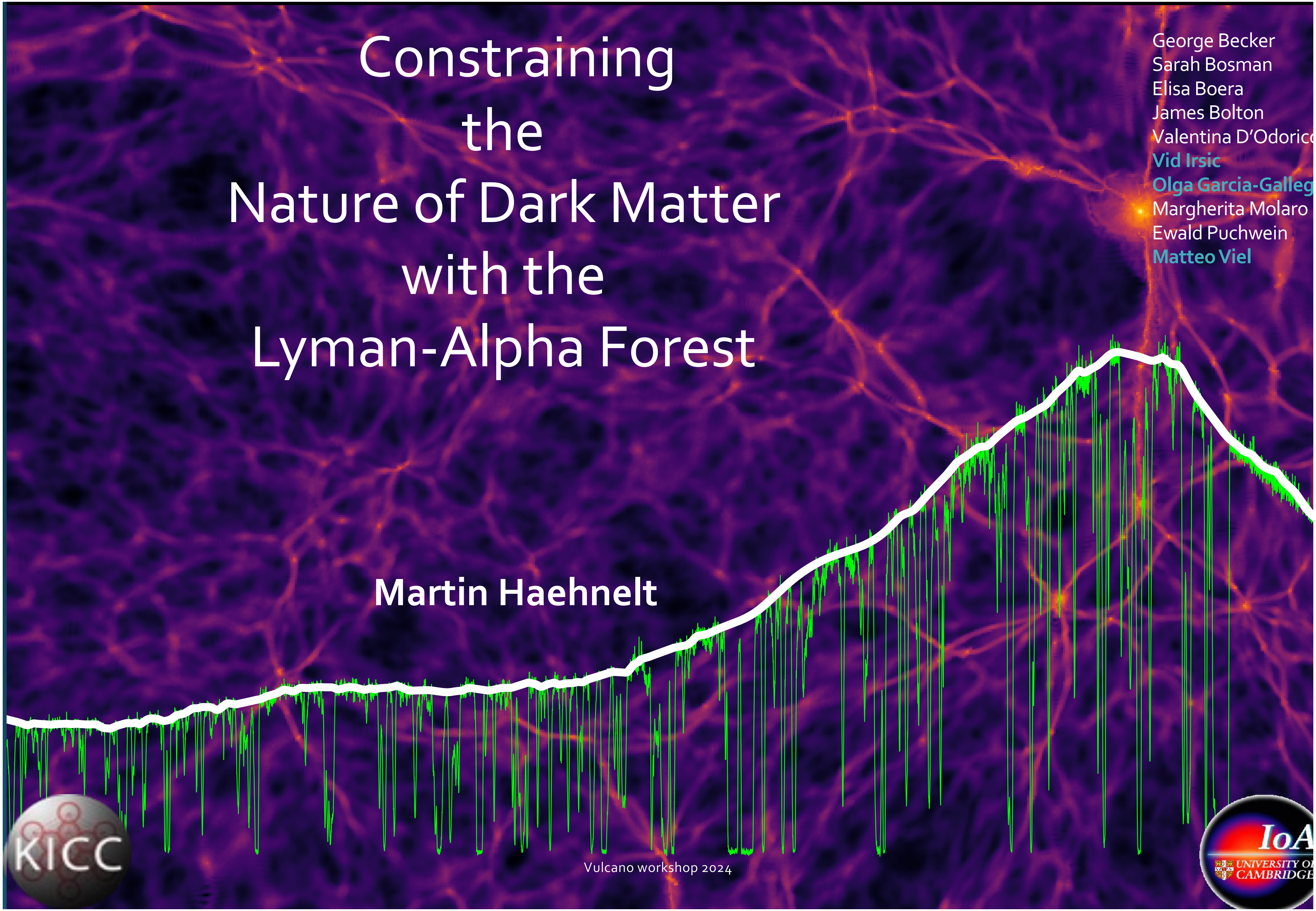
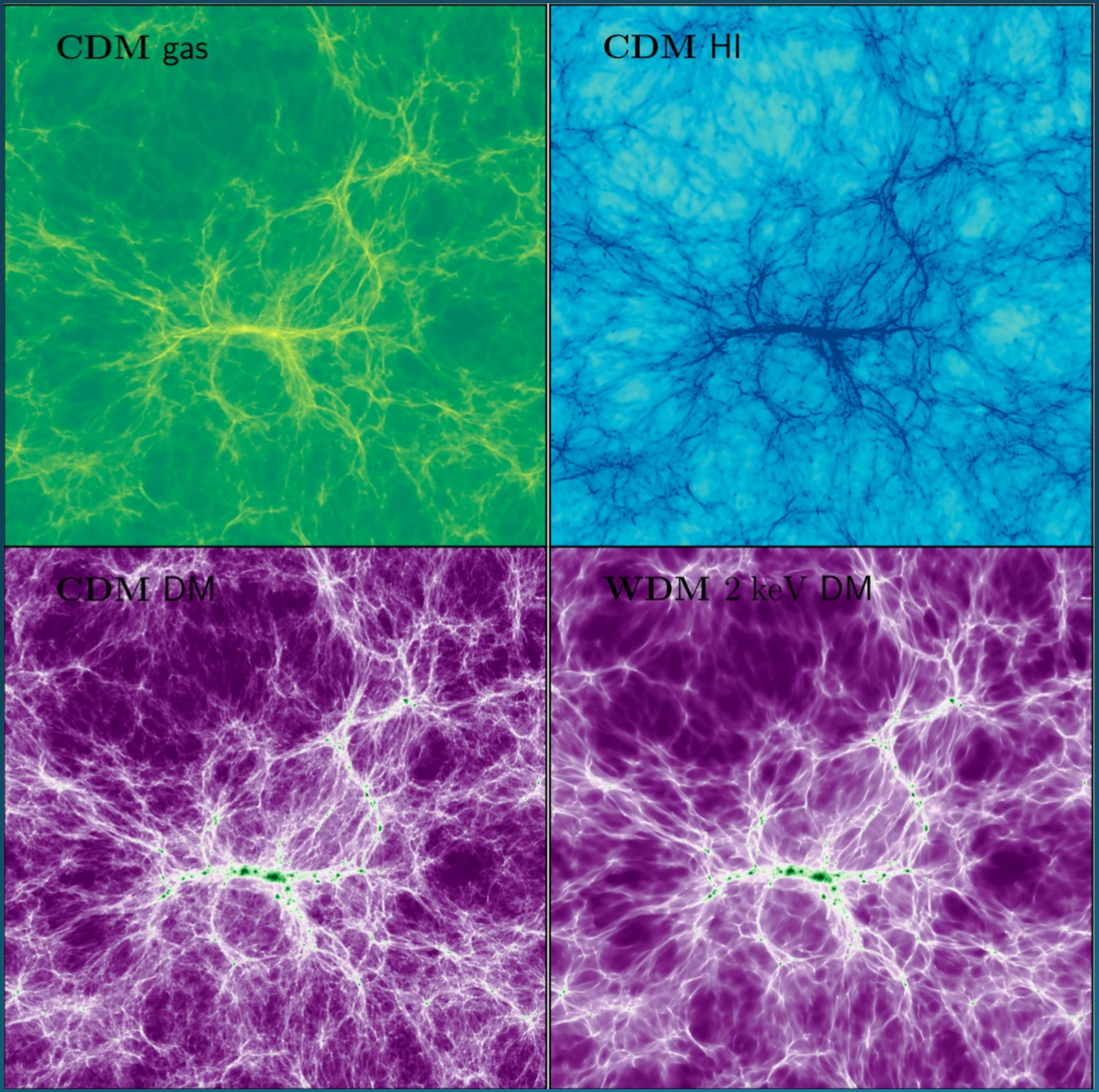


Constraining the Nature of Dark Matter with the Lyman-Alpha Forest

George Becker
Sarah Bosman
Elisa Boera
James Bolton
Valentina D'Odoric
Vid Irsic
Olga Garcia-Galleg
Margherita Molaro
Ewald Puchwein
Matteo Viel

Martin Haehnelt

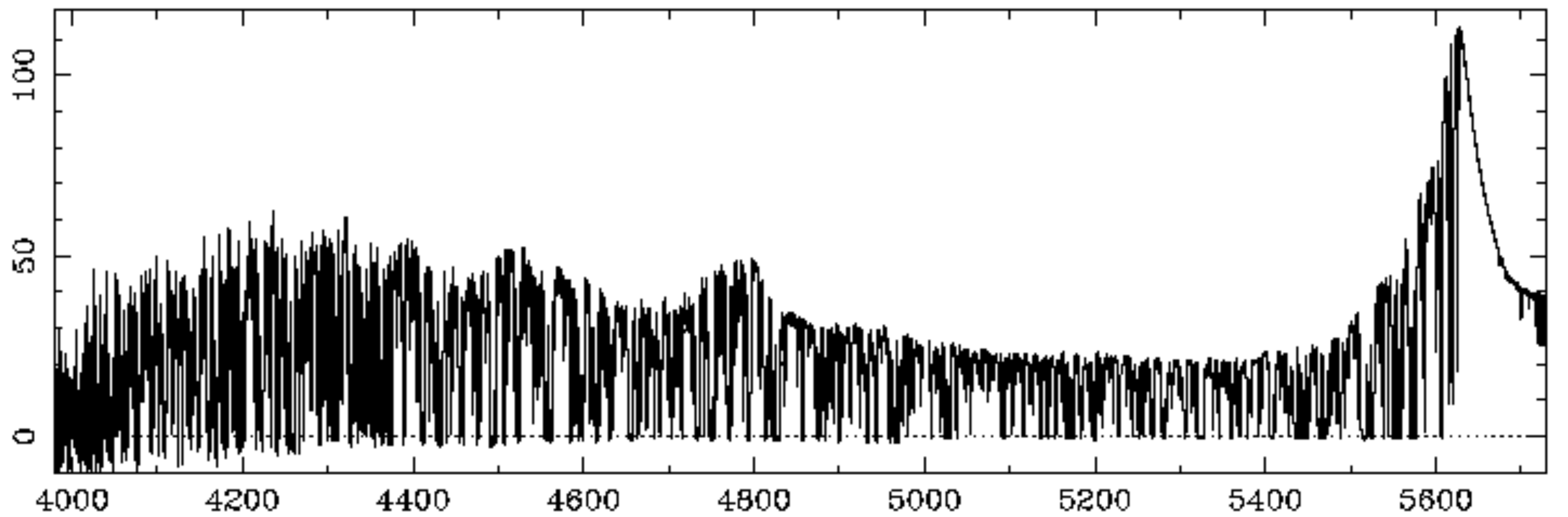
Vulcano workshop 2024



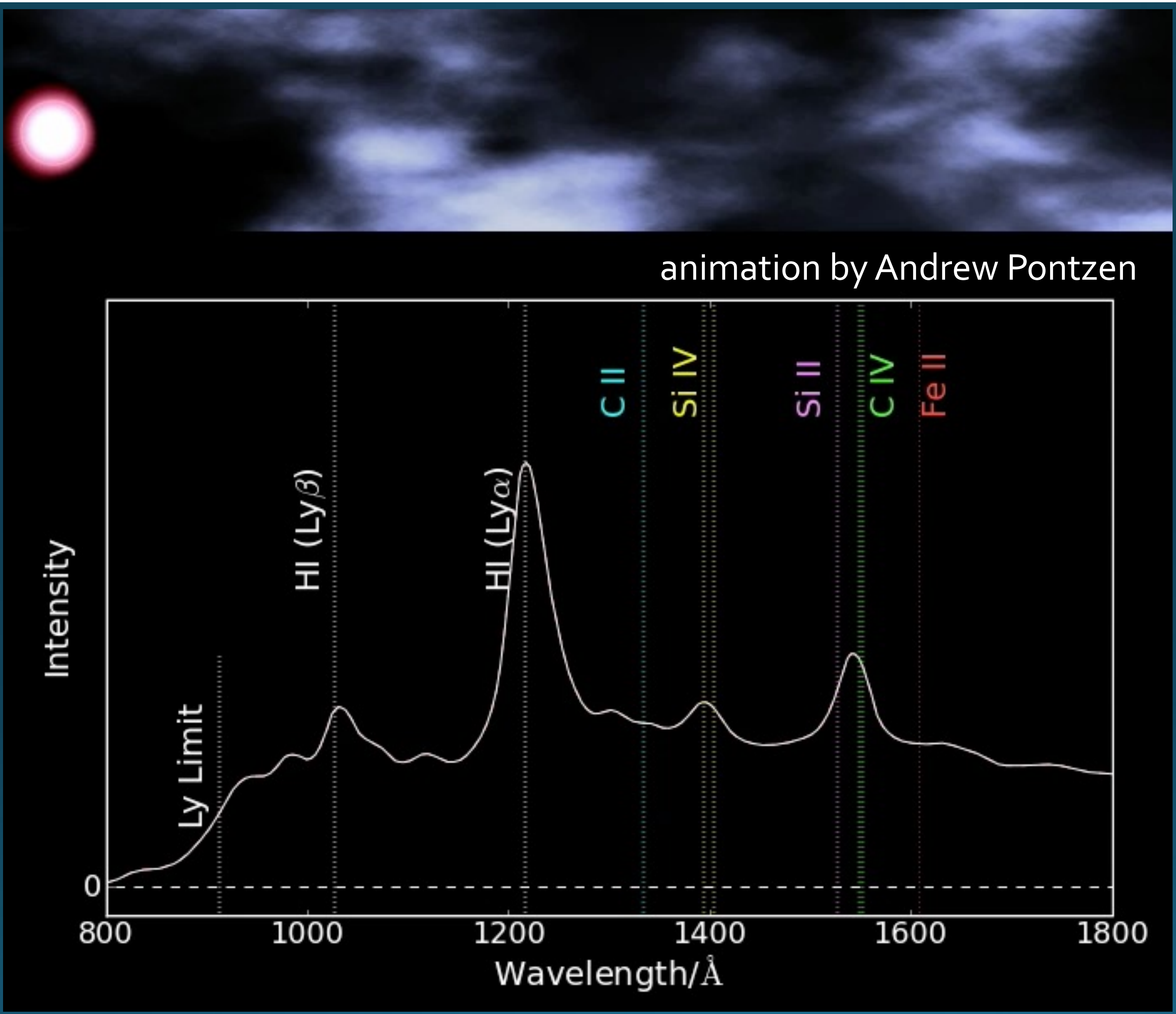
Vid Irsic

Olga
Garcia-Gallego

The Lyα forest



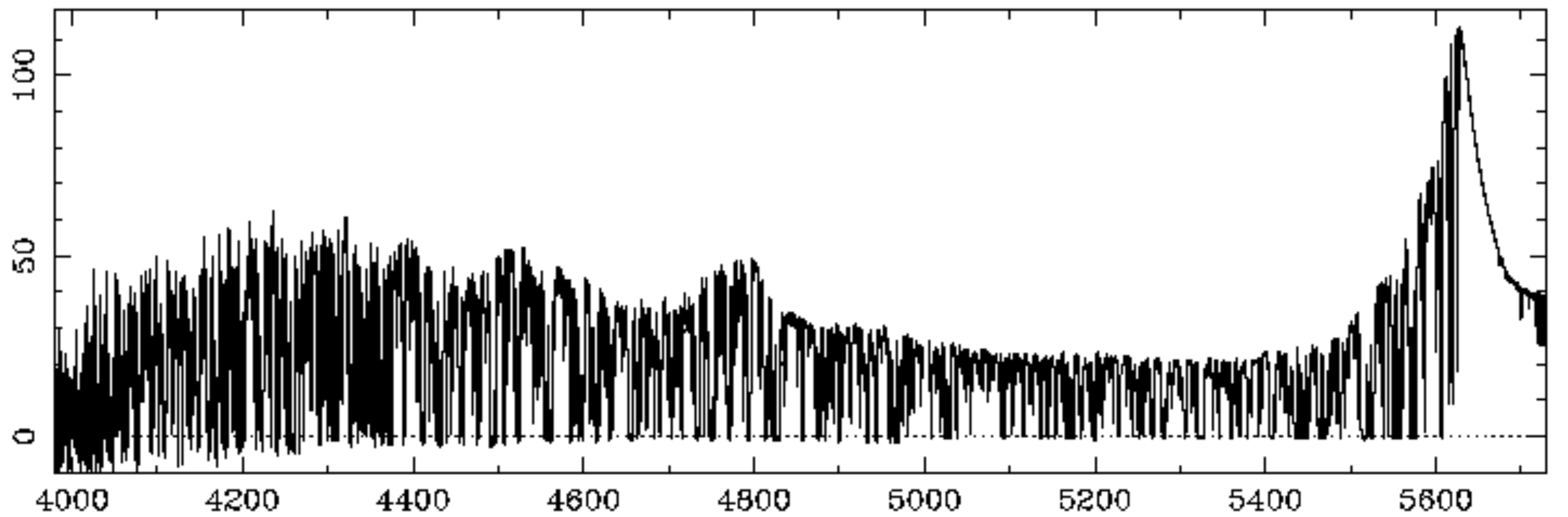
$\lambda_{Ly\alpha} = 1215.67\ (1+z)$ Å



animation by Andrew Pontzen

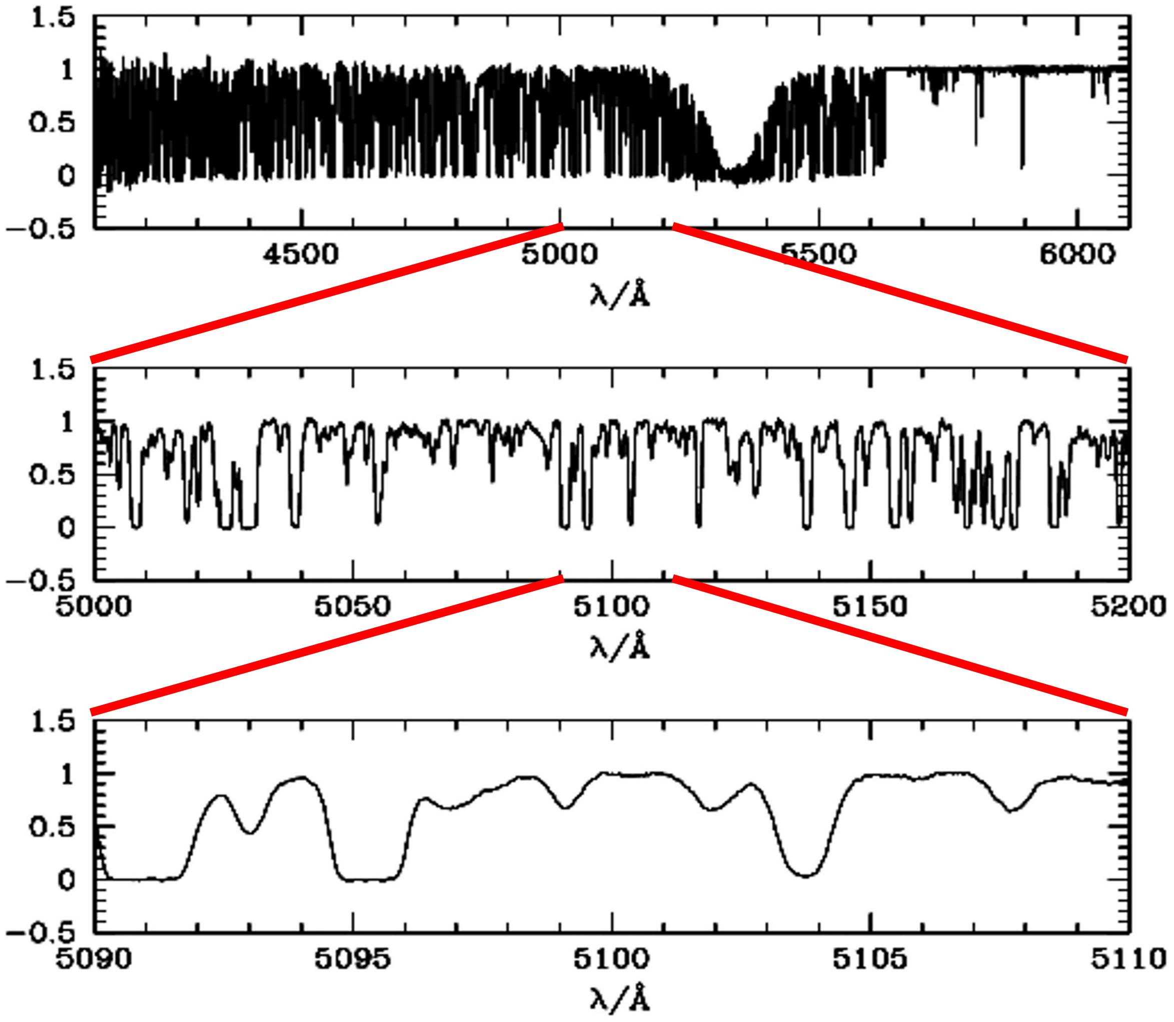
https://www.youtube.com/watch?v=6Bn7KaoTjjw

The Lyα forest



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

High resolution – High S/N!



x10

x10

A treasure trove of information!

photoionization equilibrium:

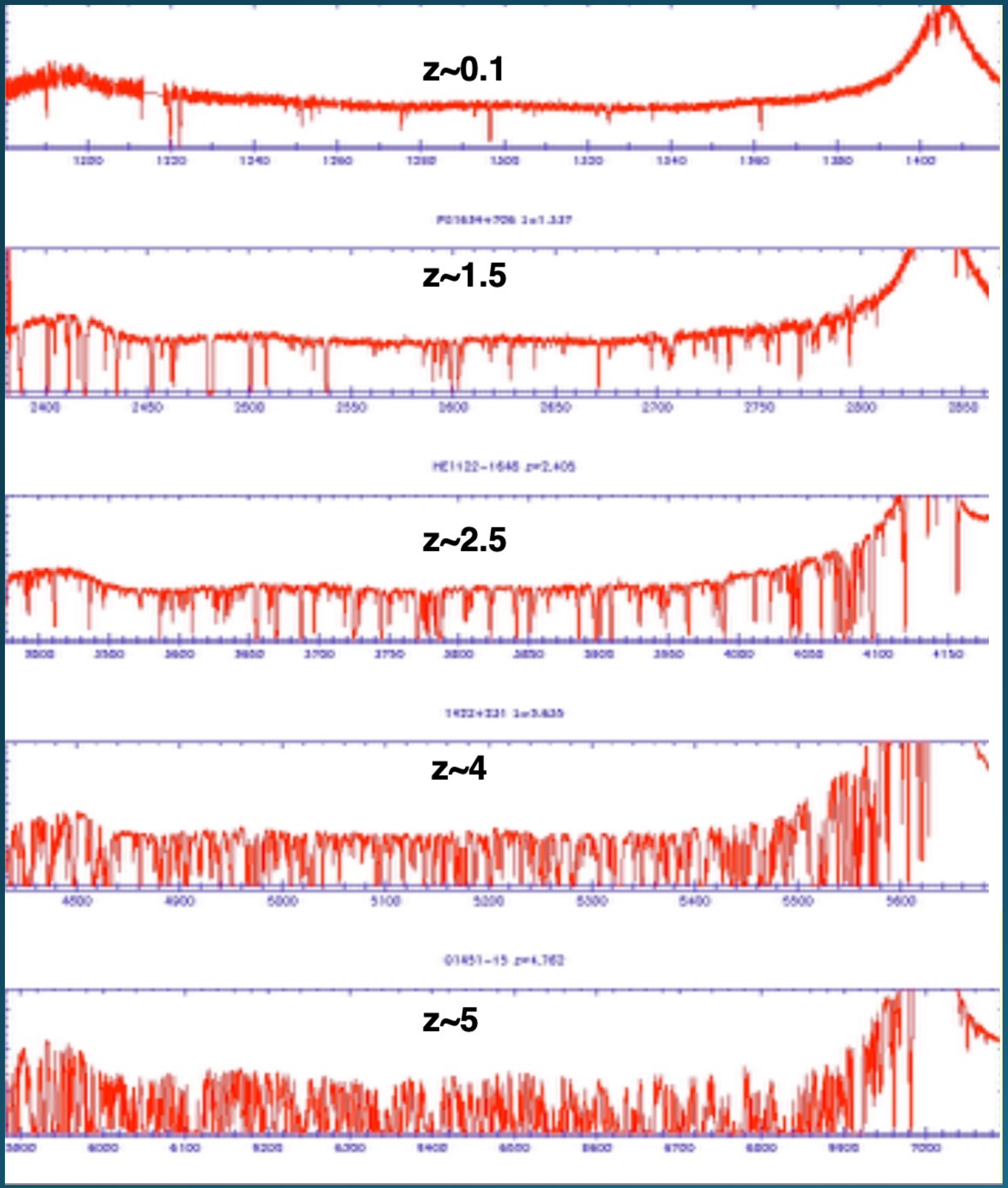
$$\underset{\underset{\text{recombination coefficient}}{\uparrow}}{\alpha} \cdot n_{HII} \cdot n_e = n_{HI} \cdot \underset{\underset{\text{photoionization rate}}{\uparrow}}{\Gamma} \qquad \frac{n_{HI}}{n_H} \sim 5 \cdot 10^{-6} \, \frac{\rho}{\hat{\rho}} \left(\frac{\Gamma}{10^{-12} s^{-1}} \right)^{-1} \left(\frac{T}{10^4 K} \right)^{-0.7}$$

photoheating vs adiabatic cooling:

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

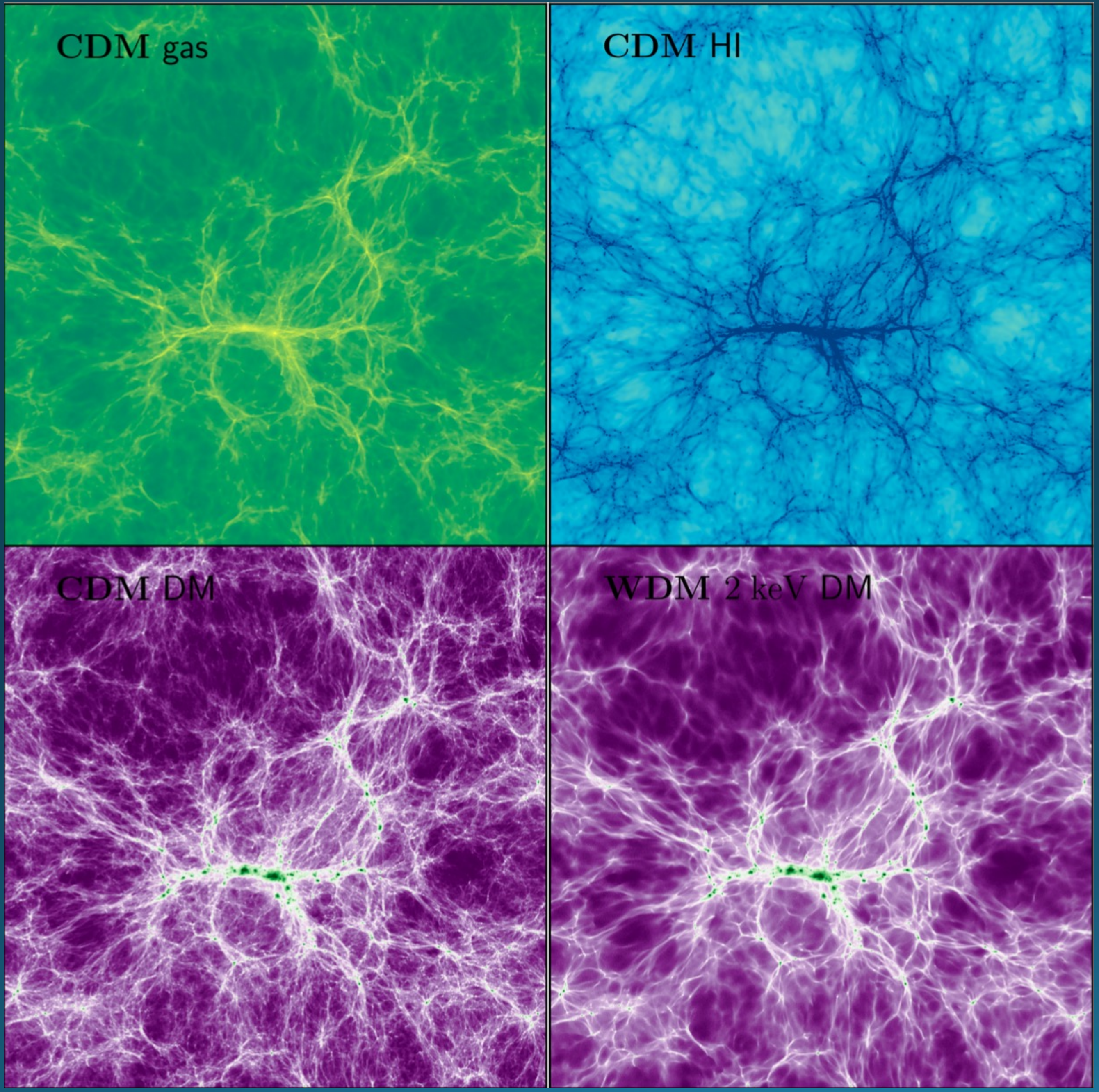
Fluctuating Gunn-Peterson approximation:

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



from Xiaohui Fan's Sao Paolo lectures

The Lyα forest evolves rapidly



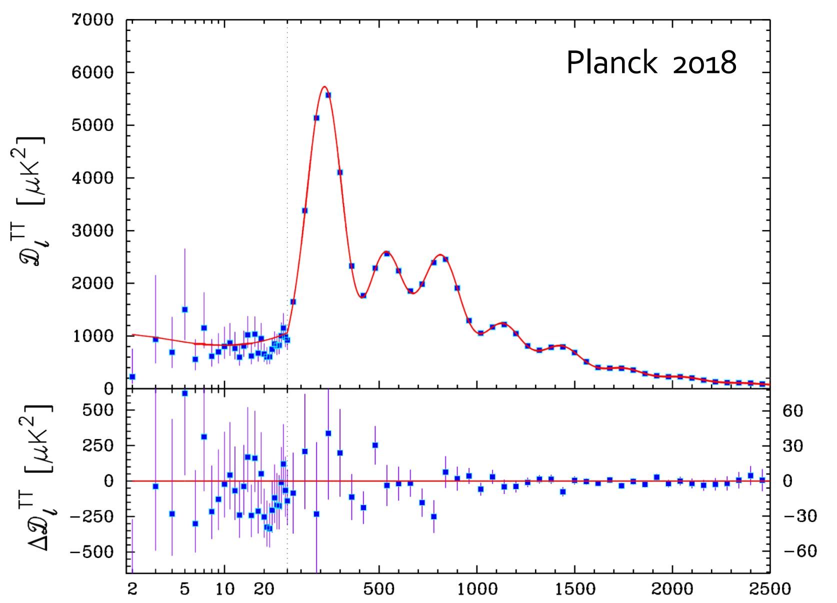
Vid Irsic

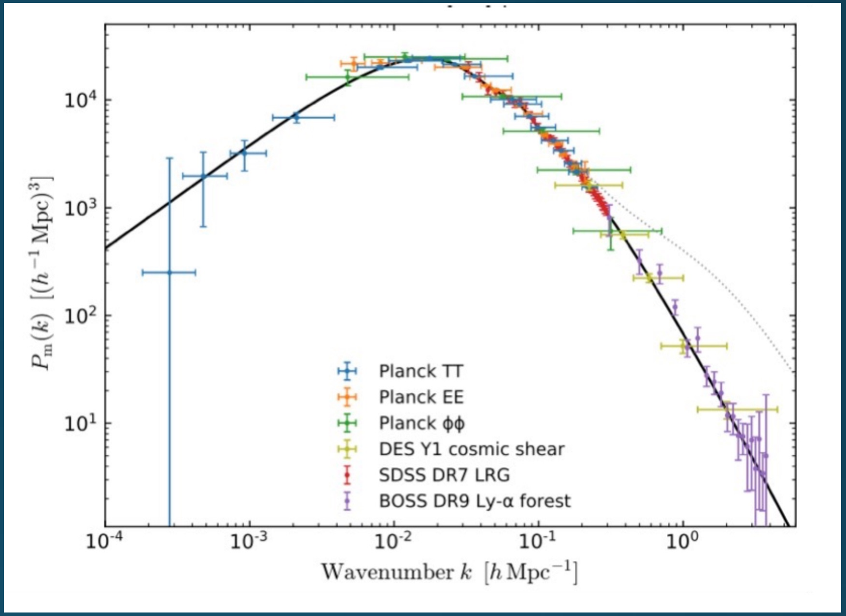
Olga Garcia-Gallego

KICC

IoA UNIVERSITY OF CAMBRIDGE

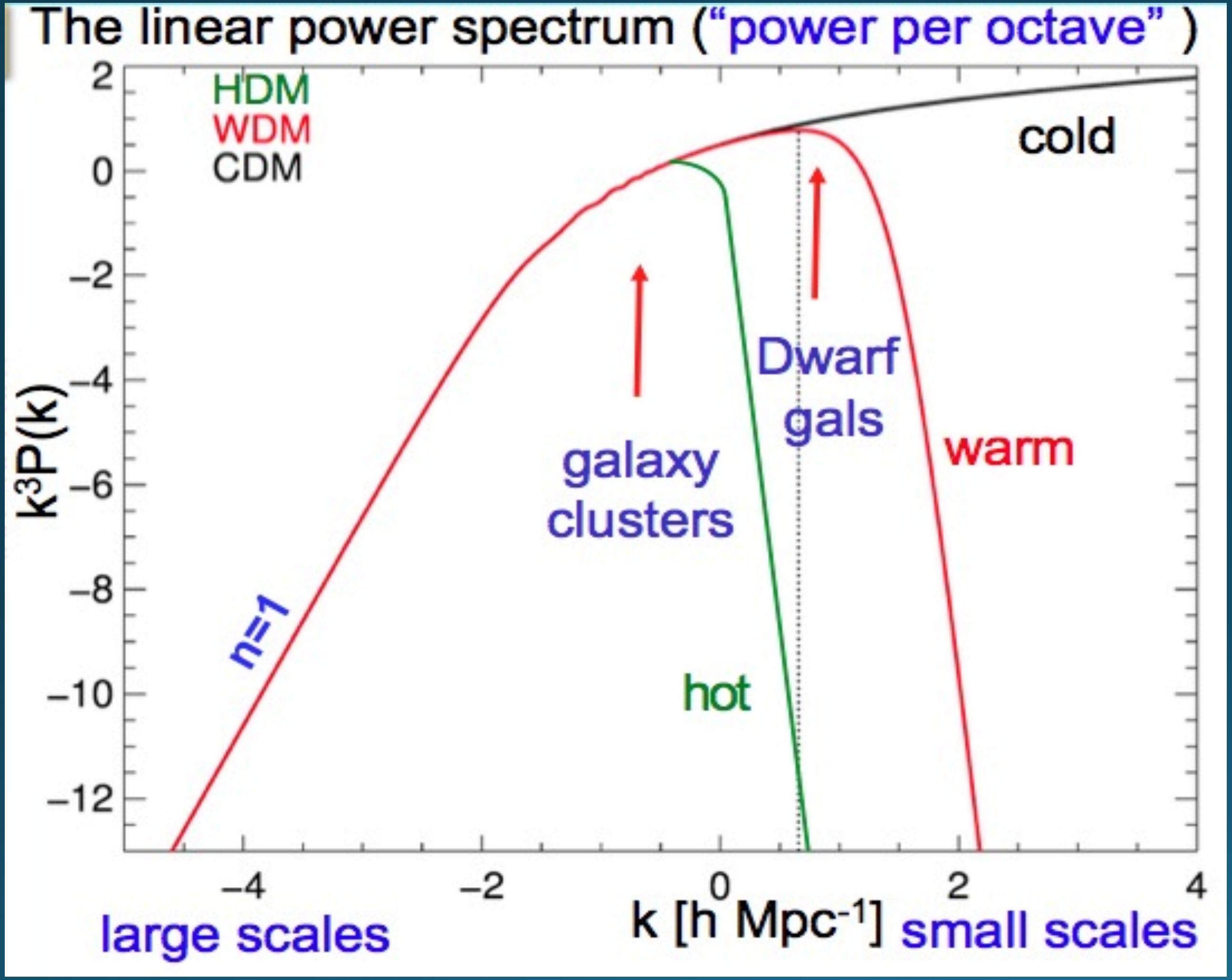
Probing dark matter with the Lyα forest





Six-parameter ΛCDM fits data on a wide range of scales remarkably well, but is dark matter really cold?

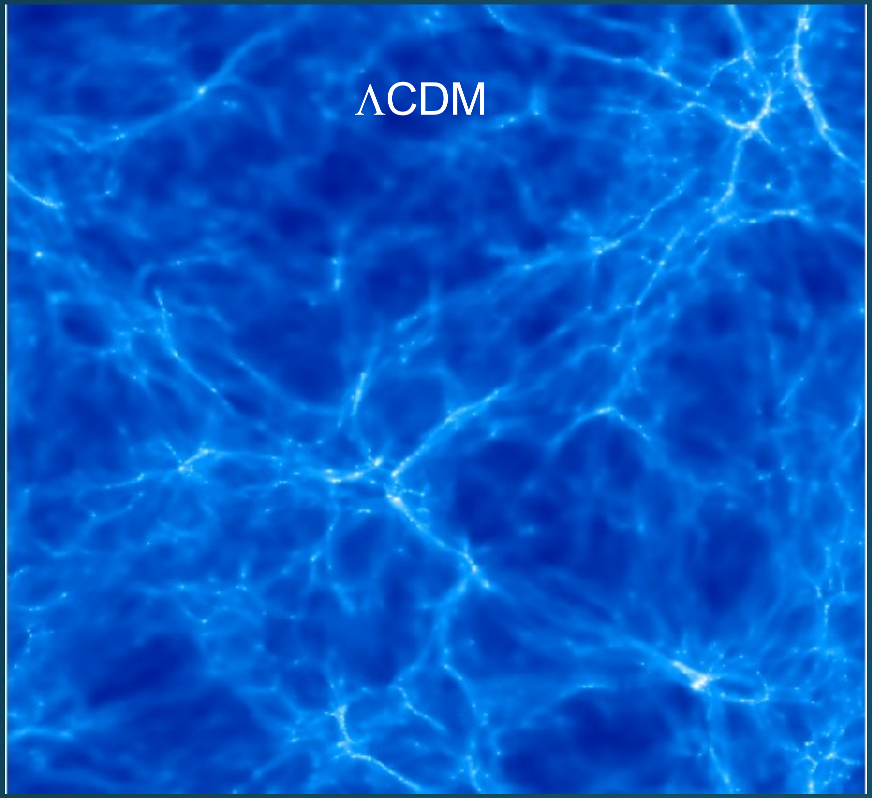
Cut-off in the matter power spectrum on astrophysically interesting scales due to free-streaming or FDM?

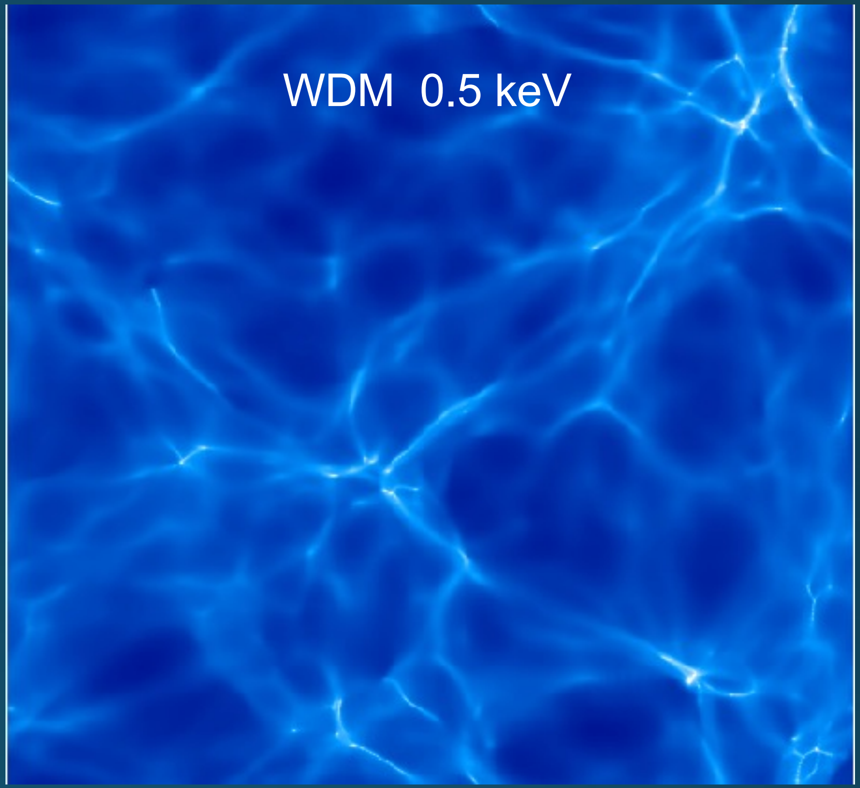


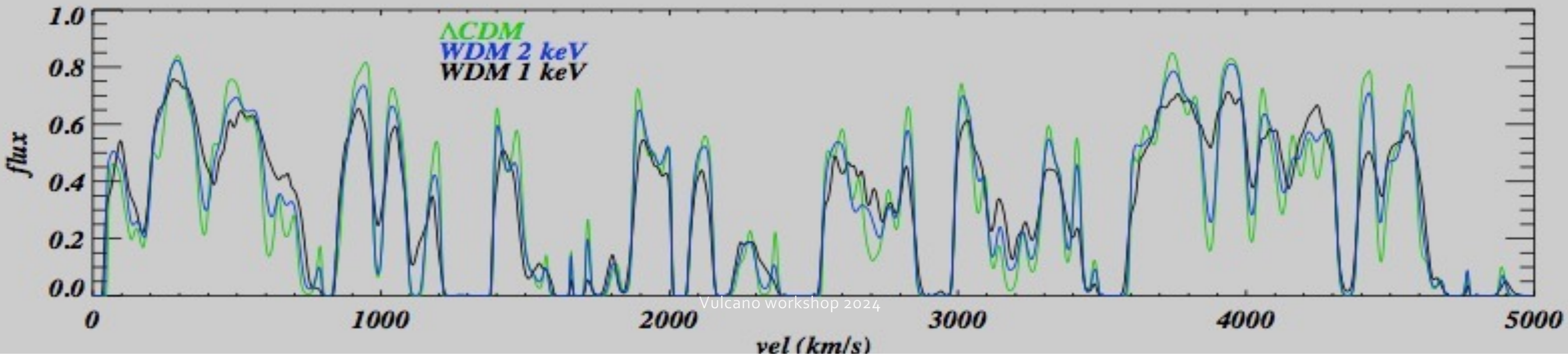
- early decoupling thermal relics
- sterile neutrinos
- ultralight axions
- gravitinos
- ….

courtesy of
Carlos Frenk

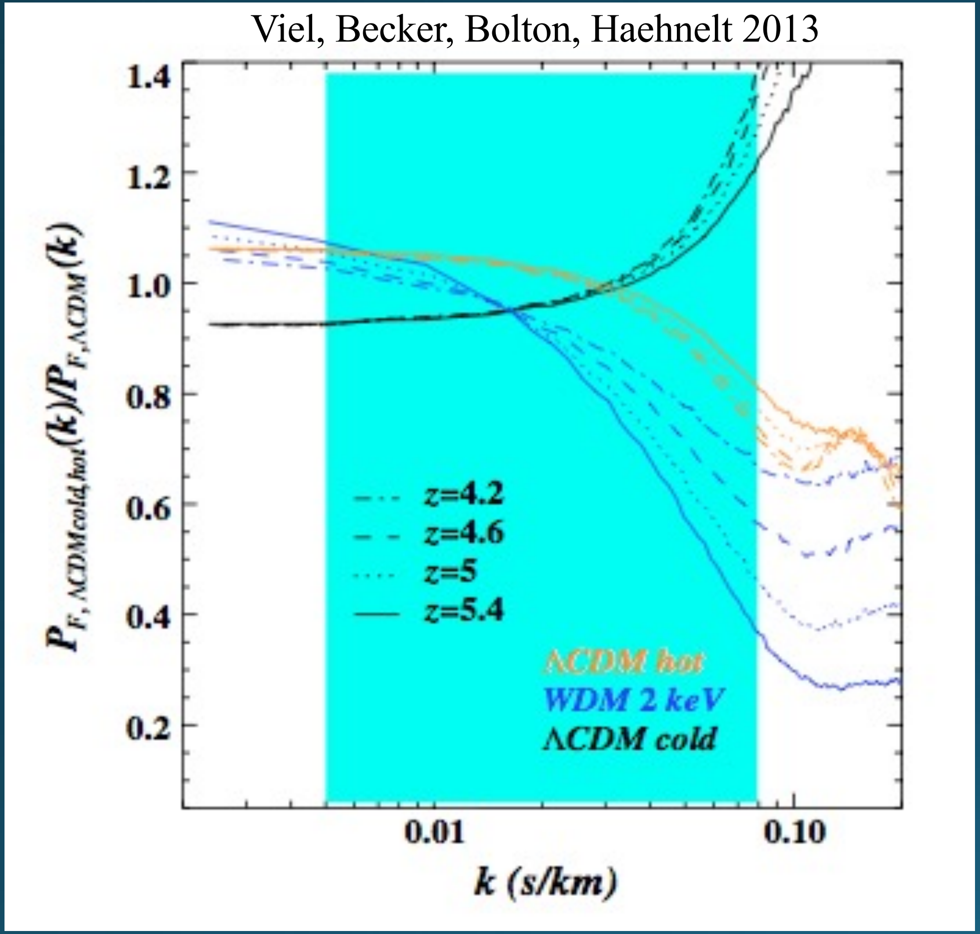
Free-streaming erases structure







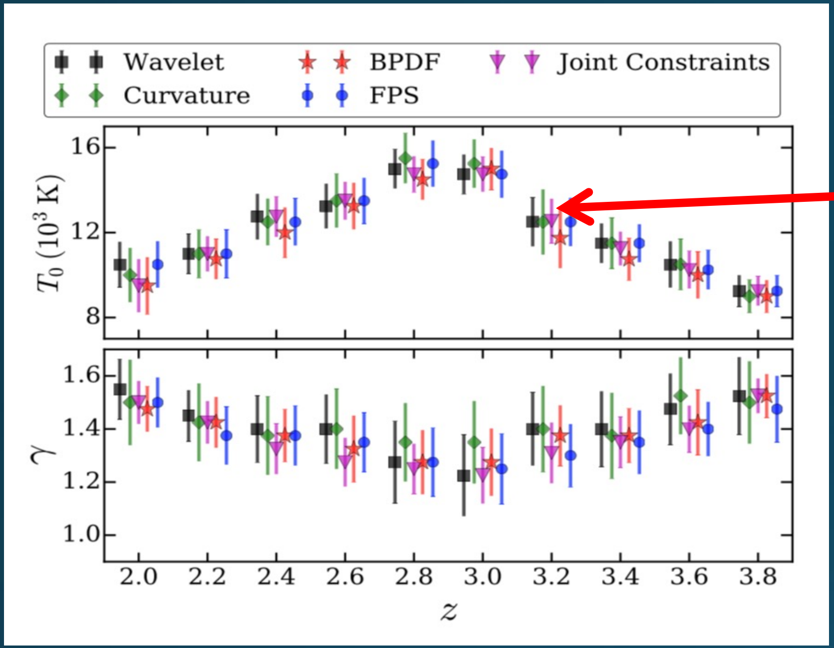
The effects of temperature and free streaming are not degenerate

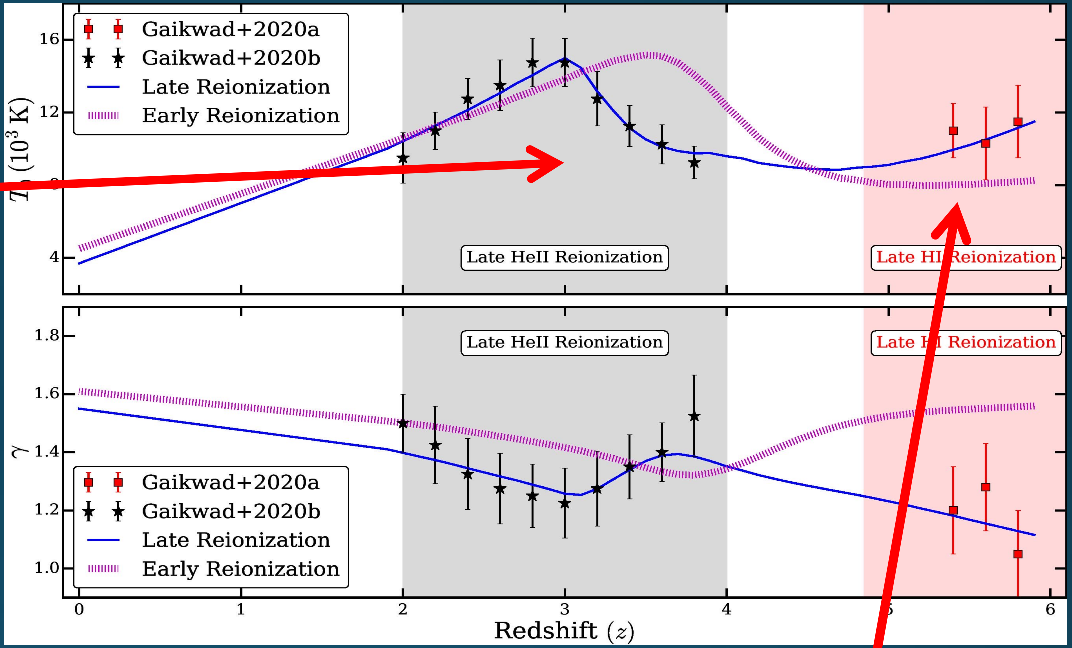


For fixed comoving free-streaming length the cut-off in velocity space is at larger scales/smaller k at higher redshift , and thus in principle easier to detect.

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

IGM Temperature measurements are getting accurate (and consistent)





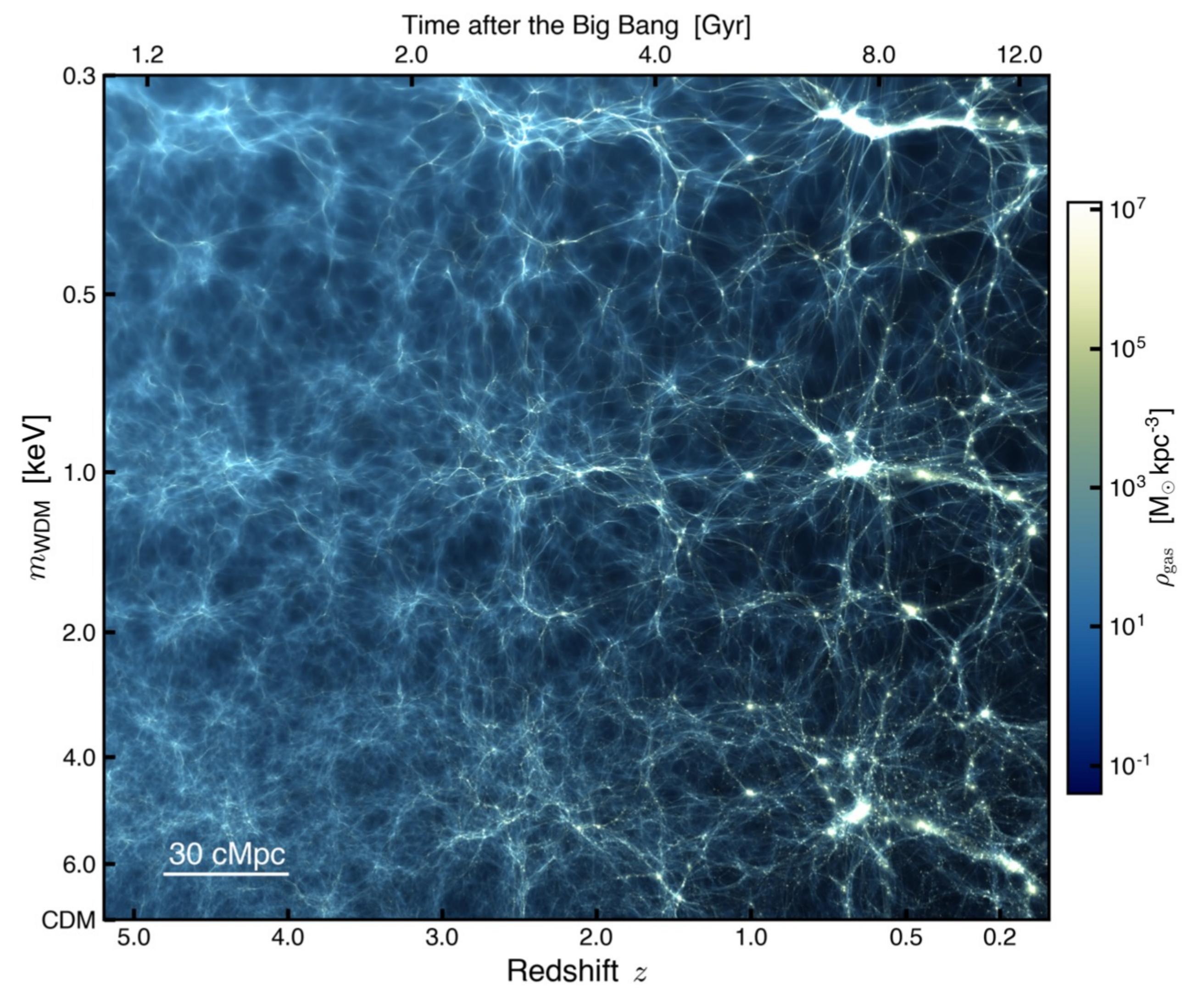
Gaikwad et al. 2021:

- 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

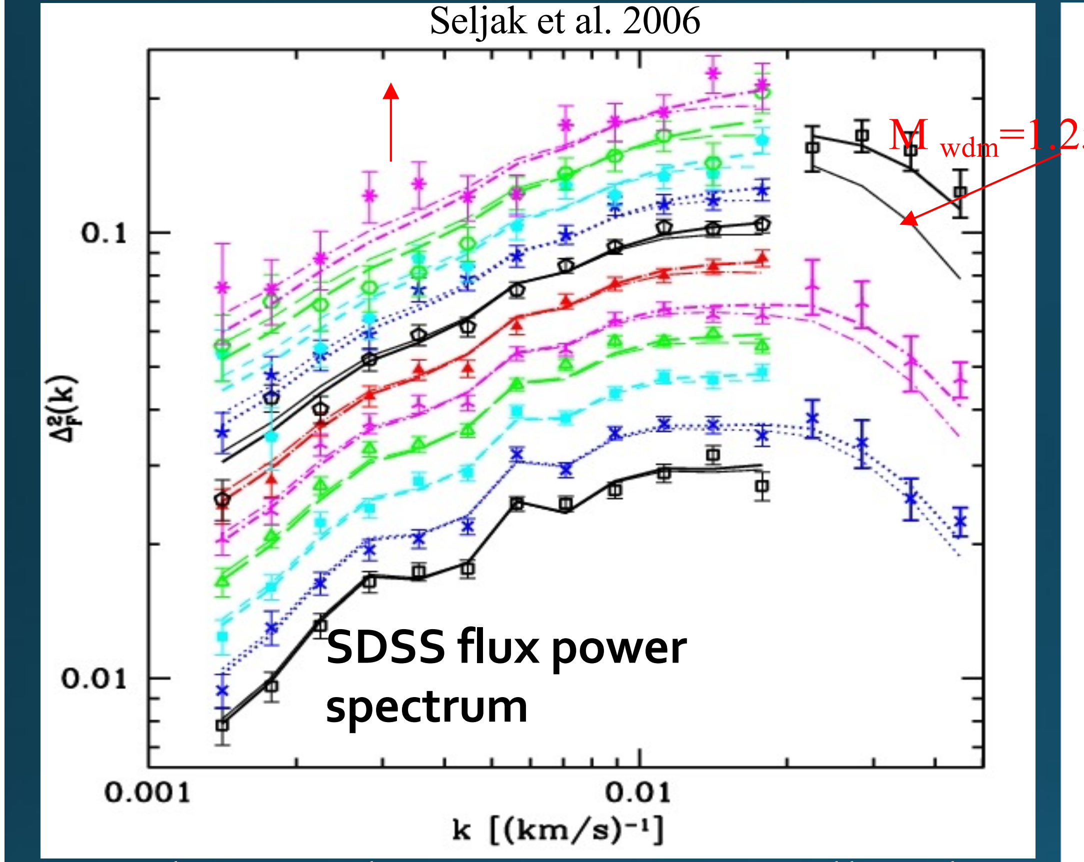
Visualising the free-streaming of dark matter



Villasenor et al. 2022

Observational results in 2005-2008

Seljak et al. 2006



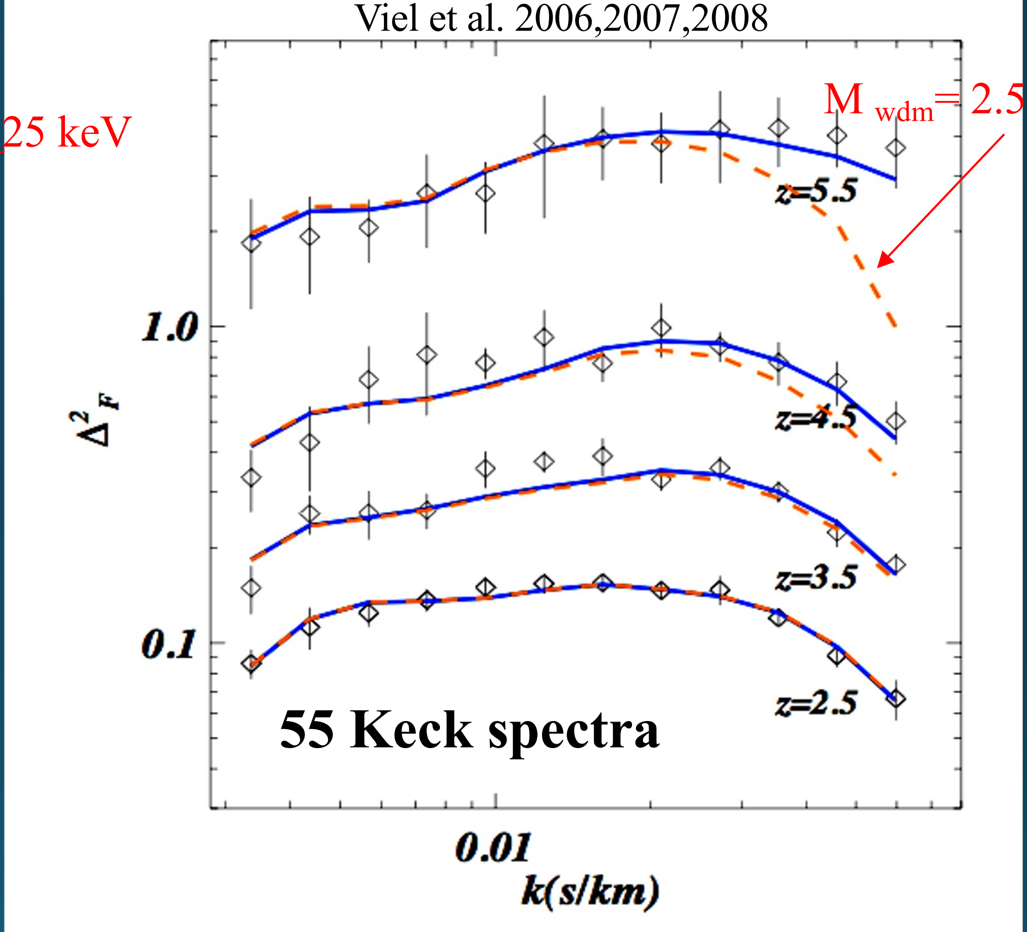
M_{wdm}=1.25 keV

SDSS flux power spectrum

large scales small scales

M_{wdm} >2.4 keV

Viel et al. 2006,2007,2008

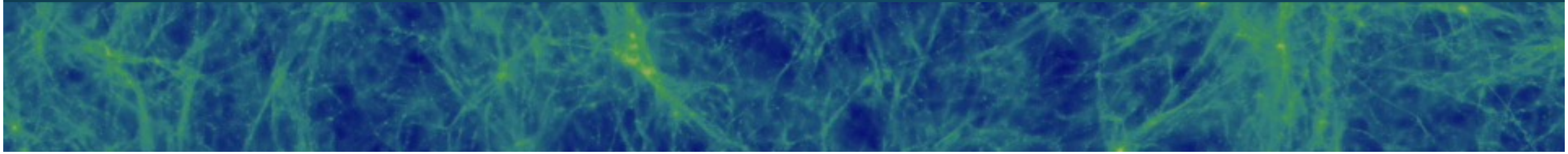


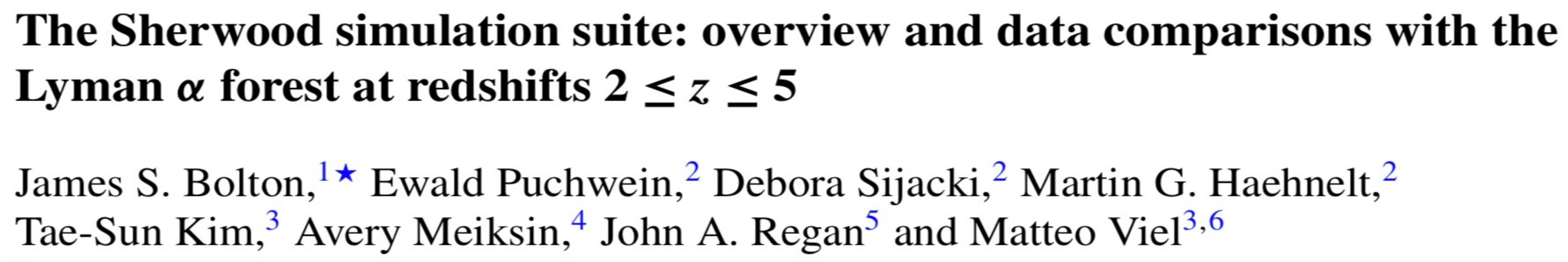
M_{wdm}= 2.5 keV

55 Keck spectra

M_{wdm} > 4 keV

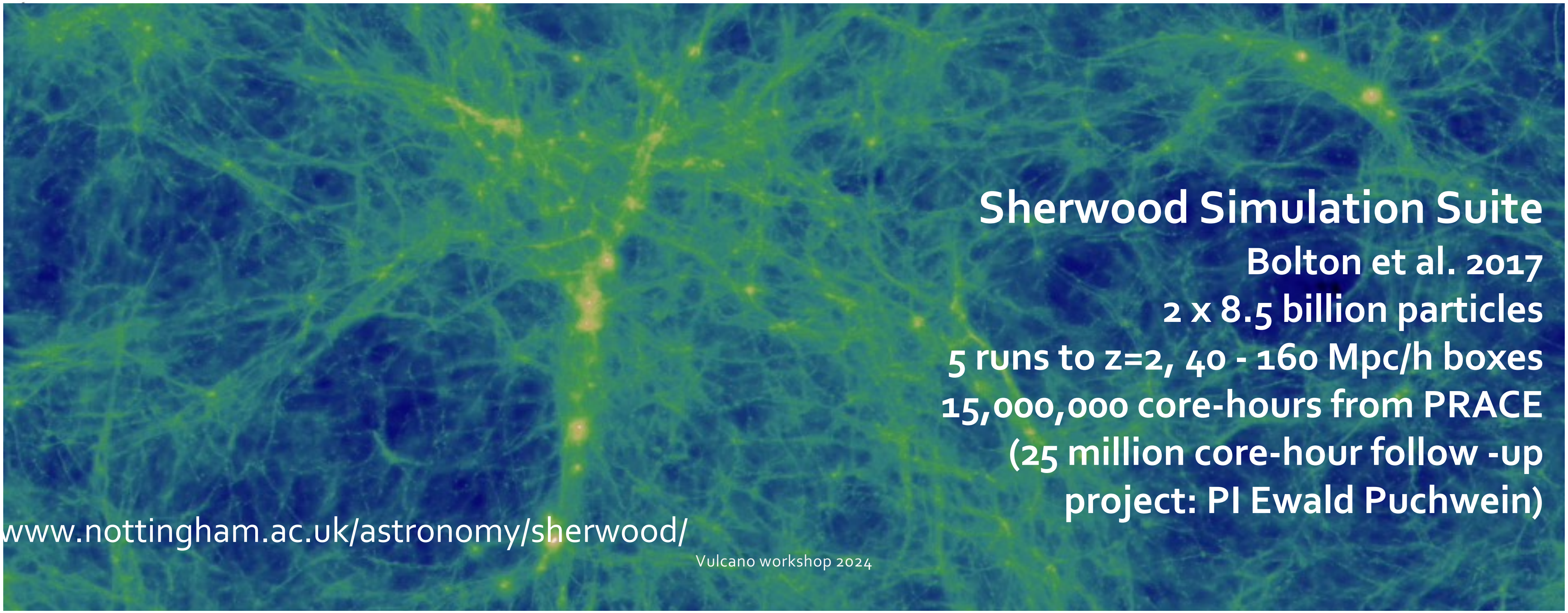
These are the limits for thermal relics. For sterile neutrinos the story is more complicated. Limits based on improved data/modelling/analysis presented in Viel et al. 2013 and Irsic et al 2017a/b.





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]



Sherwood Simulation Suite

Bolton et al. 2017
2 x 8.5 billion particles
5 runs to z=2, 40 - 160 Mpc/h boxes
15,000,000 core-hours from PRACE
(25 million core-hour follow -up project: PI Ewald Puchwein)

www.nottingham.ac.uk/astronomy/sherwood/

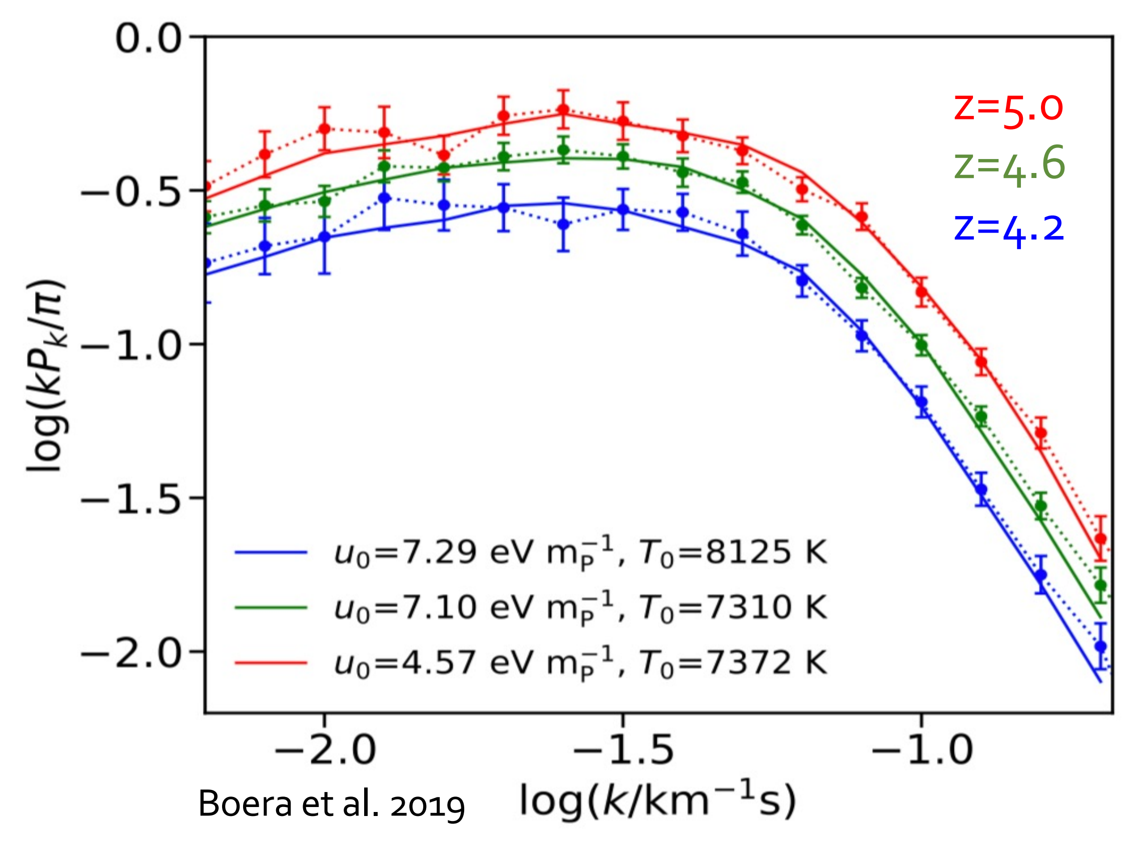
Nuisance effects /parameters

- 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

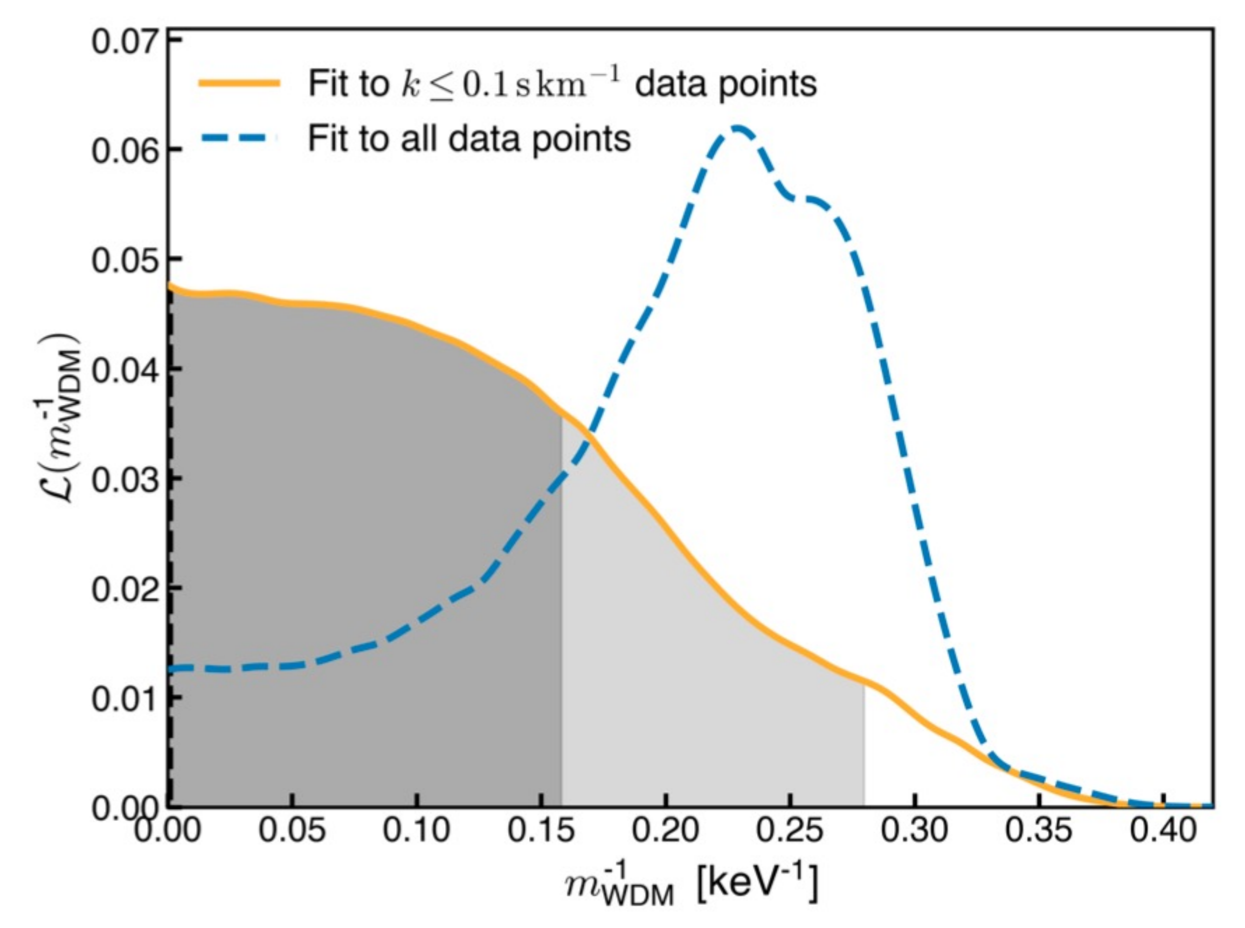
A (not so) new (any more) measurement of the high-redshift flux power spectrum



Boera et al. 2019

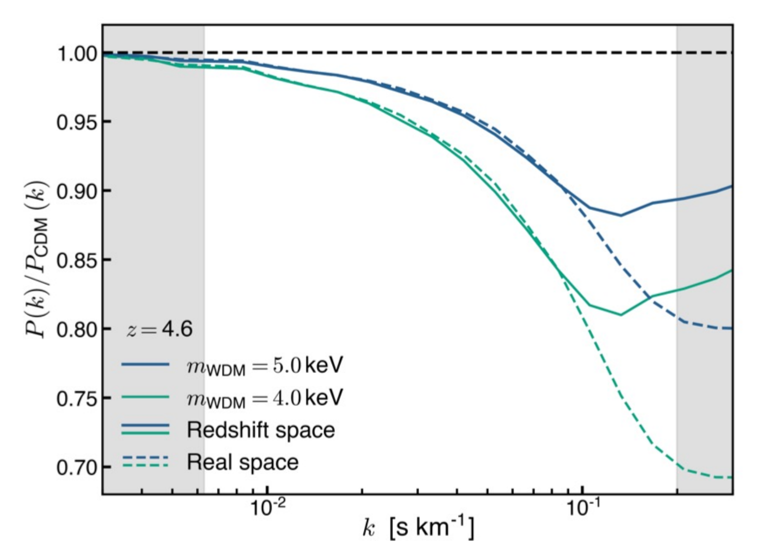
15 high-quality spectra

extends to higher redshift
and to smaller scales

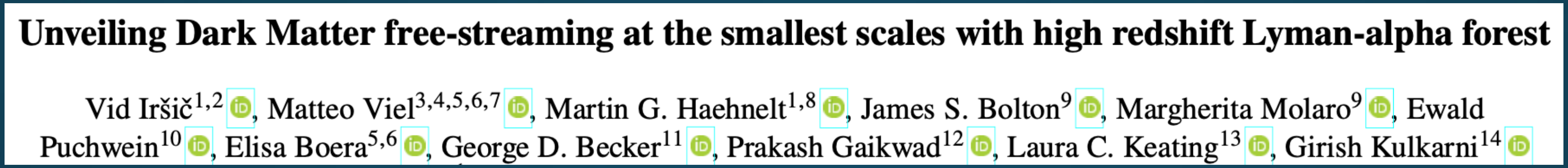


An intriguing peak in the likelihood for the WDM mass if the smallest scales are included.

Villasenor et al. 2022

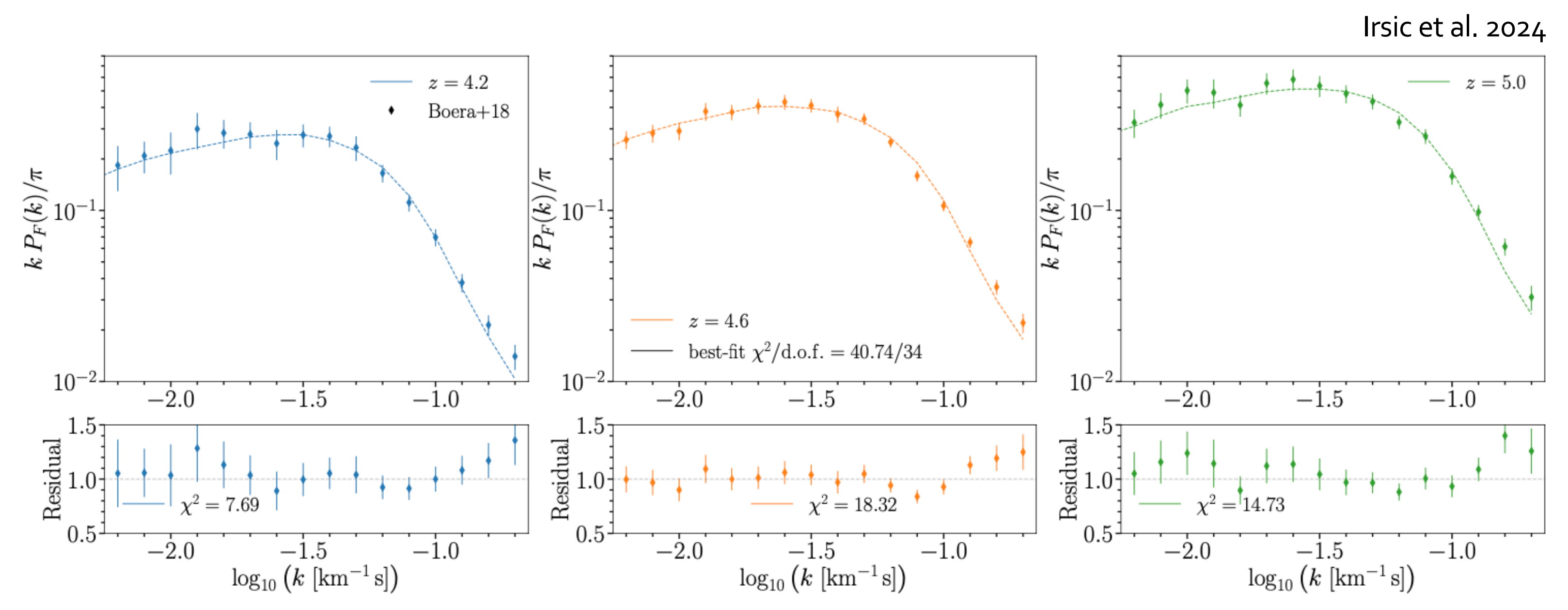


Signature of gas peculiar velocities? Difficult to model Because of inhomogeneous Reionization.



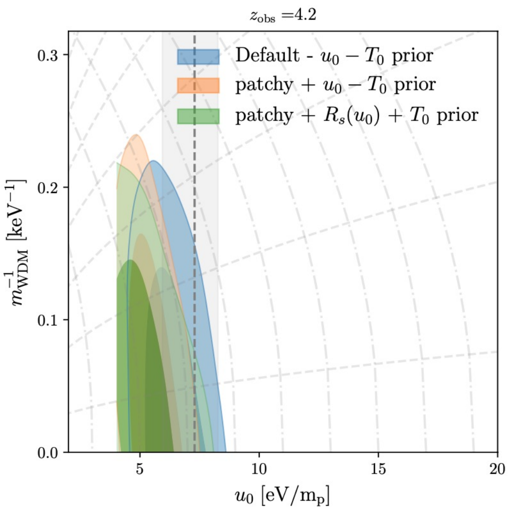
Unveiling Dark Matter free-streaming at the smallest scales with high redshift Lyman-alpha forest

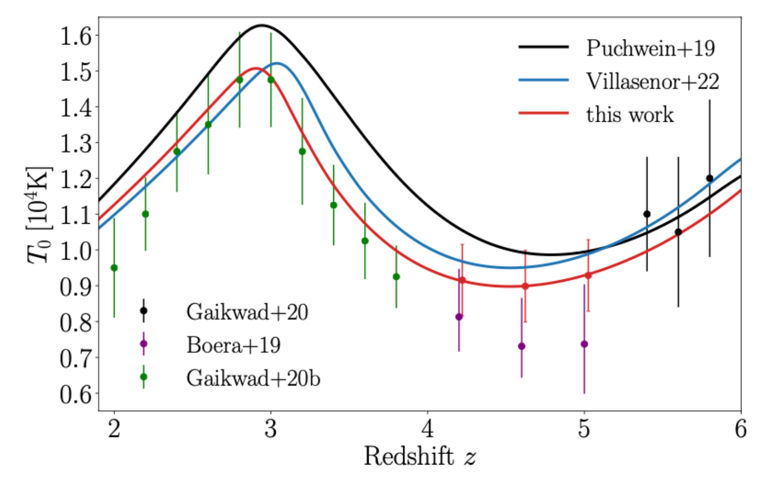
Vid Iršič[1,2], Matteo Viel[3,4,5,6,7], Martin G. Haehnelt[1,8], James S. Bolton[9], Margherita Molaro[9], Ewald Puchwein[10], Elisa Boera[5,6], George D. Becker[11], Prakash Gaikwad[12], Laura C. Keating[13], Girish Kulkarni[14]


Irsic et al. 2024

Our analysis of the Boera et al. data taking into account the effect s
of inhomogeneous reionization (and a lot of other nuisance parameters.)

Our latest results (Irsic et al. 2024)



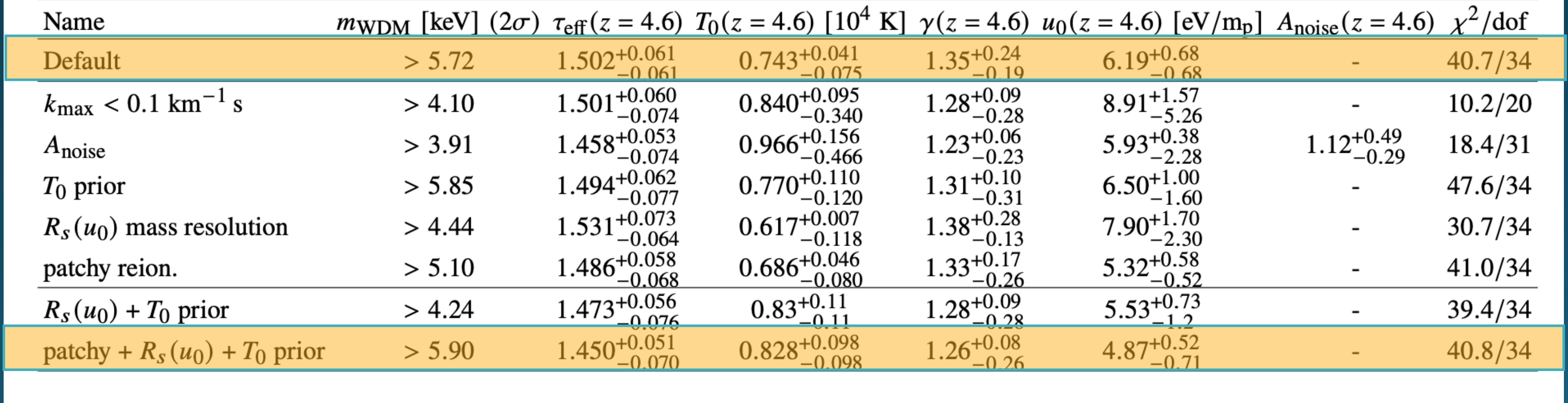


For reasonable prior
on thermal history:

$m_{\rm FDM} > 40 \times 10^{-22}$ eV

$m_{\rm WDM} > 5.7$ keV

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



Name	$m_{\rm WDM}$ [keV] (2σ)	$\tau_{\rm eff}(z = 4.6)$	$T_0(z = 4.6)$ [10^4 K]	$\gamma(z = 4.6)$	$u_0(z = 4.6)$ [eV/m$_{\rm p}$]	$A_{\rm noise}(z = 4.6)$	χ^2/dof
Default	> 5.72	$1.502^{+0.061}_{-0.061}$	$0.743^{+0.041}_{-0.075}$	$1.35^{+0.24}_{-0.19}$	$6.19^{+0.68}_{-0.68}$	-	40.7/34
$k_{\rm max} < 0.1$ km^{-1} s	> 4.10	$1.501^{+0.060}_{-0.074}$	$0.840^{+0.095}_{-0.340}$	$1.28^{+0.09}_{-0.28}$	$8.91^{+1.57}_{-5.26}$	-	10.2/20
$A_{\rm noise}$	> 3.91	$1.458^{+0.053}_{-0.074}$	$0.966^{+0.156}_{-0.466}$	$1.23^{+0.06}_{-0.23}$	$5.93^{+0.38}_{-2.28}$	$1.12^{+0.49}_{-0.29}$	18.4/31
T_0 prior	> 5.85	$1.494^{+0.062}_{-0.077}$	$0.770^{+0.110}_{-0.120}$	$1.31^{+0.10}_{-0.31}$	$6.50^{+1.00}_{-1.60}$	-	47.6/34
$R_s(u_0)$ mass resolution	> 4.44	$1.531^{+0.073}_{-0.064}$	$0.617^{+0.007}_{-0.118}$	$1.38^{+0.28}_{-0.13}$	$7.90^{+1.70}_{-2.30}$	-	30.7/34
patchy reion.	> 5.10	$1.486^{+0.058}_{-0.068}$	$0.686^{+0.046}_{-0.080}$	$1.33^{+0.17}_{-0.26}$	$5.32^{+0.58}_{-0.52}$	-	41.0/34
$R_s(u_0) + T_0$ prior	> 4.24	$1.473^{+0.056}_{-0.076}$	$0.83^{+0.11}_{-0.11}$	$1.28^{+0.09}_{-0.28}$	$5.53^{+0.73}_{-1.2}$	-	39.4/34
patchy + $R_s(u_0) + T_0$ prior	> 5.90	$1.450^{+0.051}_{-0.070}$	$0.828^{+0.098}_{-0.098}$	$1.26^{+0.08}_{-0.26}$	$4.87^{+0.52}_{-0.71}$	-	40.8/34

What next for cosmology with Lyman-alpha forest data?

High resolution

- Mixed-Dark-Matter models
- Increase the observed sample of spectra
  (the current analysis is based on only 15 high-resolution spectra)
- Better determine the thermal and reionization history of hydrogen

Low resolution

DESI/Weave → S_8 tension


Vid Irsic

Back in Trieste
in September

Summary

- Good progress with characterising thermal evolution of IGM. Quantitative modelling of the effect of helium reionization still on to do list.
- 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 (PI: Alessandro Marconi)

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)


ANDES