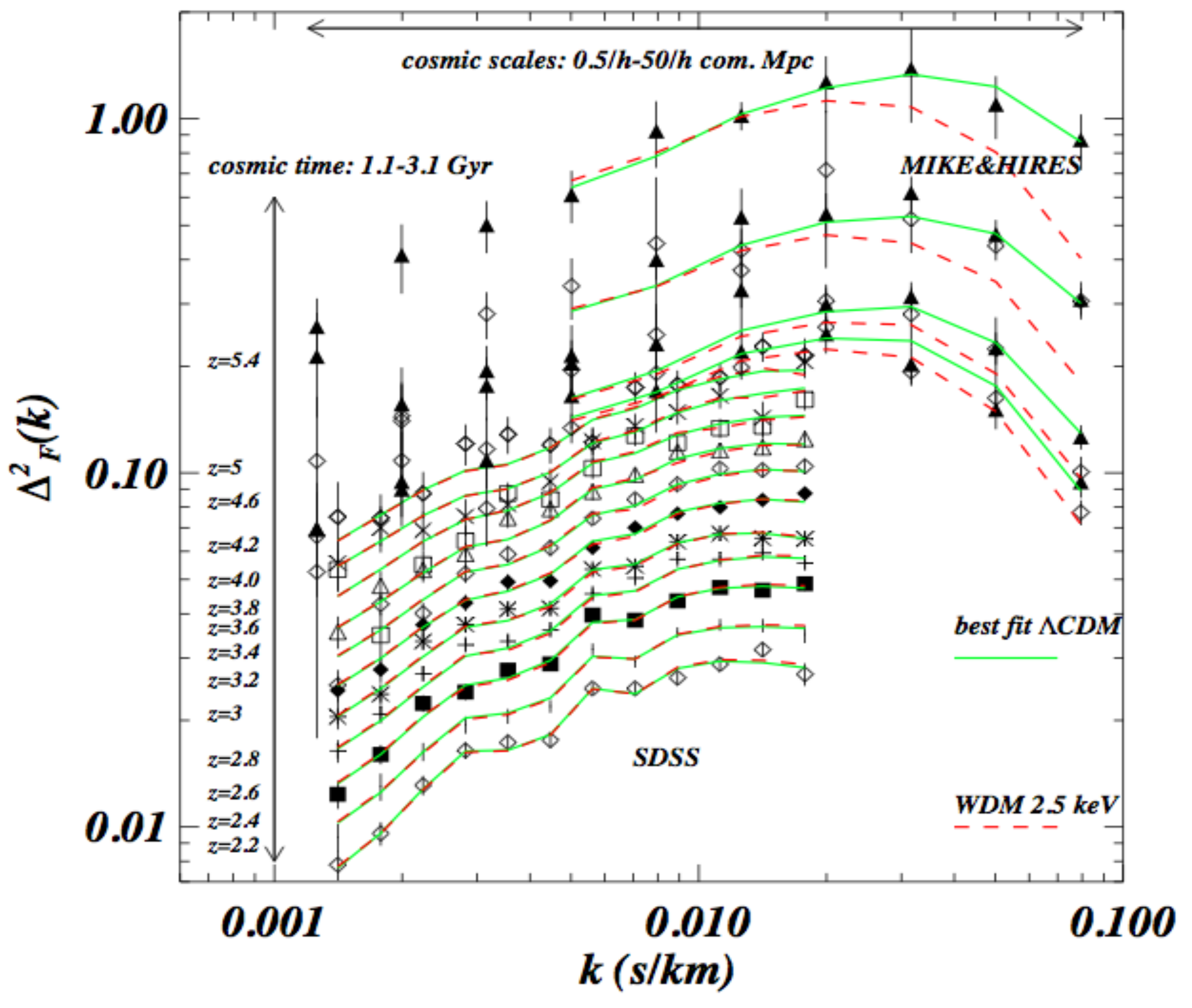
# The effects of temperature and free streaming are not degenerate




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.

# 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



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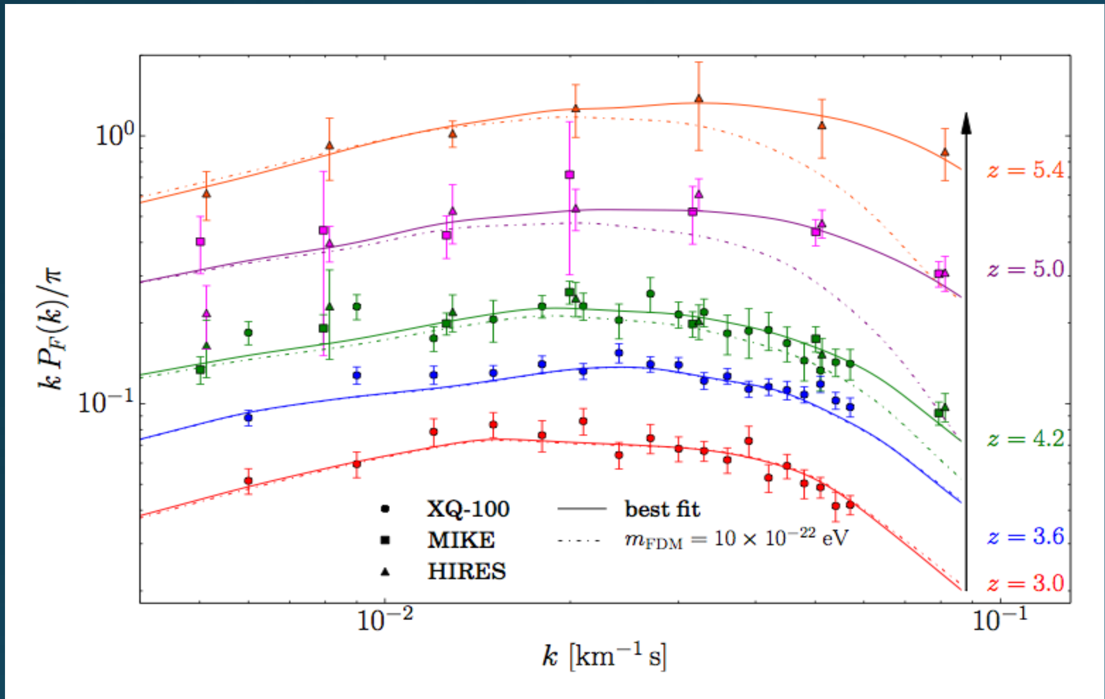
PRL 119, 031302 (2017) PHYSICAL REVIEW LETTERS week ending 21 JULY 2017

**First Constraints on Fuzzy Dark Matter from Lyman-$\alpha$ 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:

$m_{FDM} > 37.5 \times 10^{-22}$ eV (2 σ C.L.)

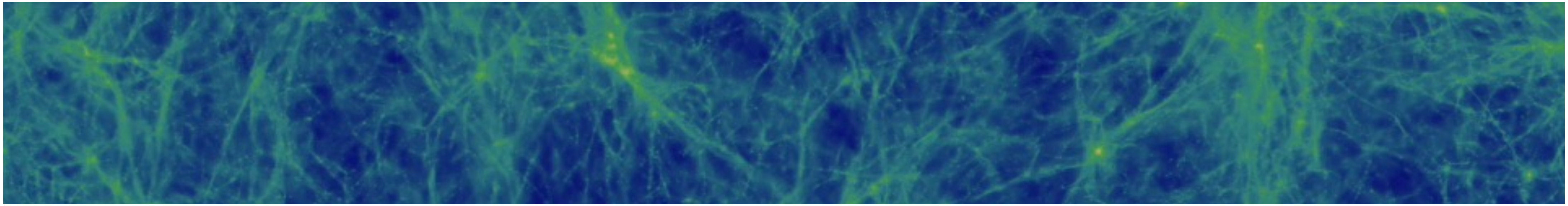
$m_{WDM} > 5.3$ keV (2σ C.L.)

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

PHYSICAL REVIEW D 96, 023522 (2017)

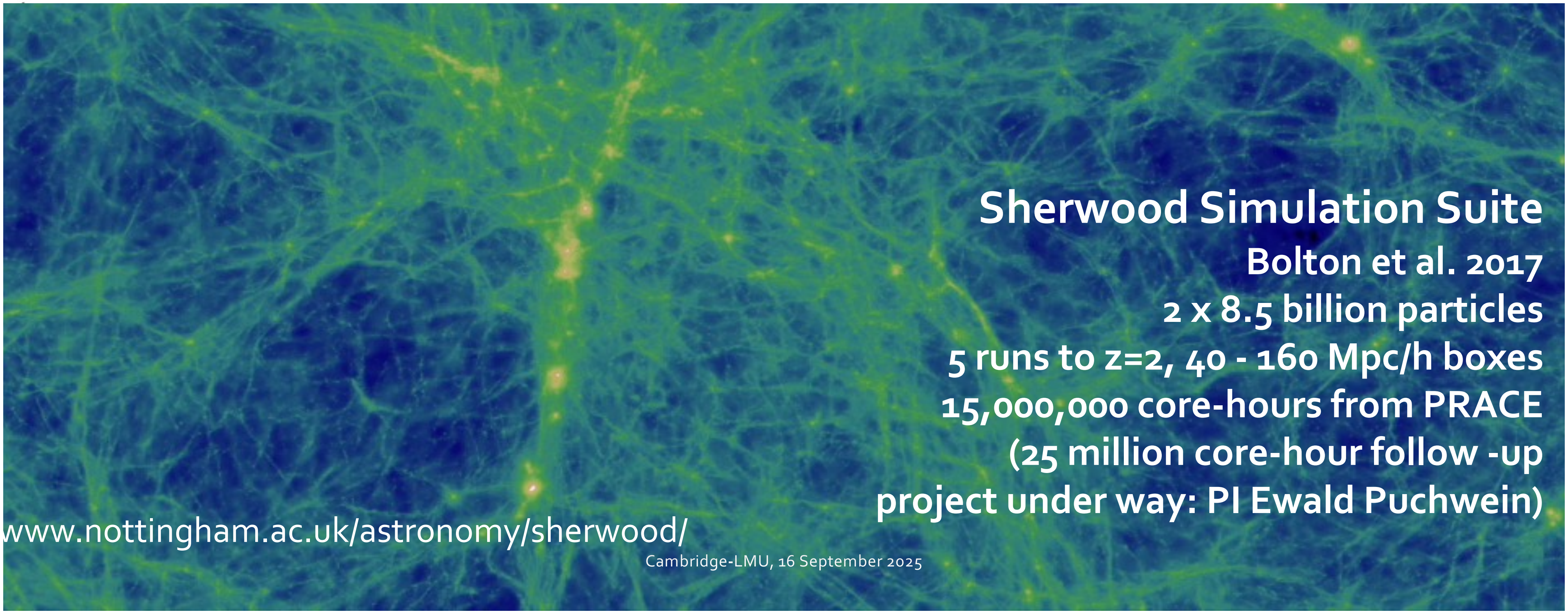
**New constraints on the free-streaming of warm dark matter from intermediate and small scale Lyman-$\alpha$ forest data**

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]



# The Sherwood simulation suite: overview and data comparisons with the Lyman $\alpha$ 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

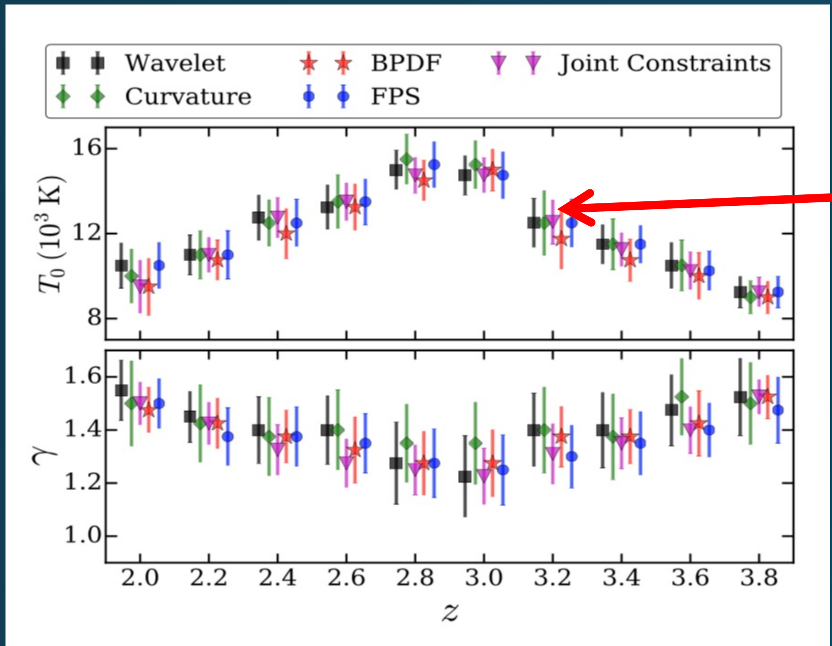
- instrumental resolution
- instrumental noise
- “continuum” fitting
- strong absorbers
- metal absorbers

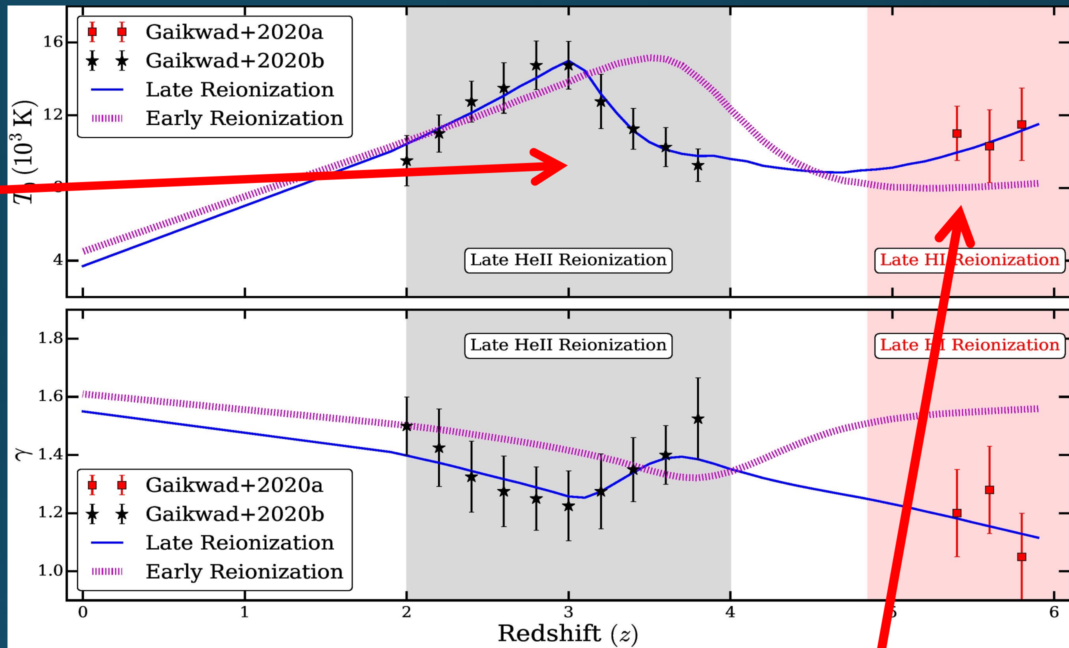
- mean flux has to be measured/assumed
  alternatively photoionization rate has to be measured/assumed
- thermal broadening (instantaneous temperature)
- Jeans smoothing (integrated energy input)
- **spatial variations of the above**

- **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

# IGM Temperature measurements are getting accurate (and consistent)



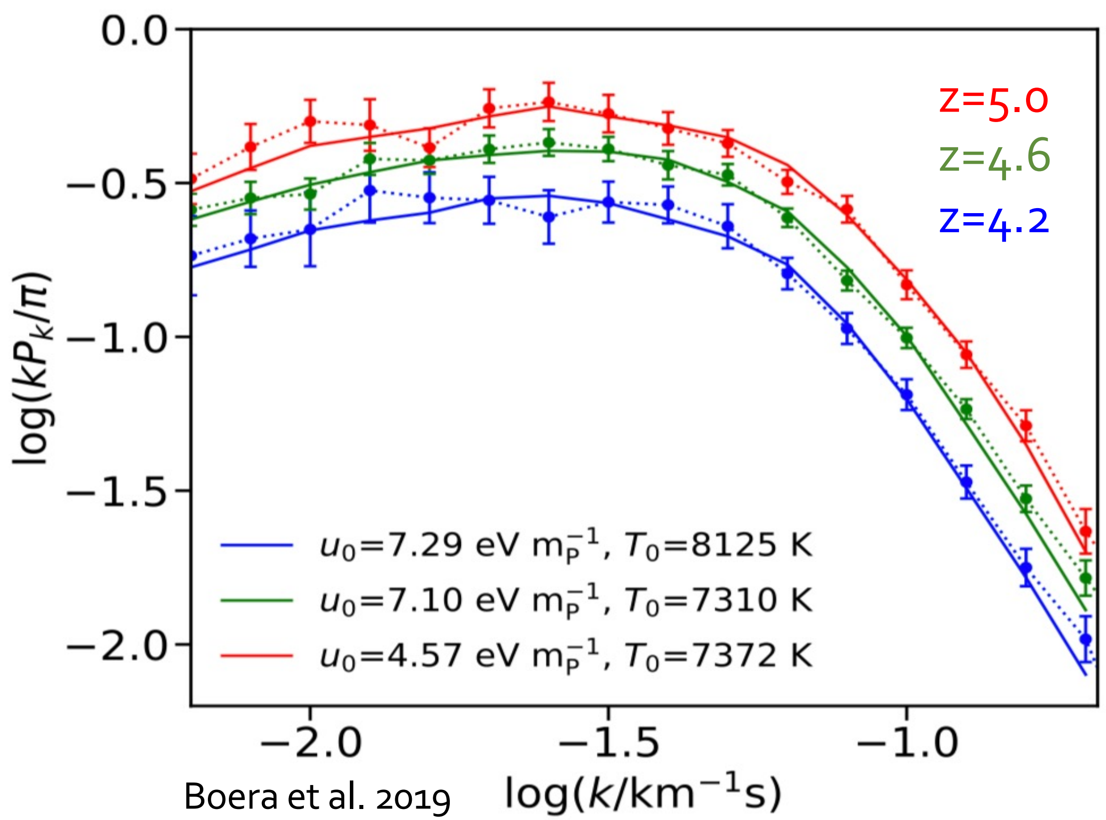

Gaikwad et al. 2021:

- 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

# The to date best 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

see Olga Gallego's talk for more recent constraints on (mixed) dark matter



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**Turning a negative neutrino mass into a positive optical depth**

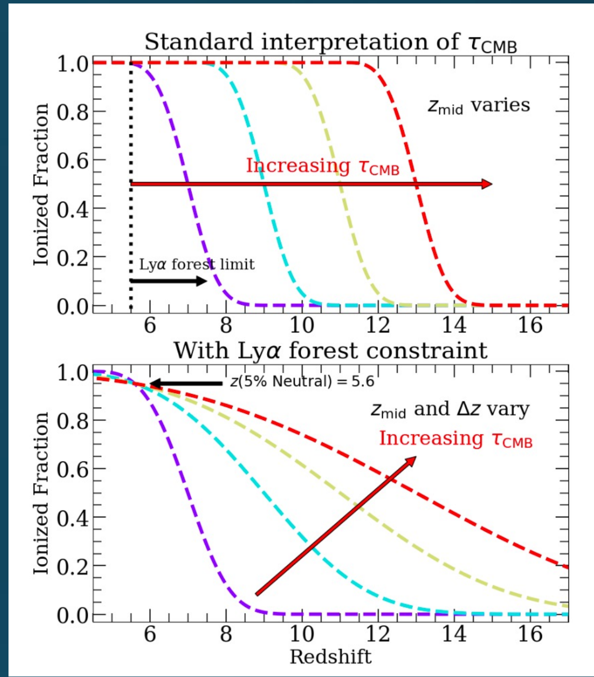
Tanisha Jhaveri,[1] Tanvi Karwal,[1] and Wayne Hu[1]

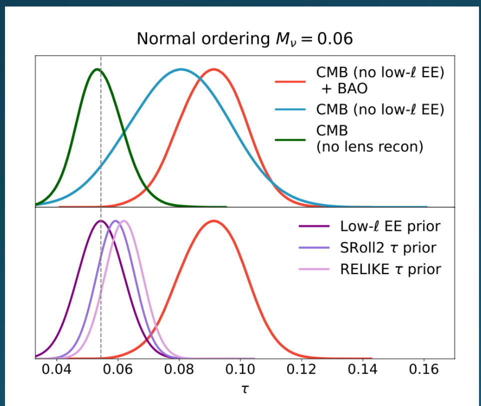
**Dispu$\tau$able: the high cost of a low optical depth**

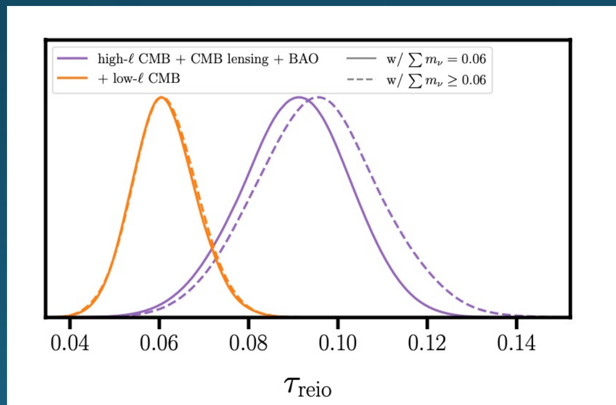
Noah Sailer[*†,1,2] Gerrit S. Farren[*‡,2,1] Simone Ferraro,[2,1] and Martin White[1,2]

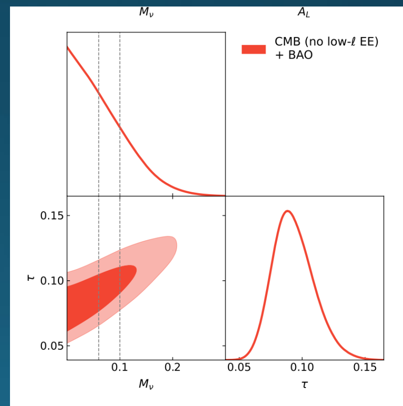
**The CMB optical depth constrains the duration of reionization**

Christopher Cain,[1] Alexander Van Engelen,[1] Kevin S. Croker,[1] Darby Kramer,[1] Anson D'Aloisio,[2] and Garett Lopez[2]



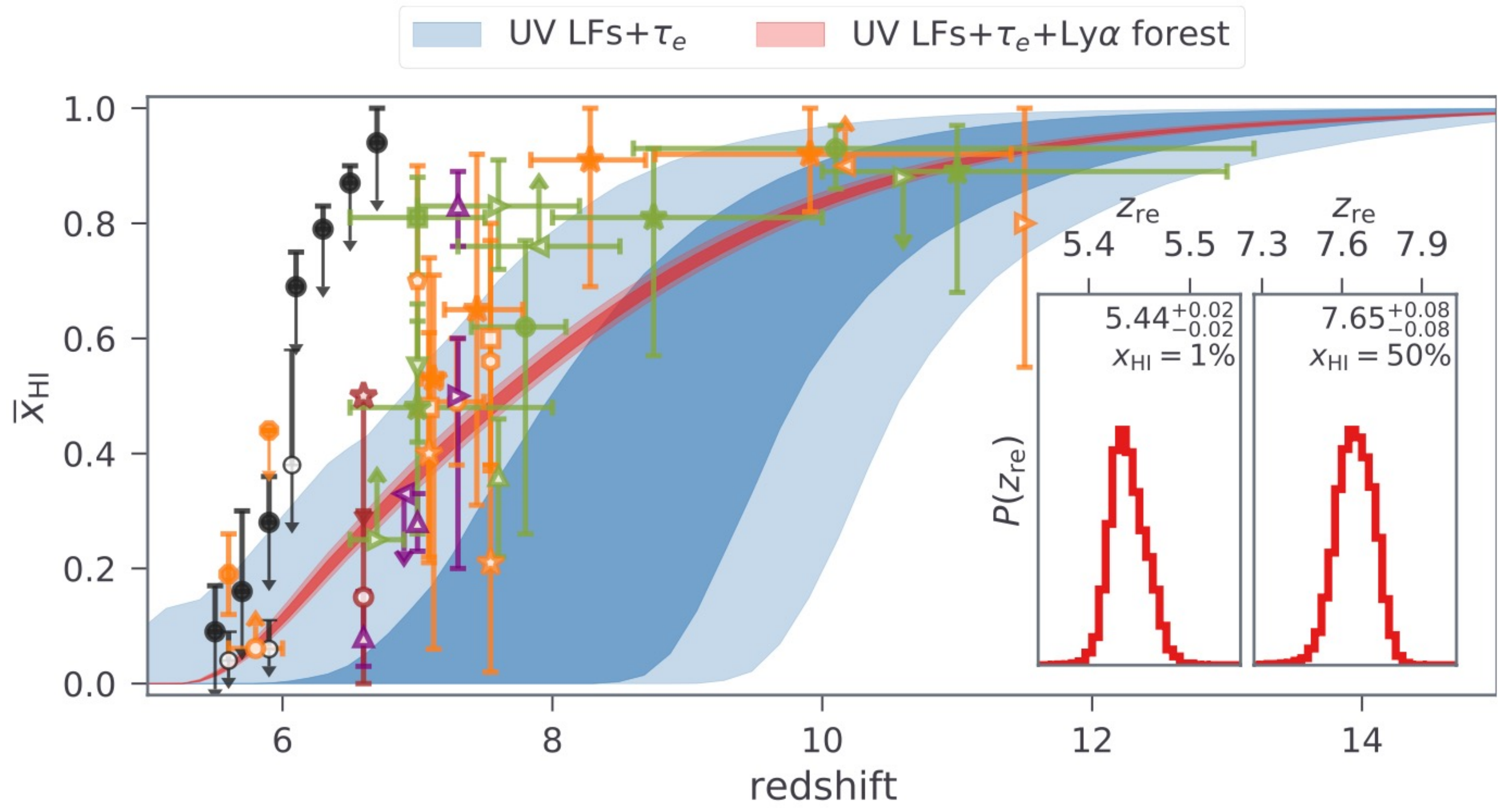




The CMB/cosmology community appears to be willing to drop the rather low Planck $\tau$

# Percent-level timing of reionization: self-consistent, implicit-likelihood inference from XQR-30+ Ly$\alpha$ forest data

Yuxiang Qin [1,2] Andrei Mesinger [3] David Prelogović [3,4] George Becker [5] Manuela Bischetti [6,7] Sarah E. I. Bosman [8,9] Frederick B. Davies [9] Valentina D'Odorico [10,3] Prakash Gaikwad [9] Martin G. Haehnelt [11] Laura Keating [12] Samuel Lai [13] Emma Ryan-Weber [14,2] Sindhu Satyavolu [15,16] Fabian Walter [9,17] and Yongda Zhu [18]



# 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 (end of) reionization → spatial fluctuations of temperature-density relation and photoionization rate more pronounced.
- Lively discussion of possibility of significantly larger $\tau_{CMB}$ than published by Planck. Should be measurable independently.
- Exciting new data and more to come. Lyman-alpha forest data and its analysis is (rapidly) improving.