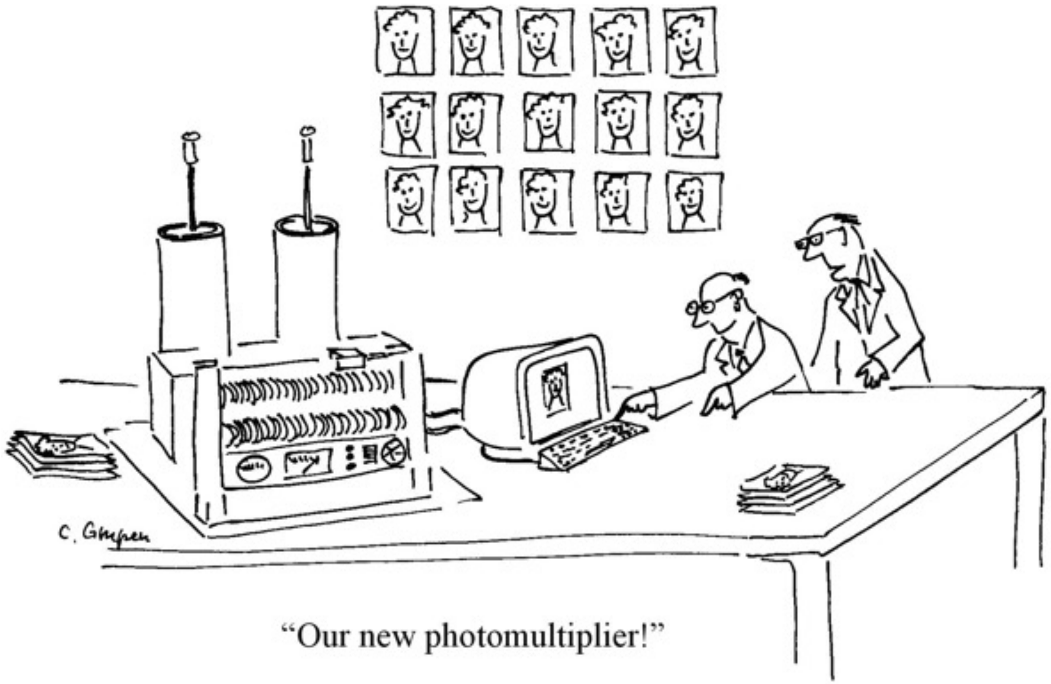
Intergalactic Medium

Alexander Knebe (*Universidad Autonoma de Madrid*)



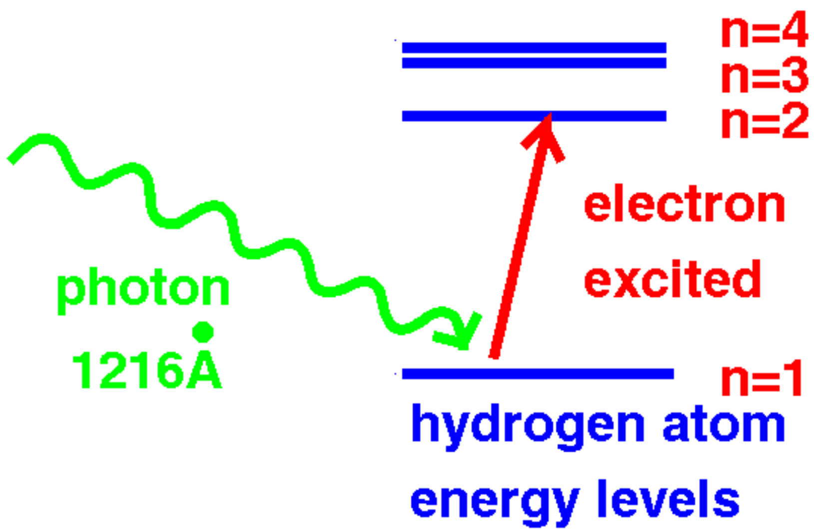
"Our new photomultiplier!"

- the Ly-a forest
- cosmic reionisation
- the warm-hot intergalactic medium

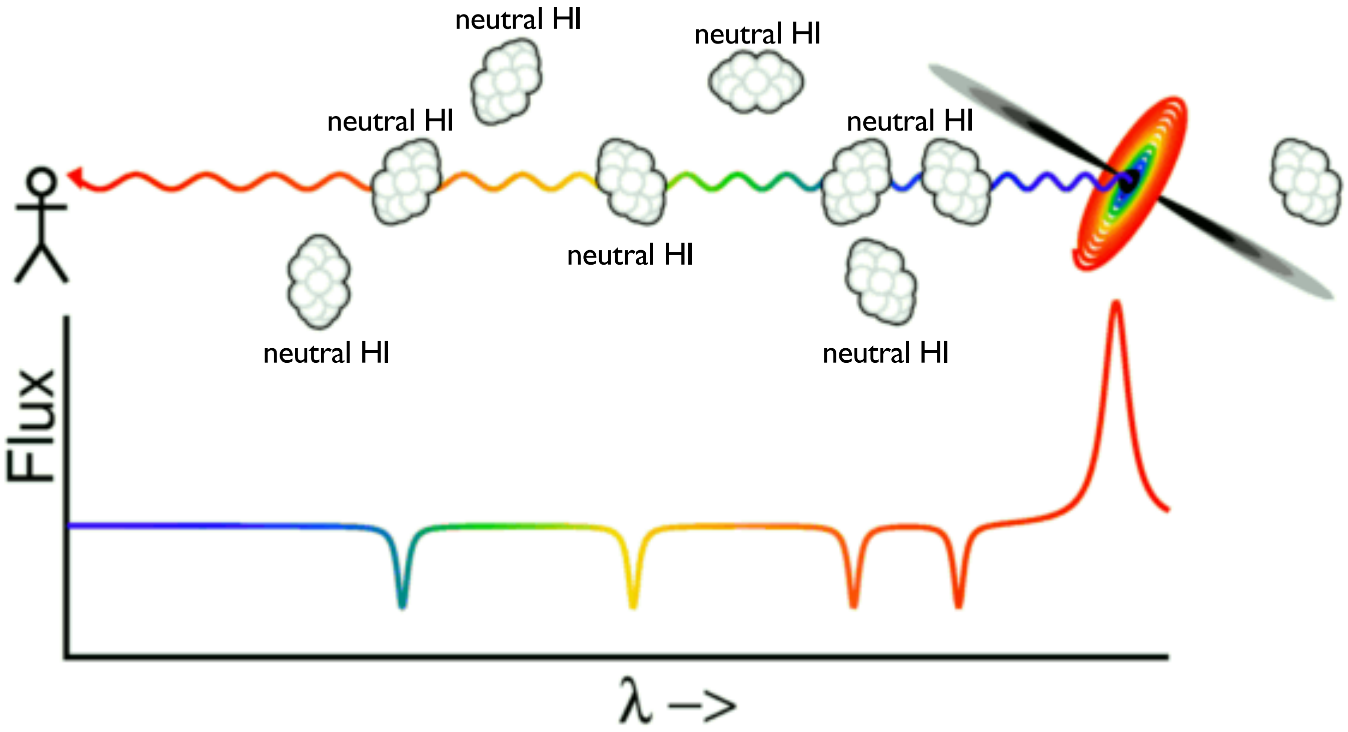
- **the Ly-a forest**
- cosmic reionisation
- the warm-hot intergalactic medium

Ly-α

neutral HI



Ly-α forest



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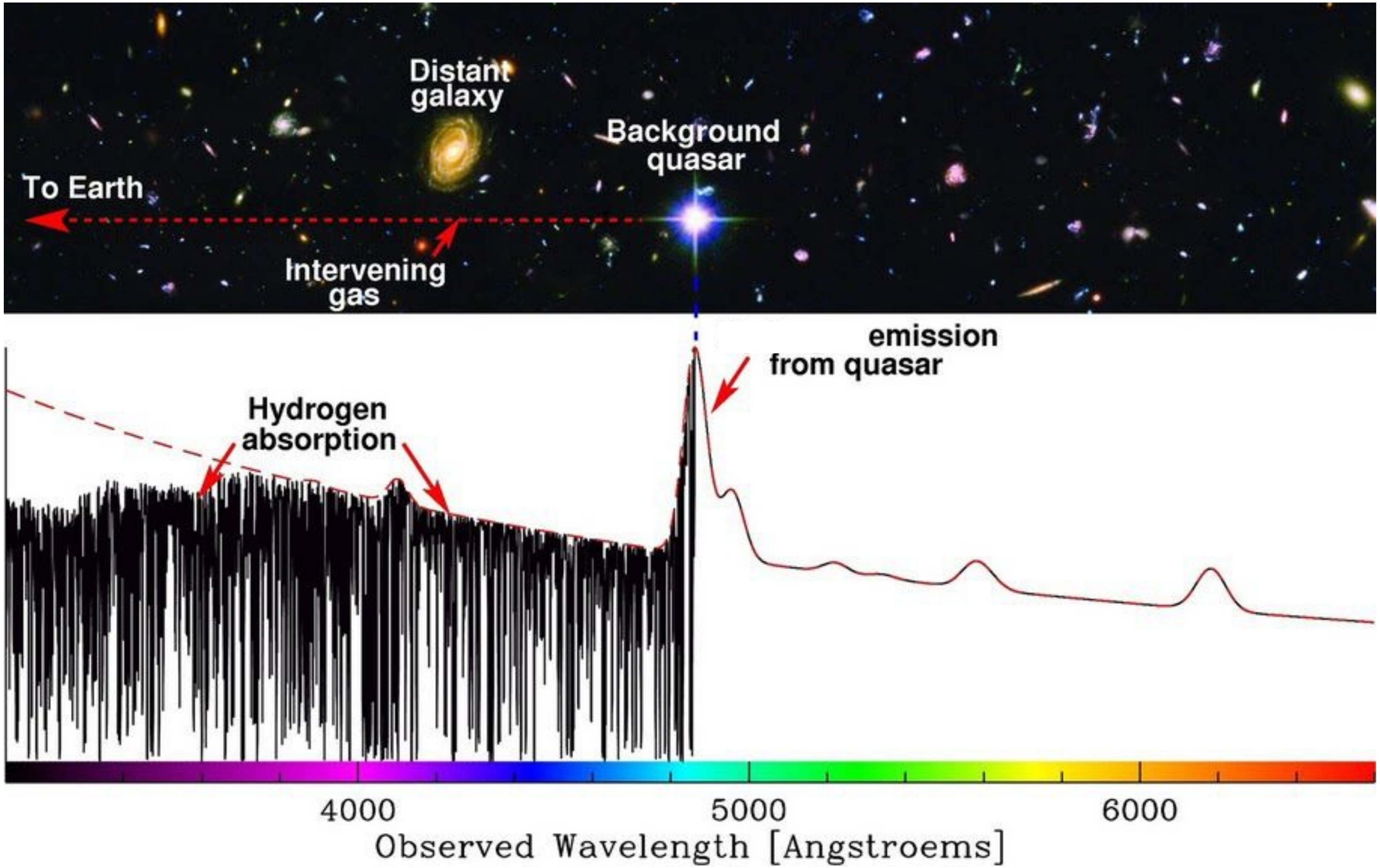

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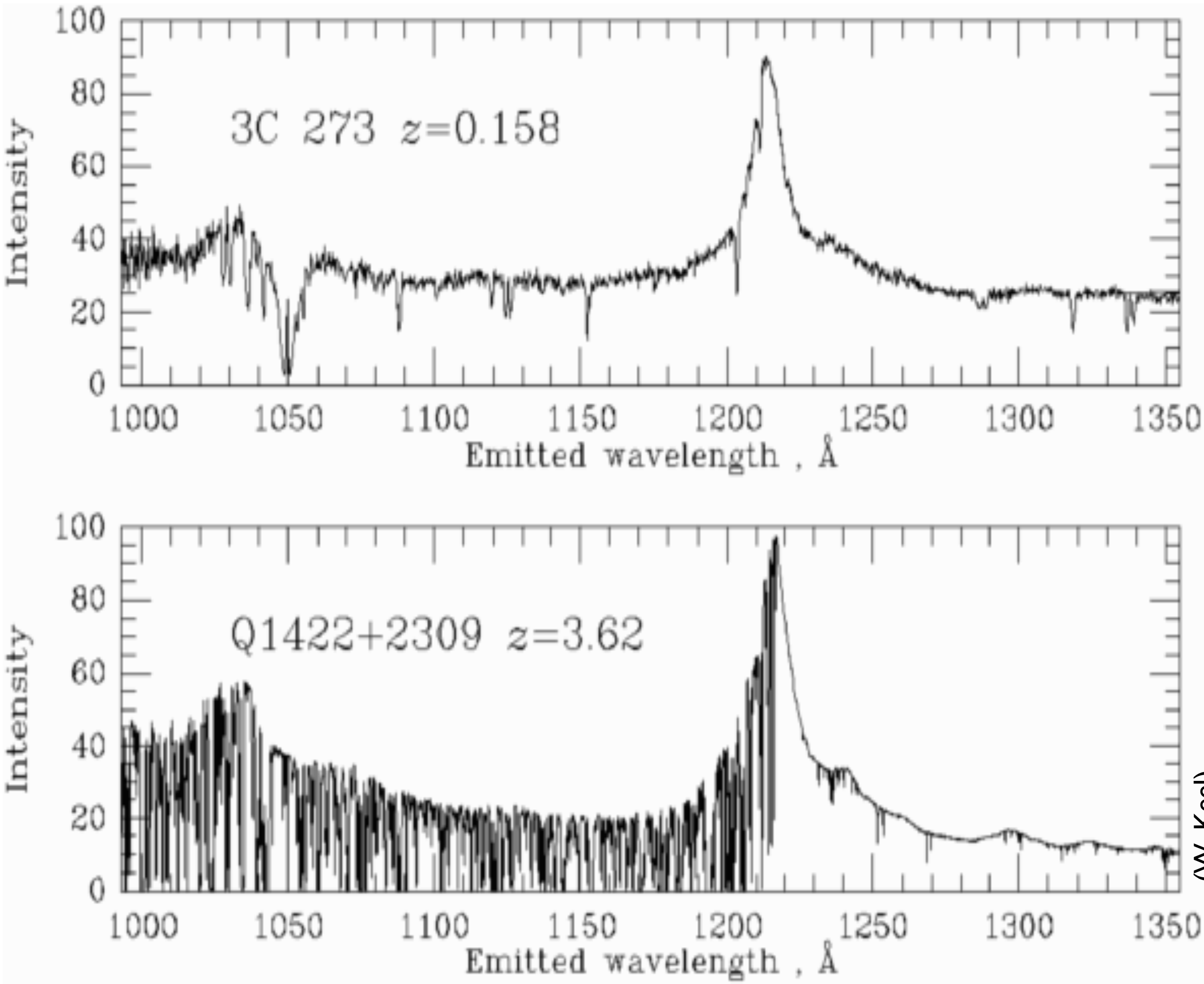
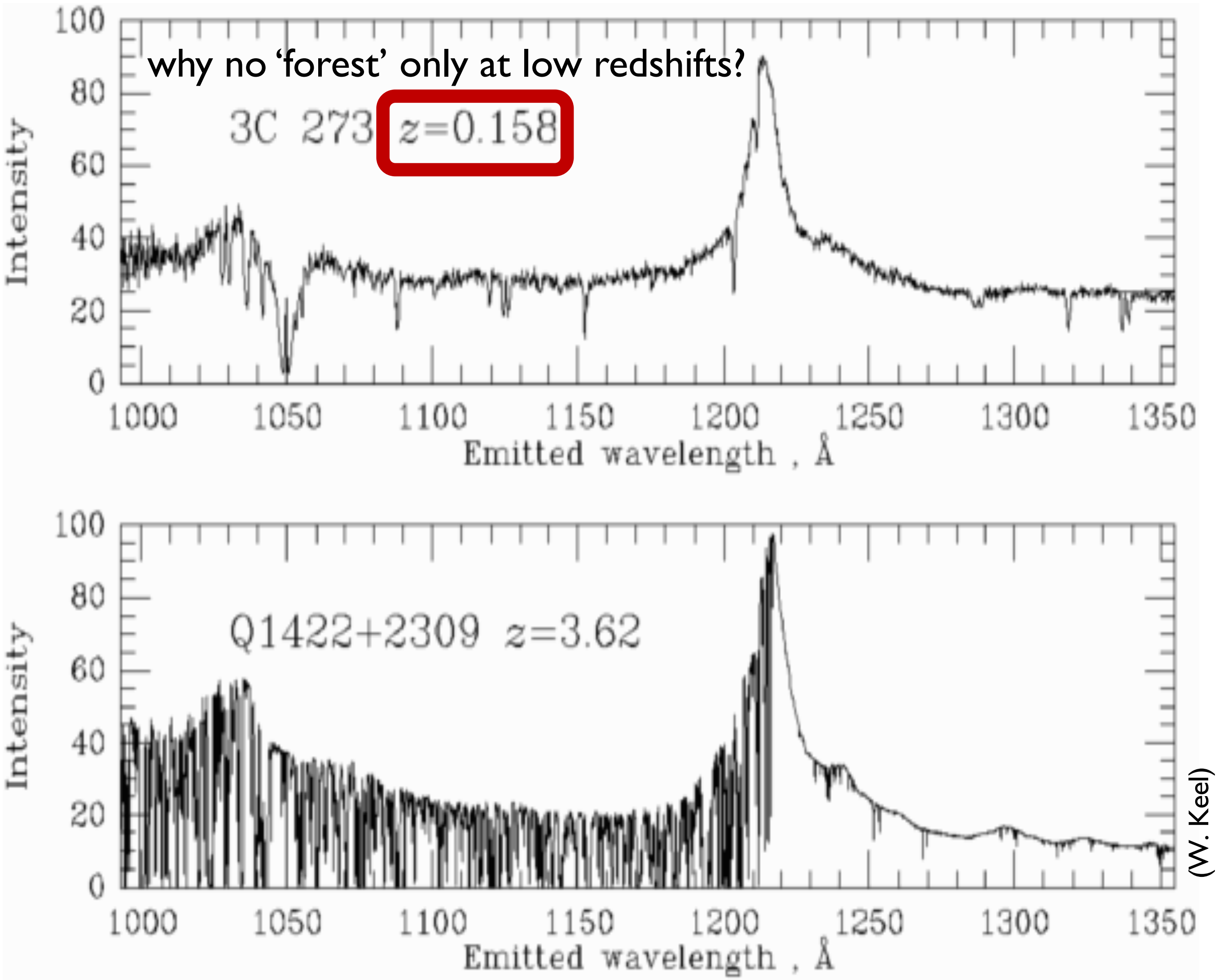


(W. Keel)

Ly-α forest



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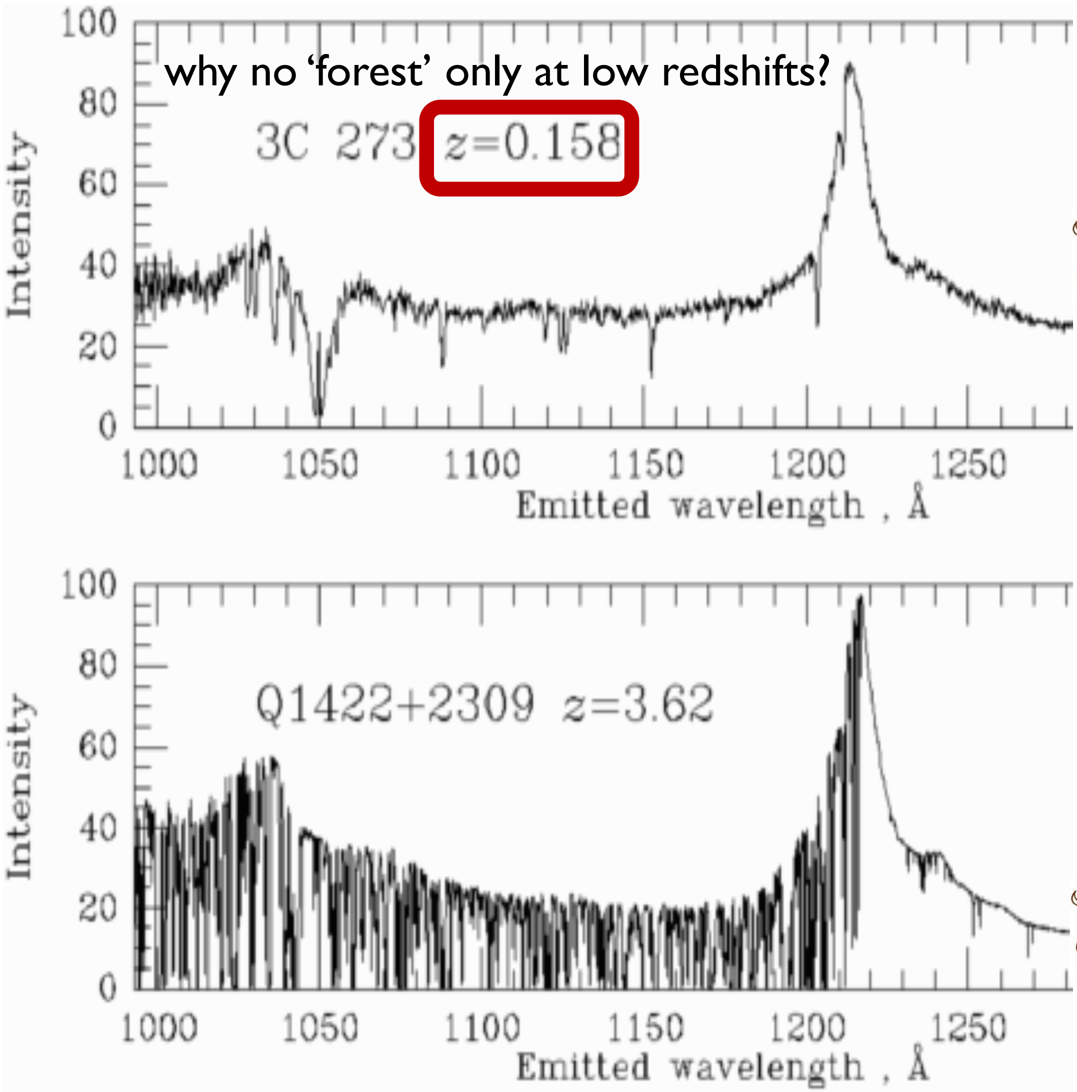
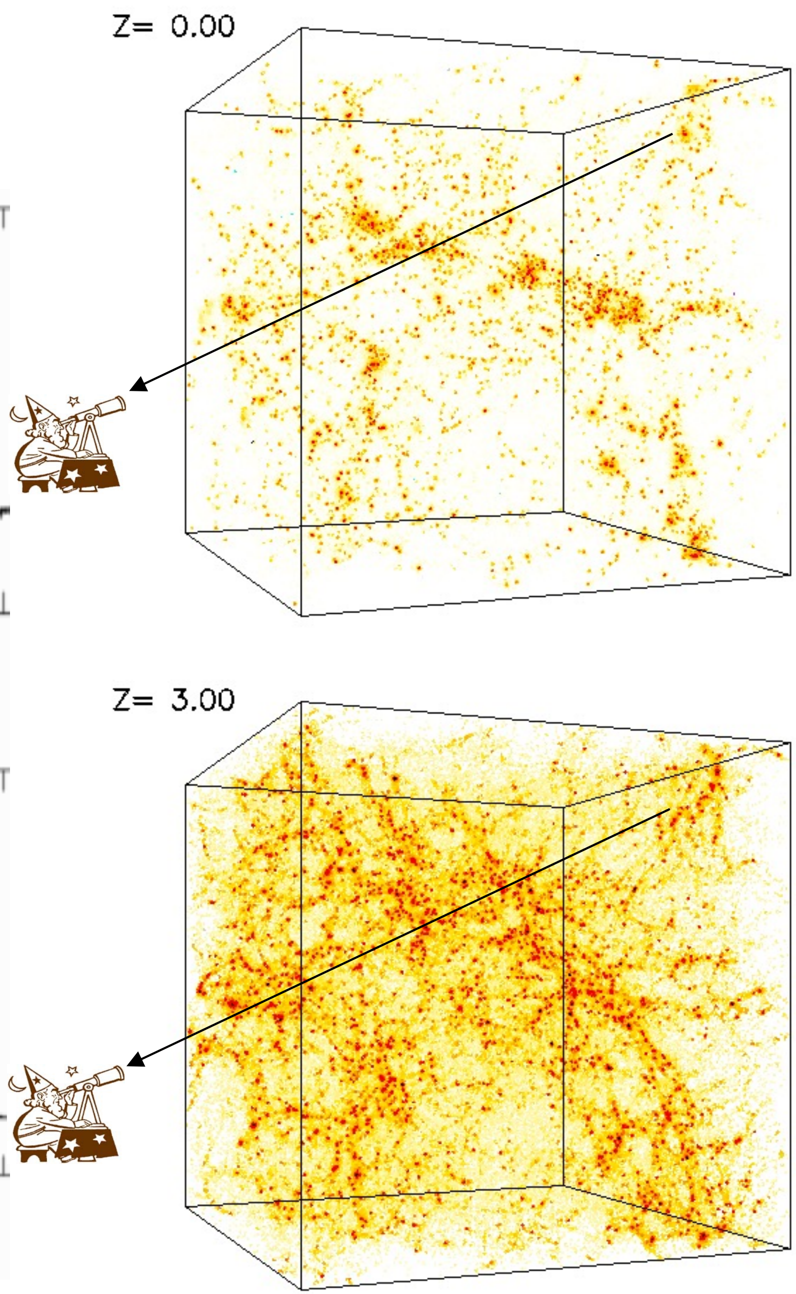
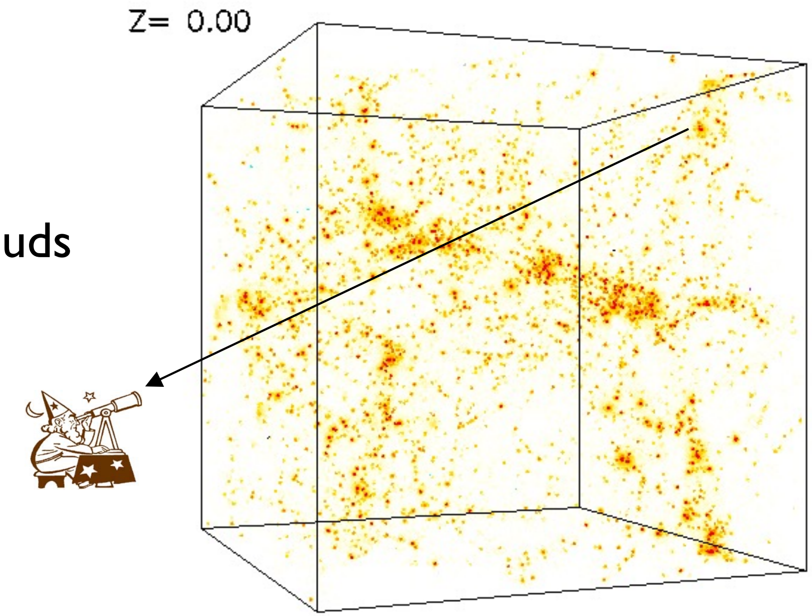
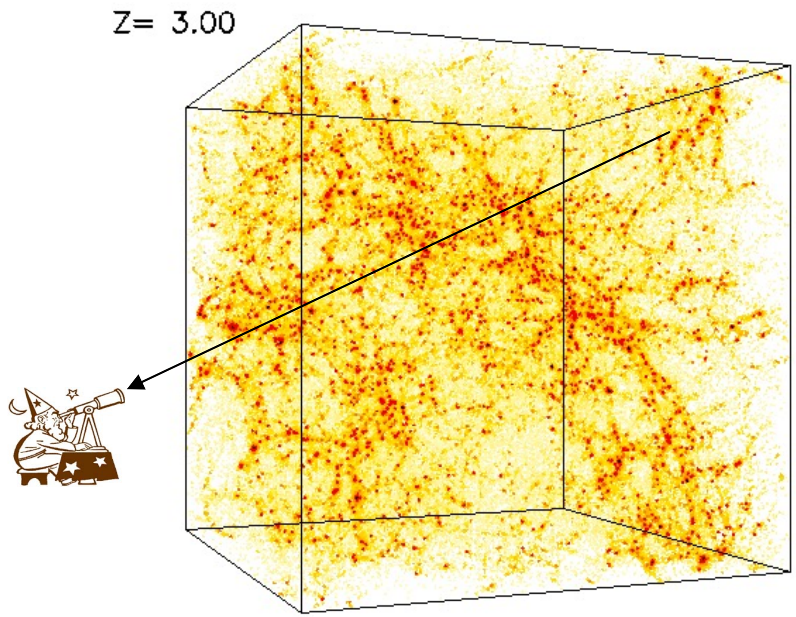




Ly-α forest:

- primarily probes distribution of low-mass clouds





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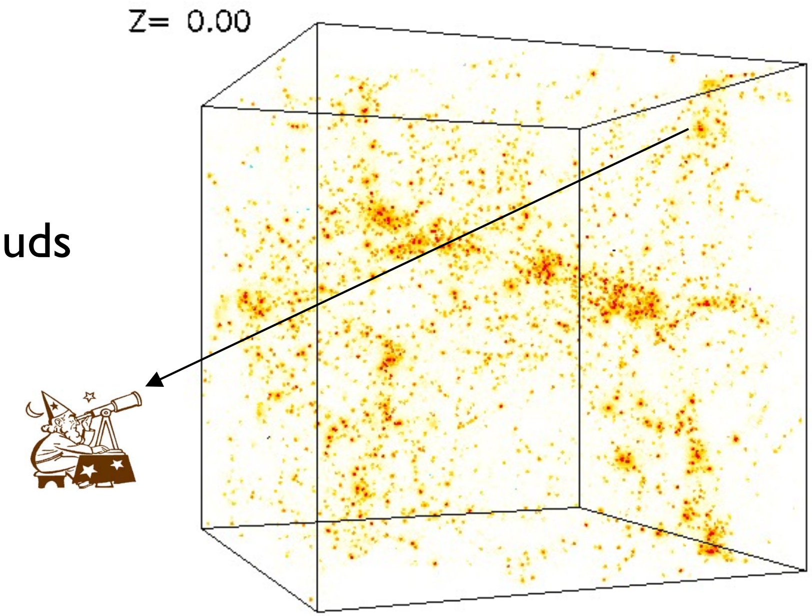
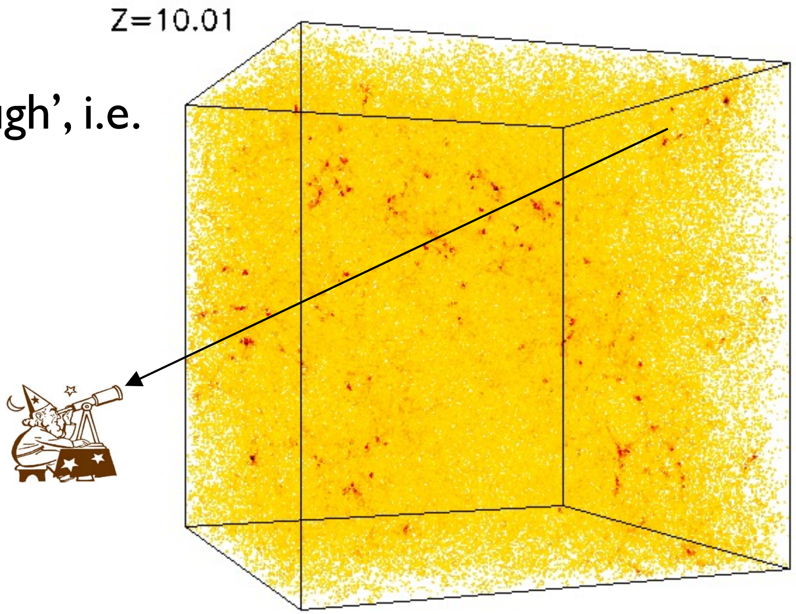


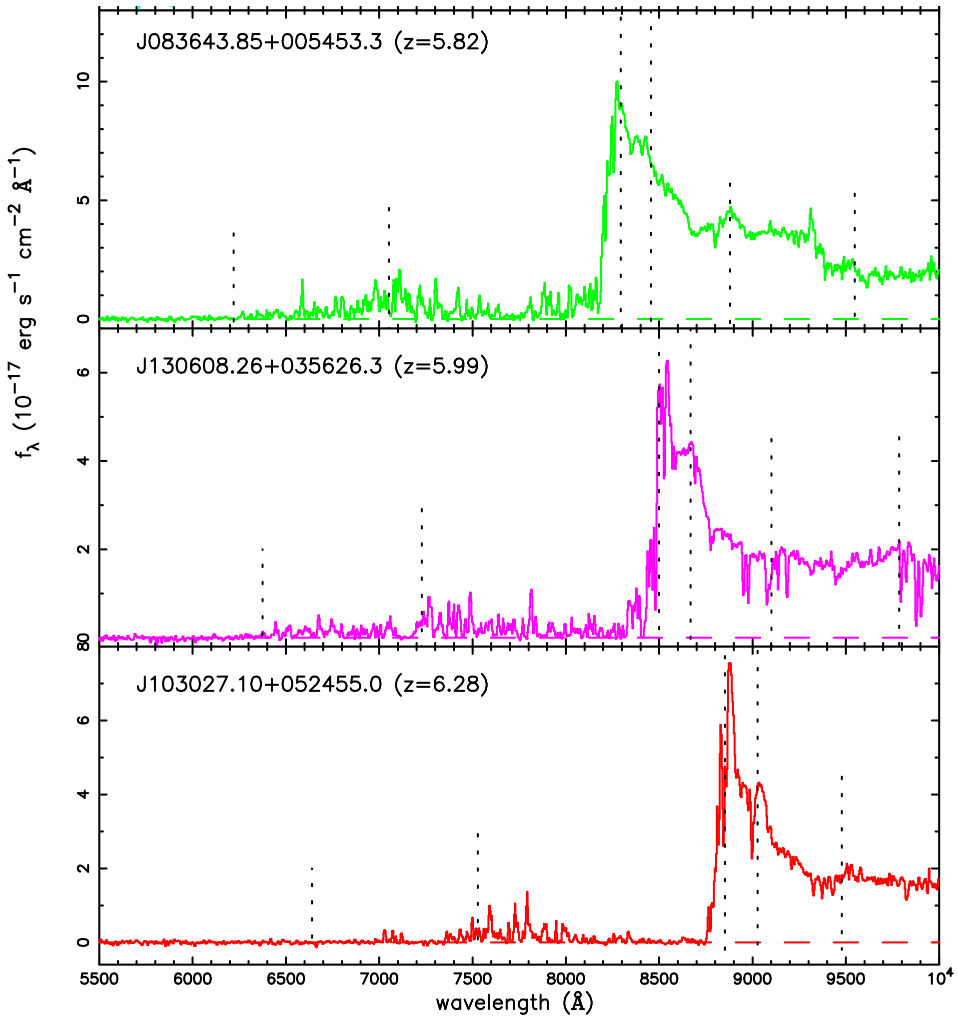
- should eventually lead to 'Gunn-Peterson trough', i.e.

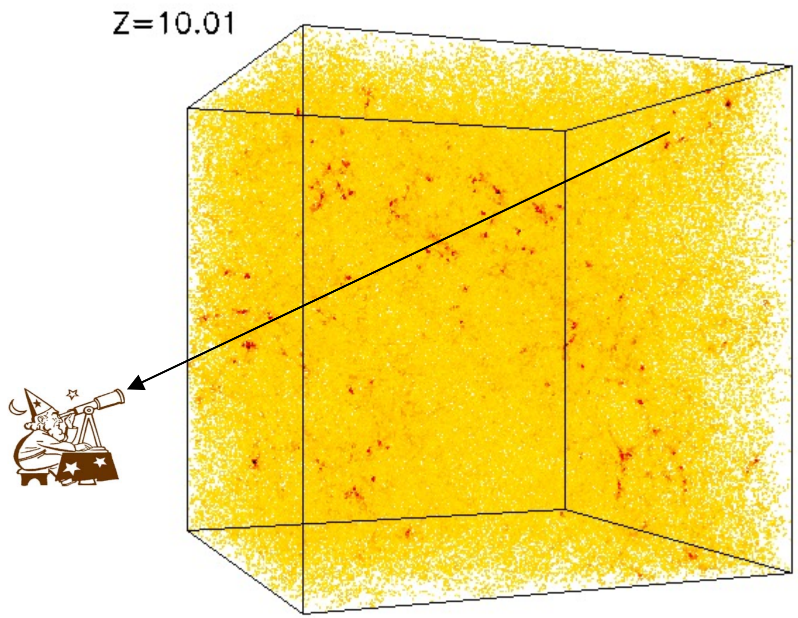
  total absorption of Ly-a flux



Gunn-Peterson trough

- first observed in 2001, for the most-distant QSO to that date!





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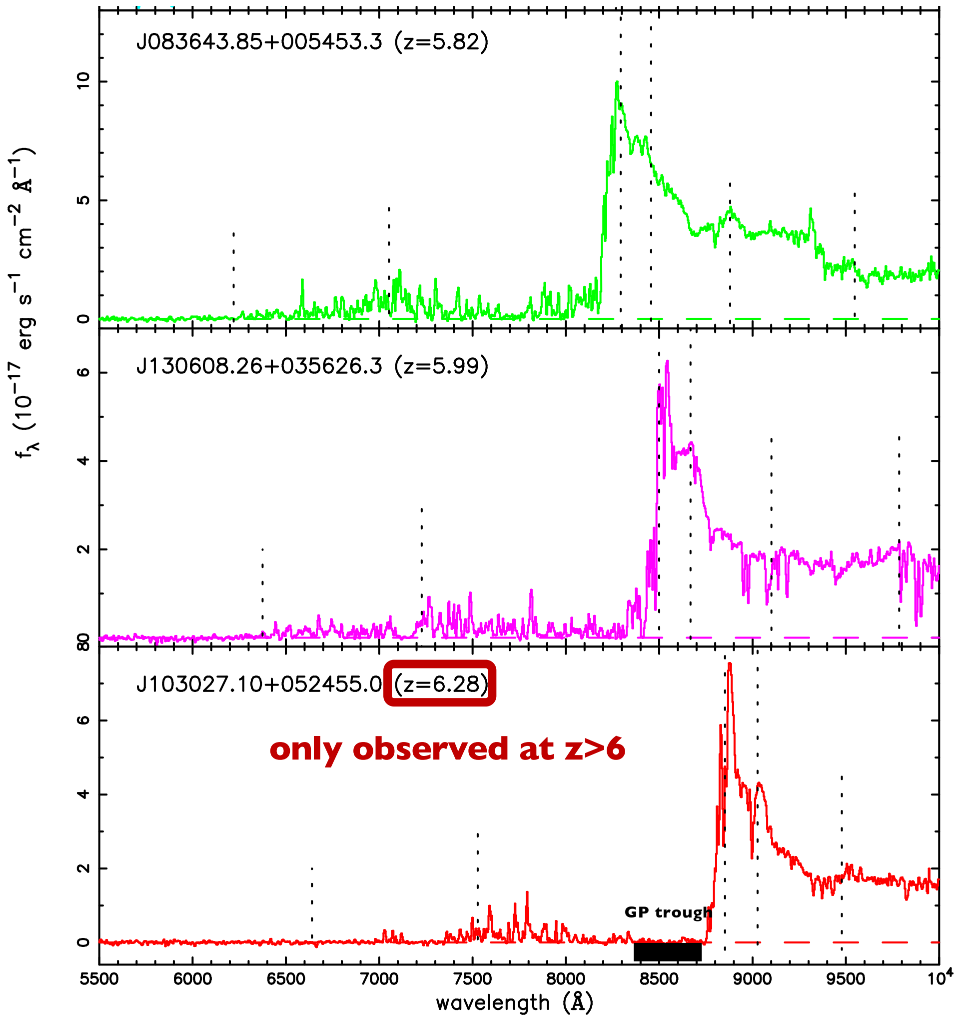
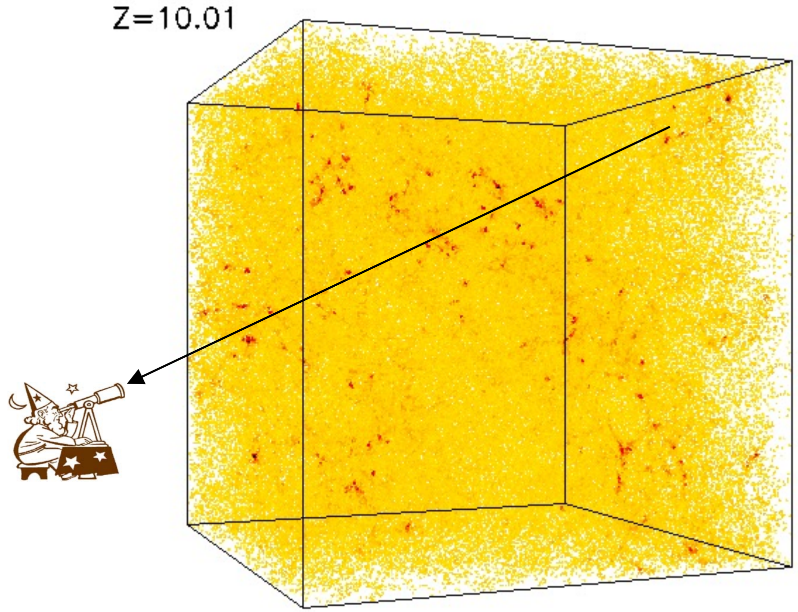
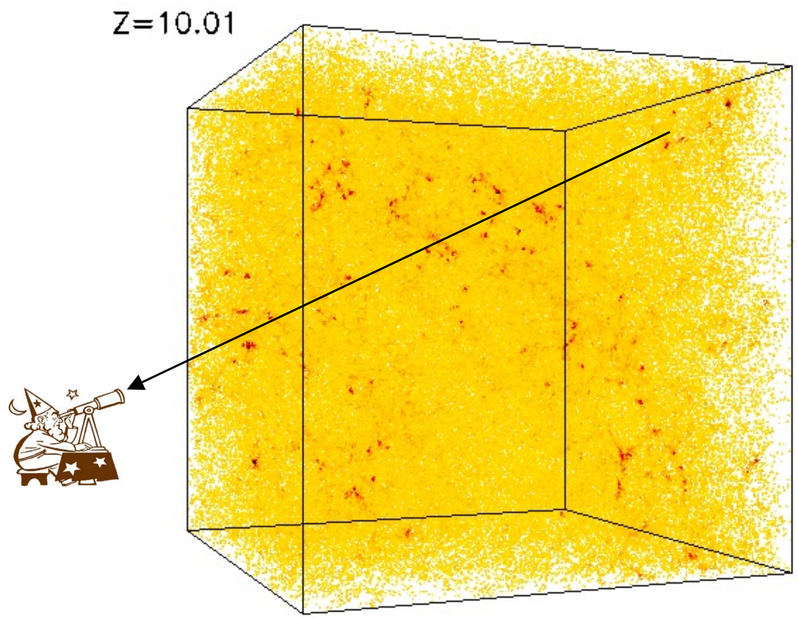




Gunn-Peterson trough

- first observed in 2001, for the most-distant QSO to that date!
- non-existence for z<6 means that...
    - *either* most of the hydrogen is not neutral, but ionized instead
    - *or* no hydrogen left in intergalactic space (all already collapsed)



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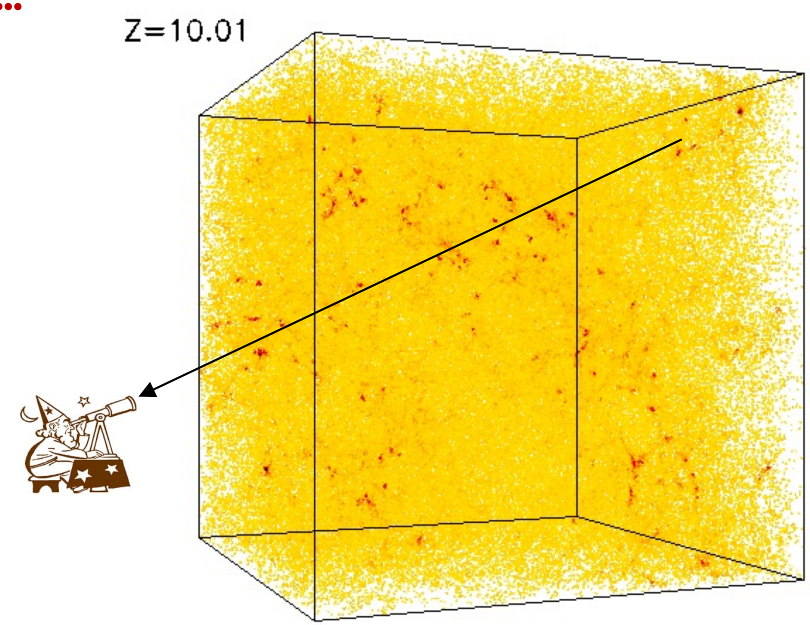
not really compliant with cosmic structure formation...



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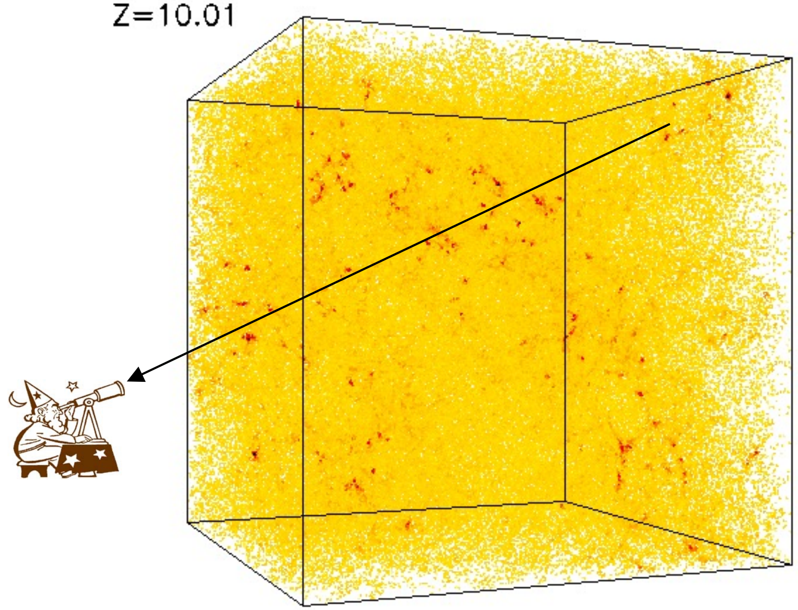

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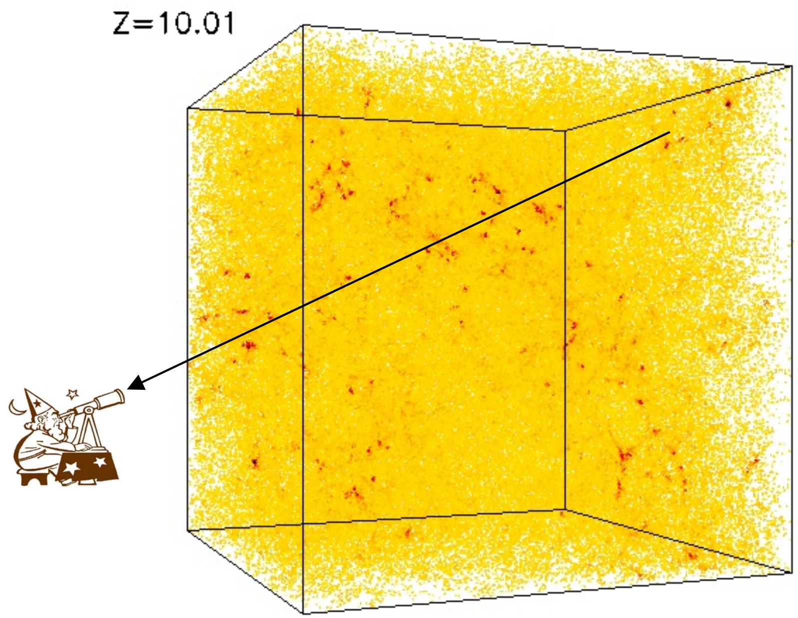
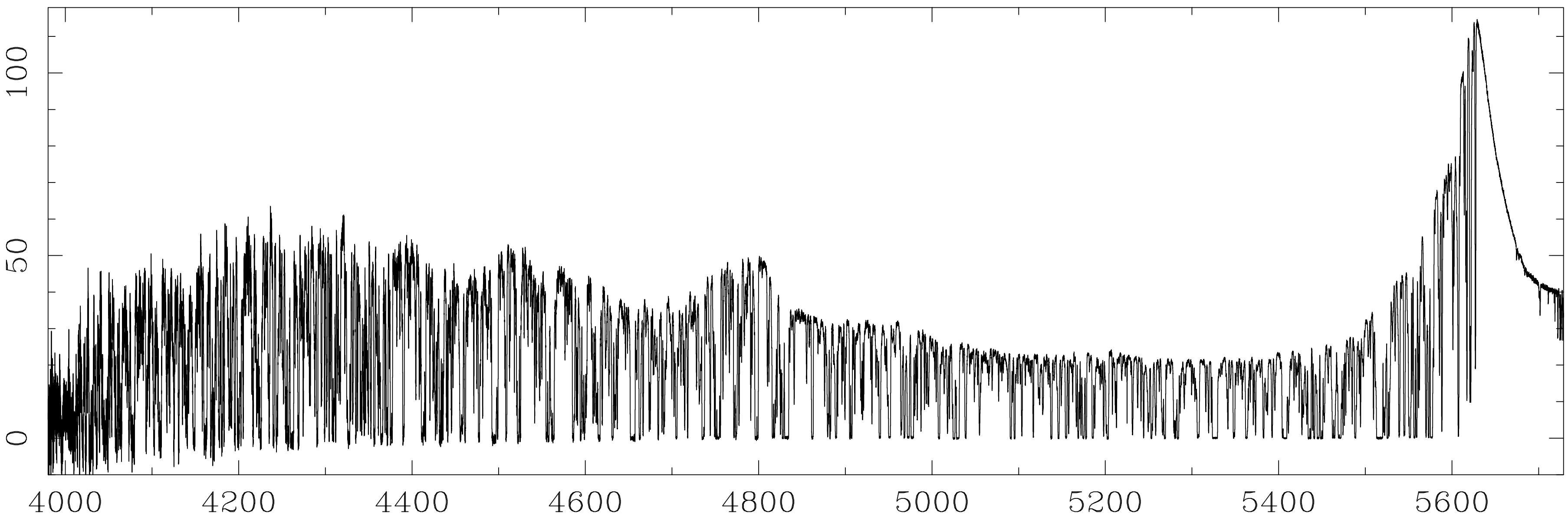
...most of the hydrogen is not neutral, but ionized instead: **cosmic reionisation**

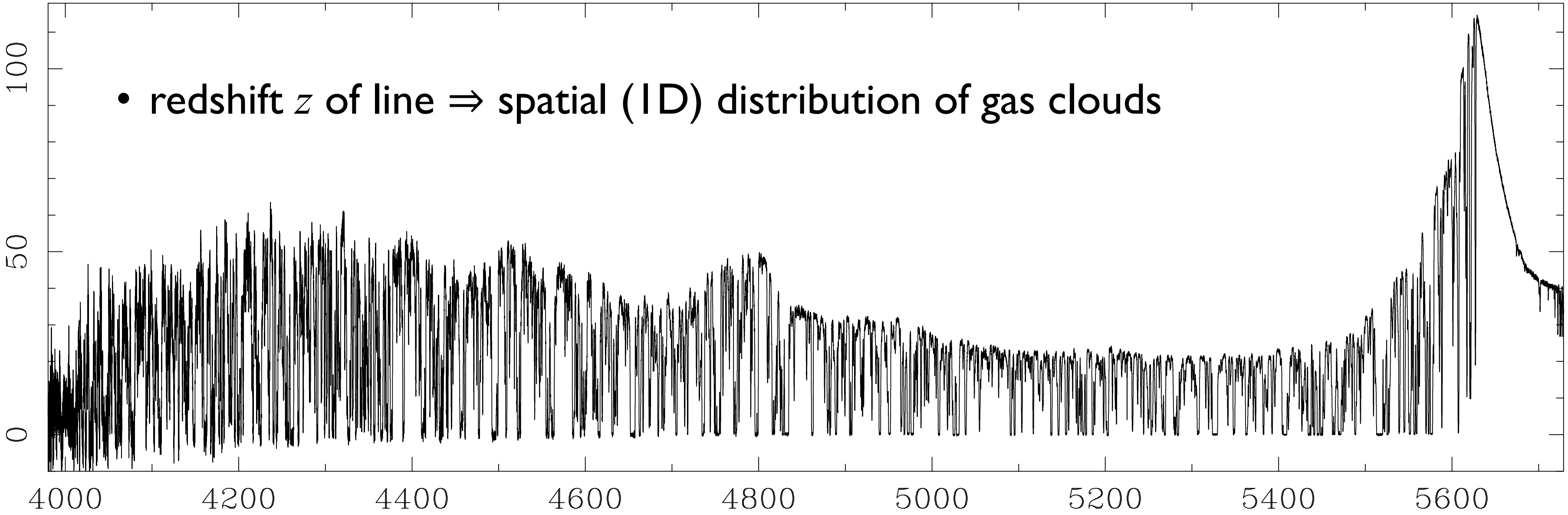


science w/ the Ly-α forest?



science w/ the Ly-α forest

- redshift z of line ⇒ spatial (1D) distribution of gas clouds



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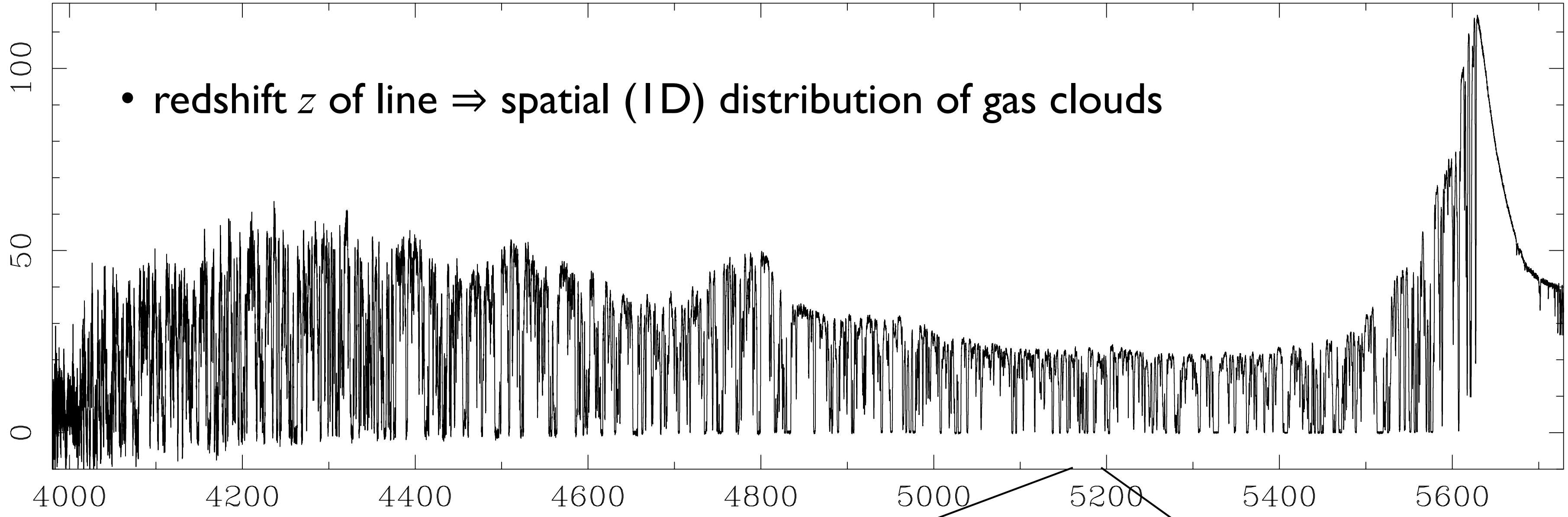
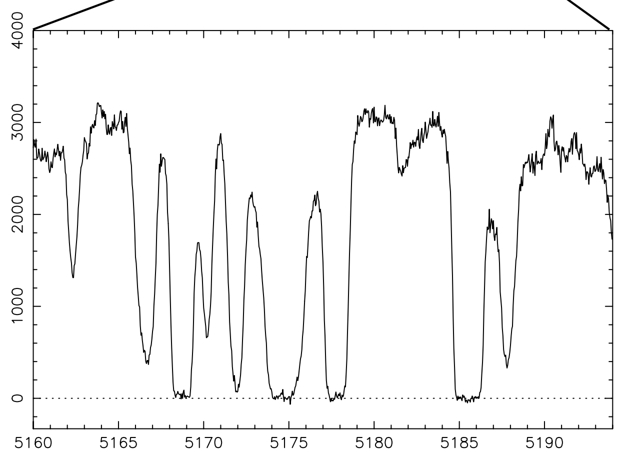
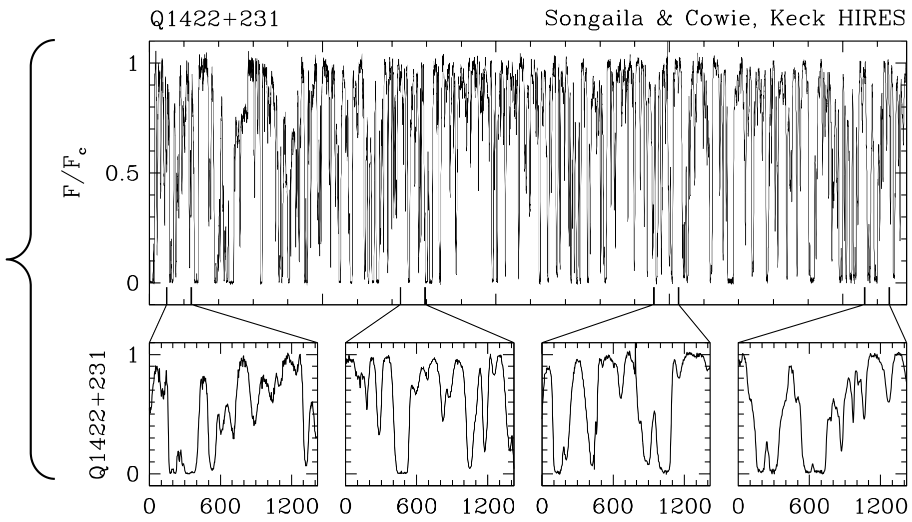


- line profile ⇒ cloud properties



science w/ the Ly-α forest – cosmology

observations

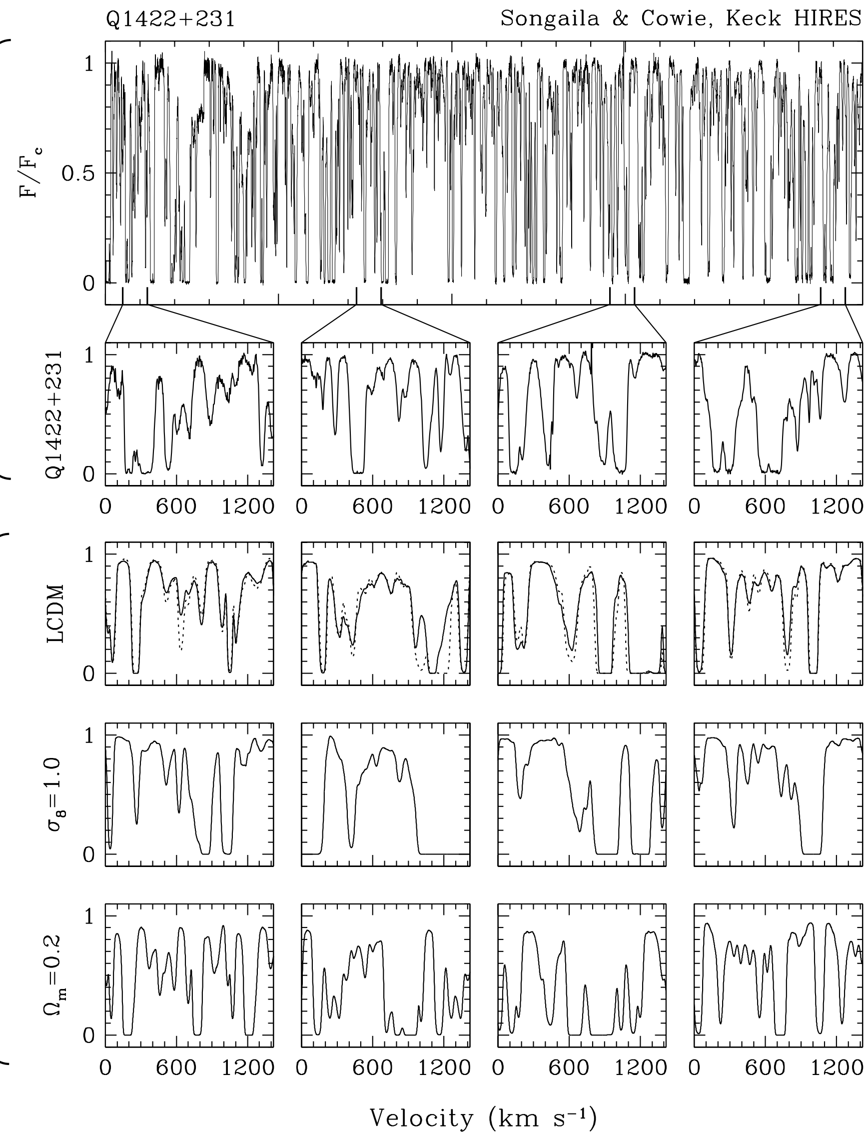


(Weinberg et al., arxiv:031186)

science w/ the Ly-α forest – cosmology

observations

theoretical models



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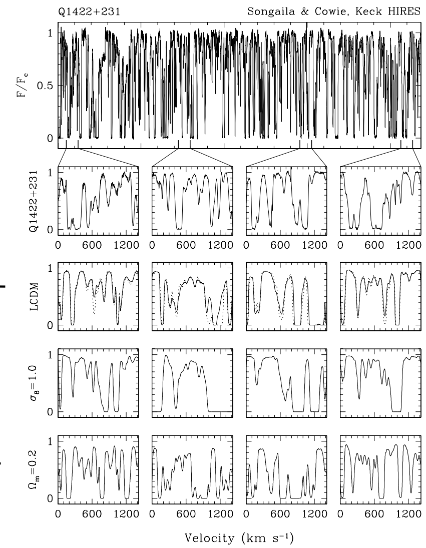
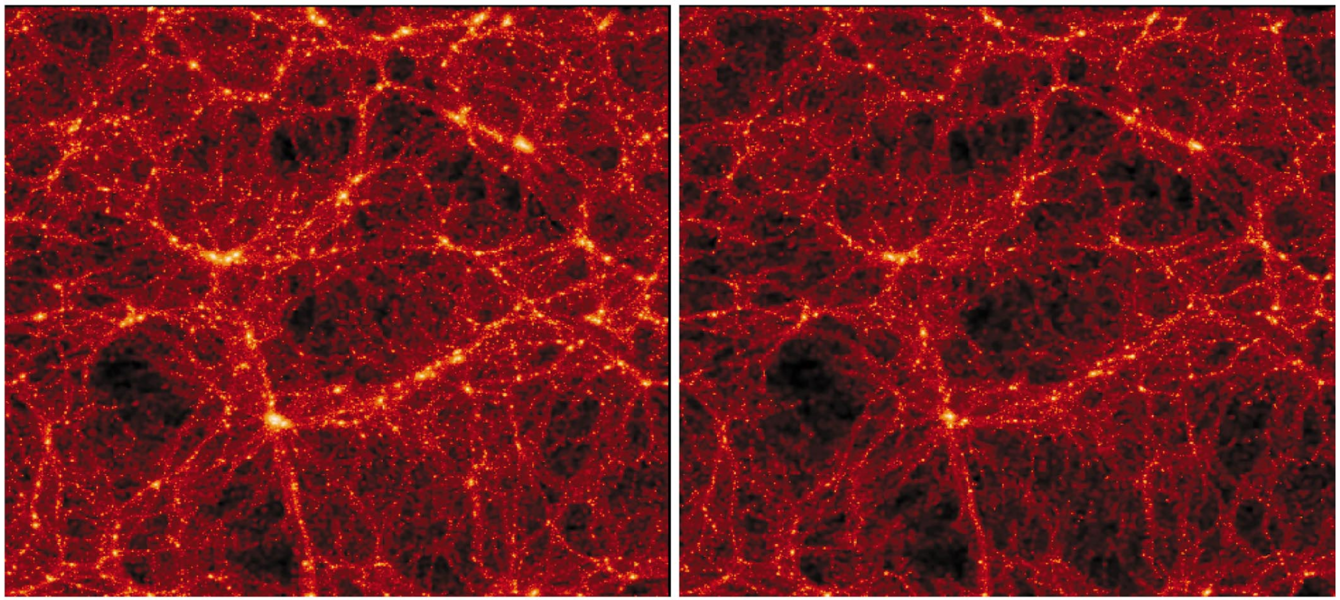


(Weinberg et al., arxiv:0311186)

(Jenkins et al. 1998)

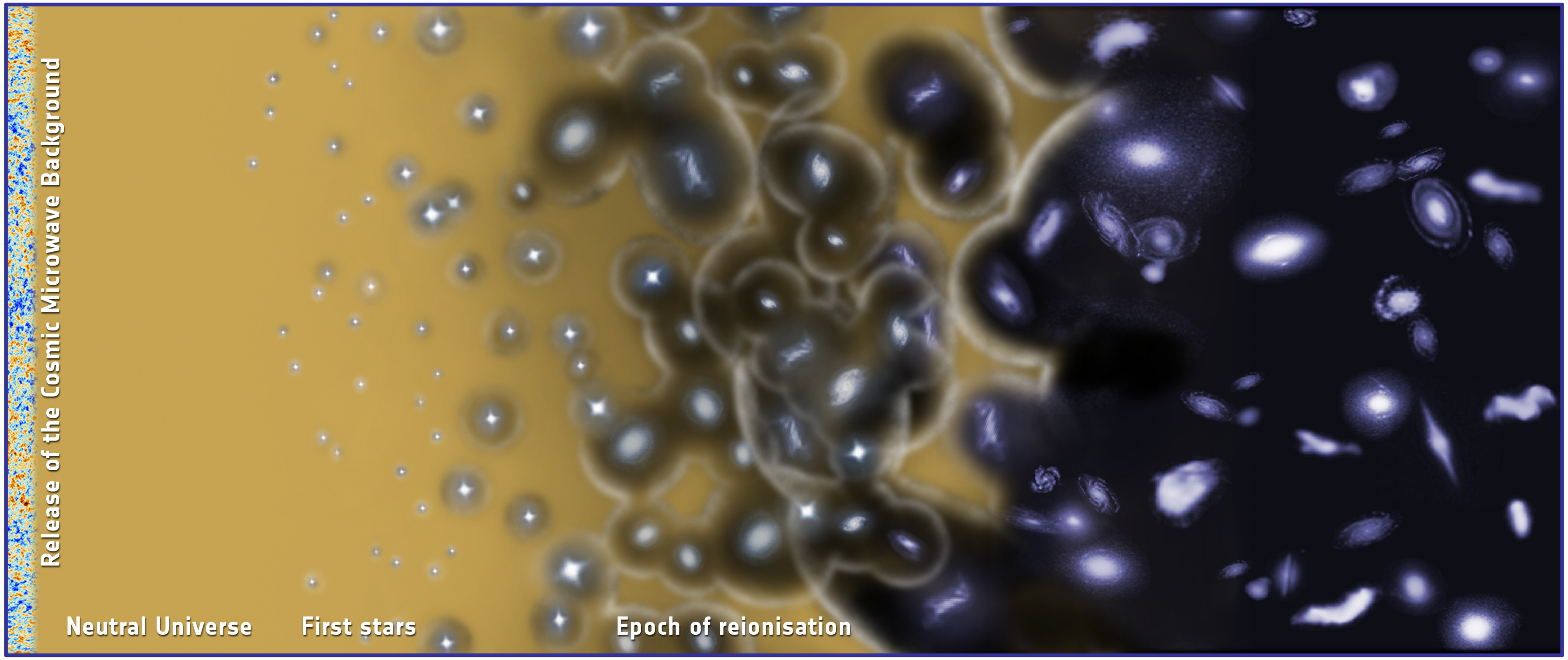


LCDM Ω_0=0.2

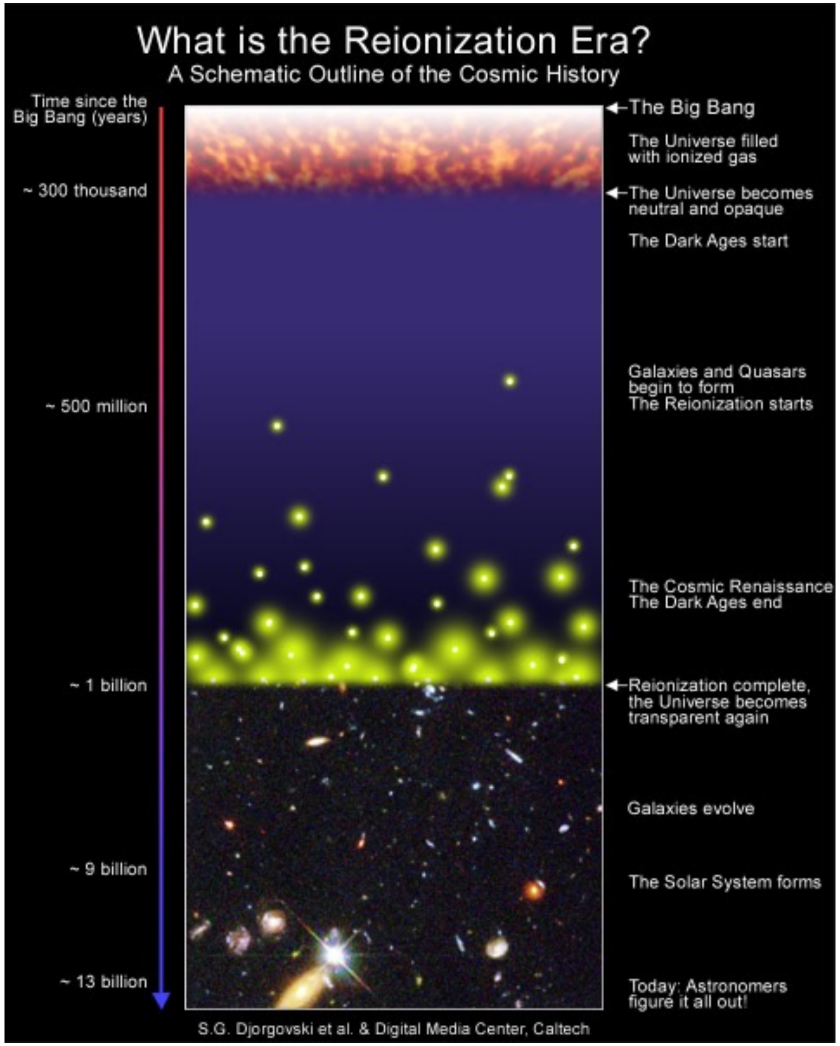
- the Ly-a forest
- **cosmic reionisation**
- the warm-hot intergalactic medium

Intergalactic Medium

time



- reionising the Universe

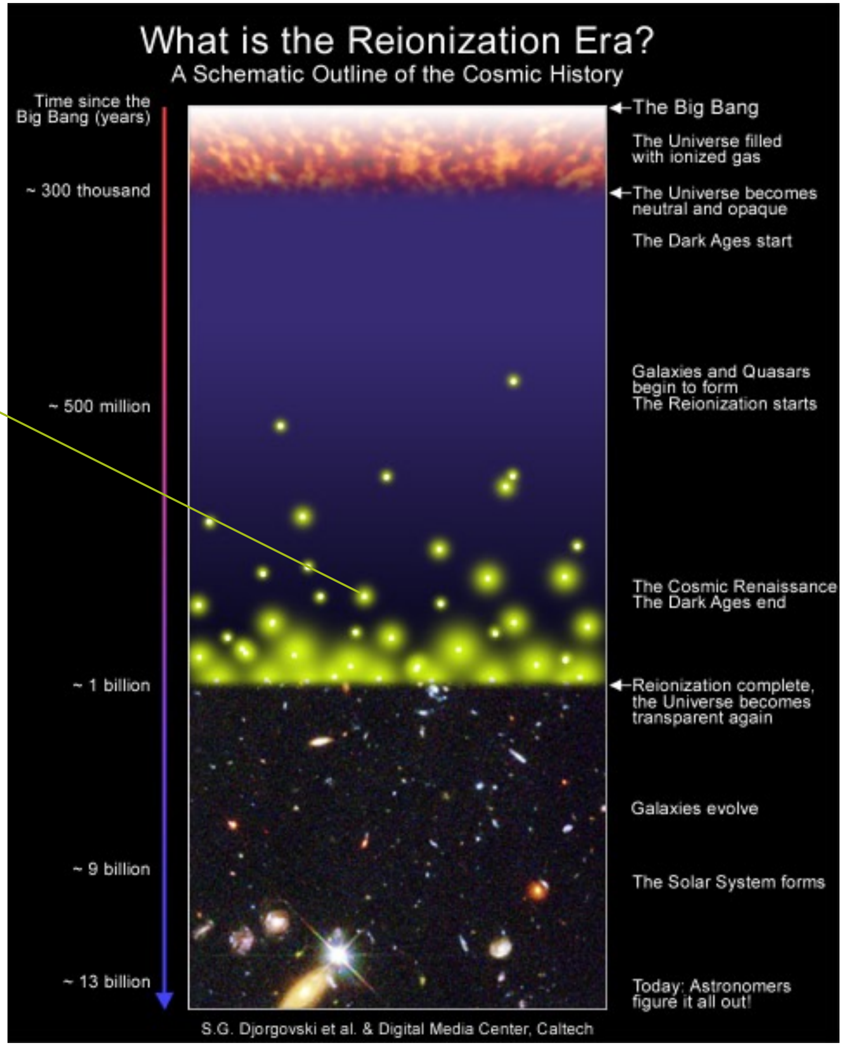


▪ reionising the Universe

• energy released by first objects ionizes neutral hydrogen

• detected via…

…Gunn-Peterson trough in QSO spectra:
neutral hydrogen along line-of-sight absorbs photons



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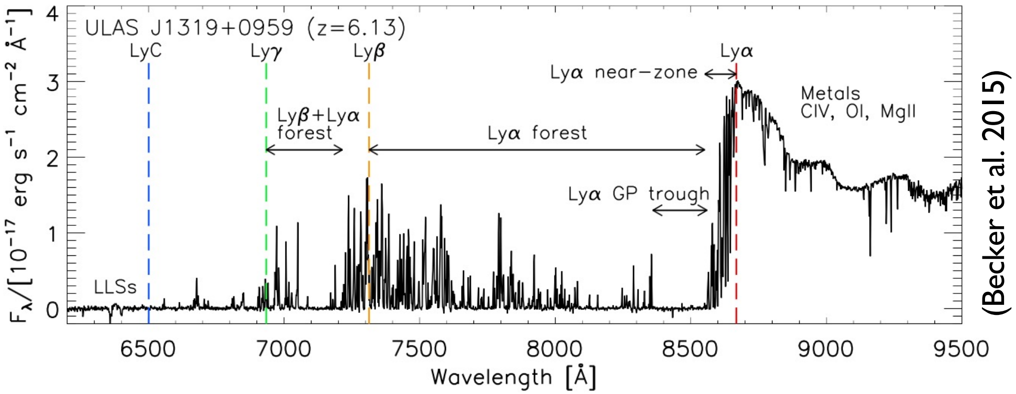
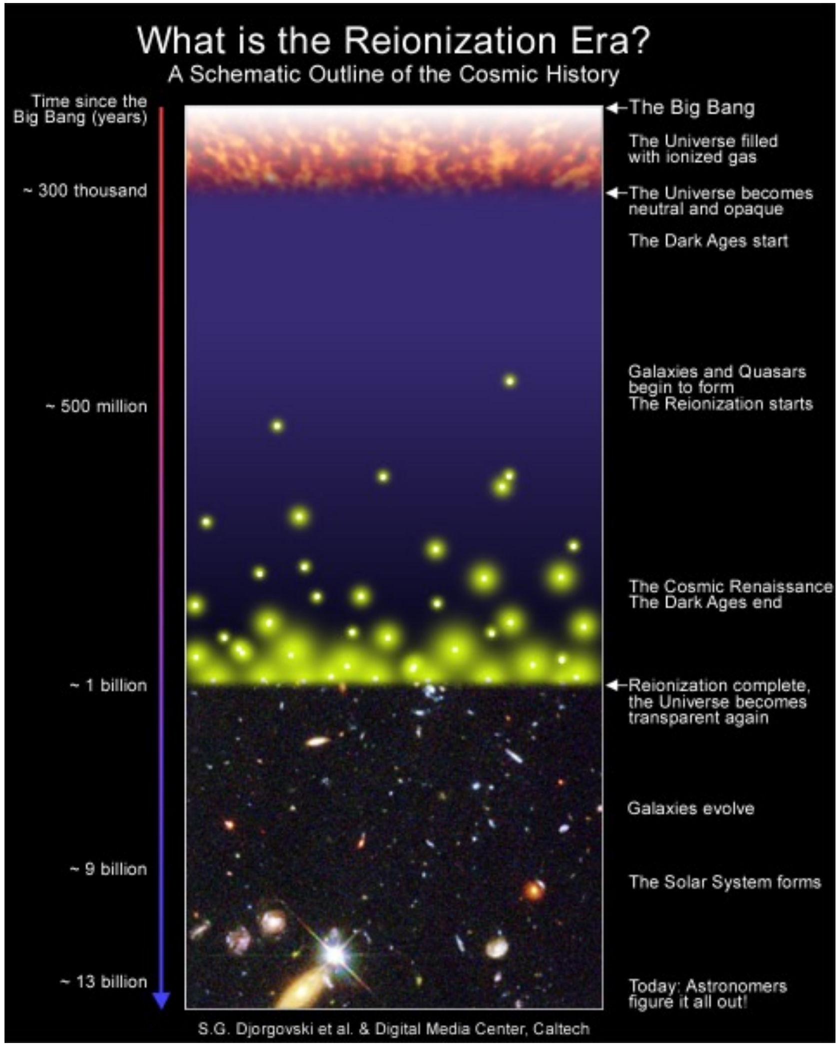
spectrum of QSO @ z=6.13



(Becker et al. 2015)



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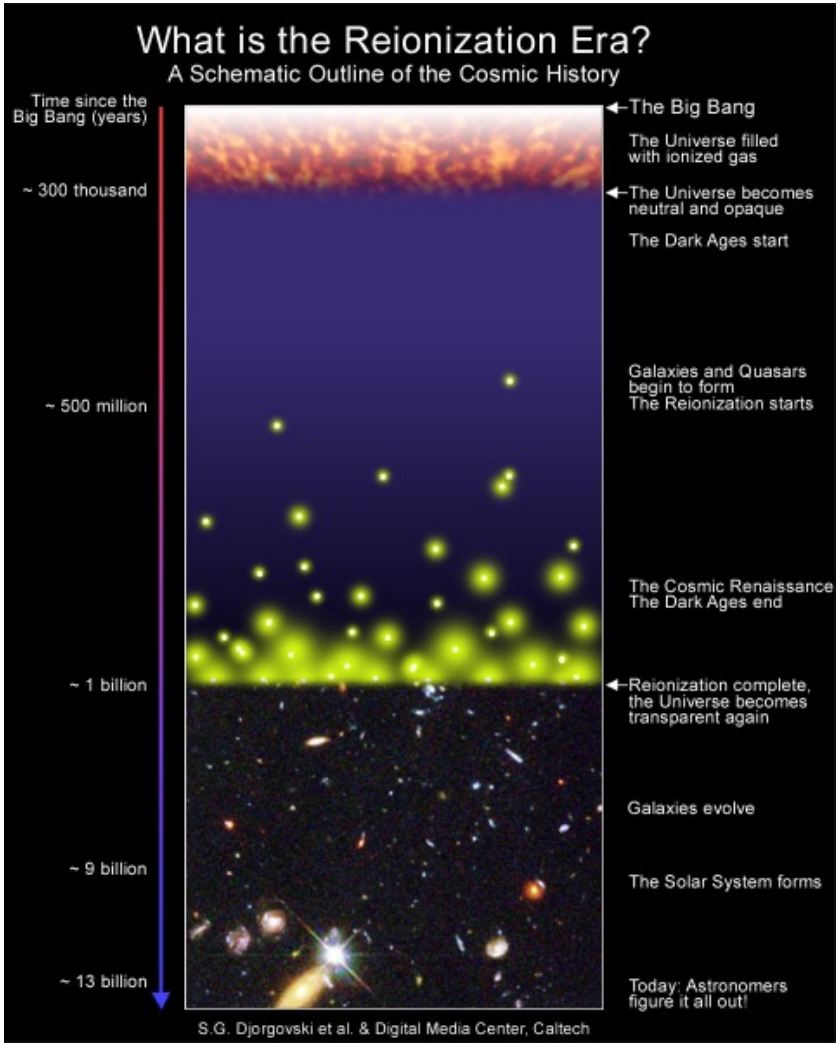
…Thomson scattering of CMB photons:
erasing of small scale anisotropies, polarization of CMB,
Planck 2013: reionisation started at z=11



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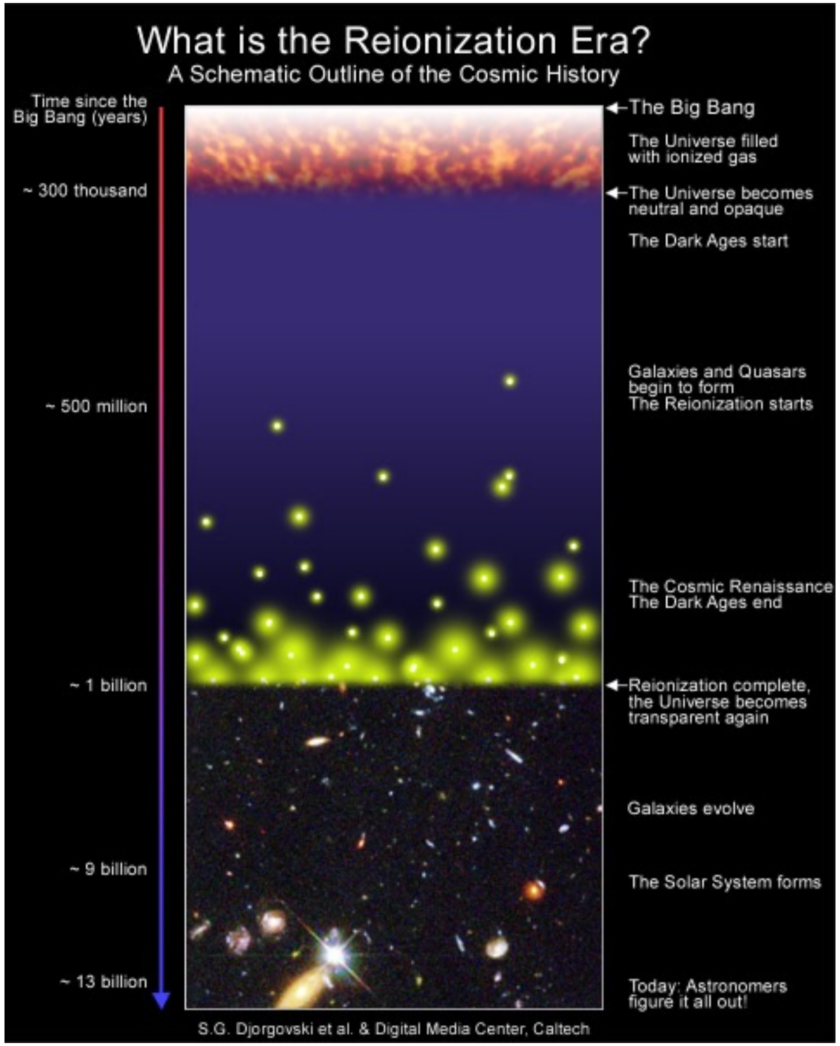
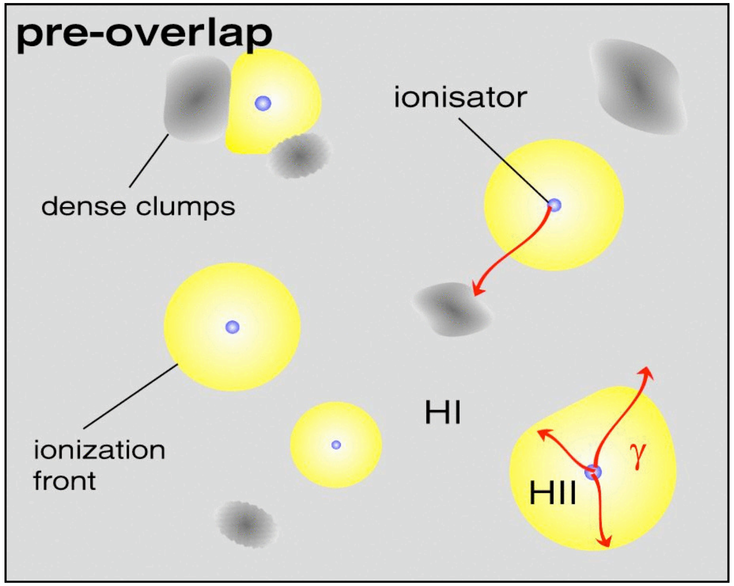
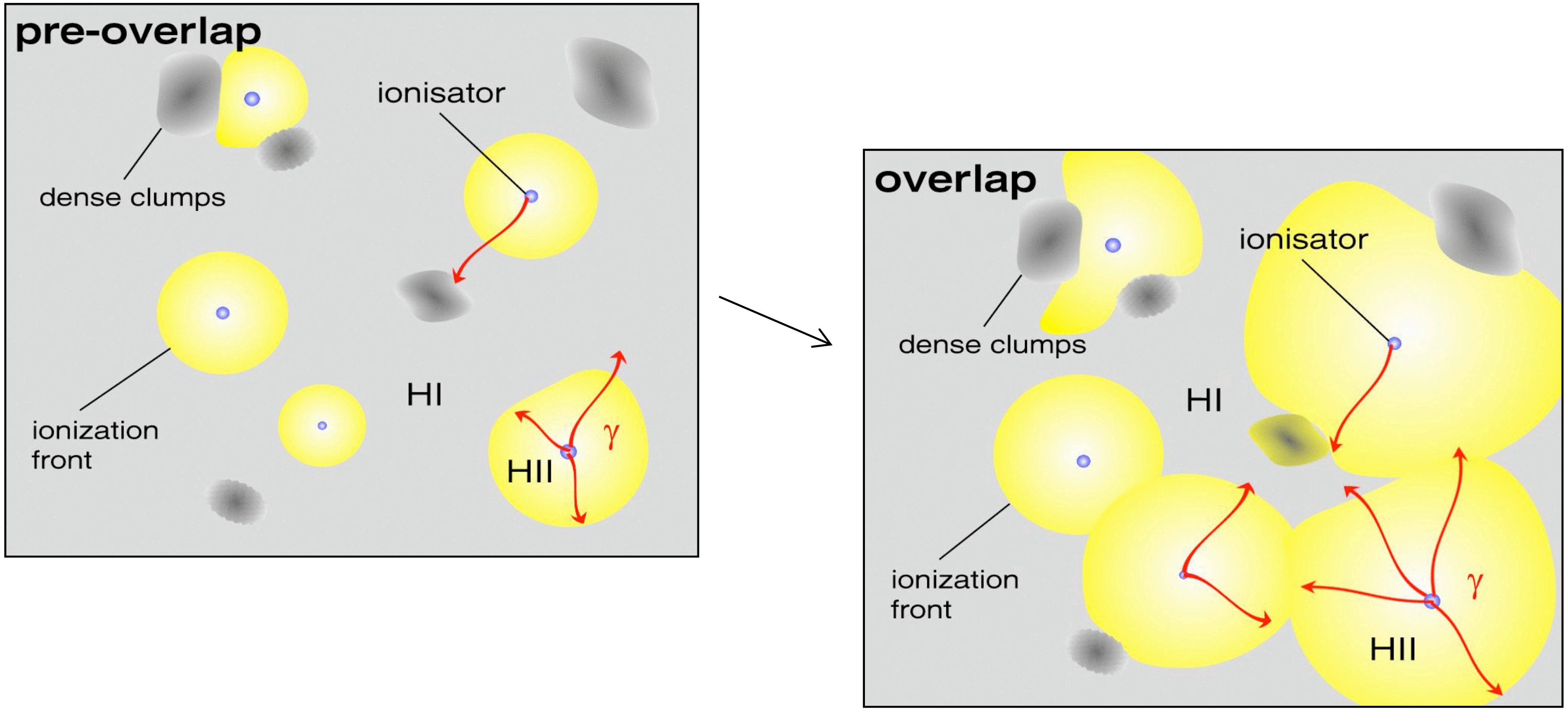
→ reionisation window: $6 < z < 11$ (ca. 500 Myrs)



- reionising the Universe - inhomogenous process



- <u>reionising the Universe - inhomogenous process</u>



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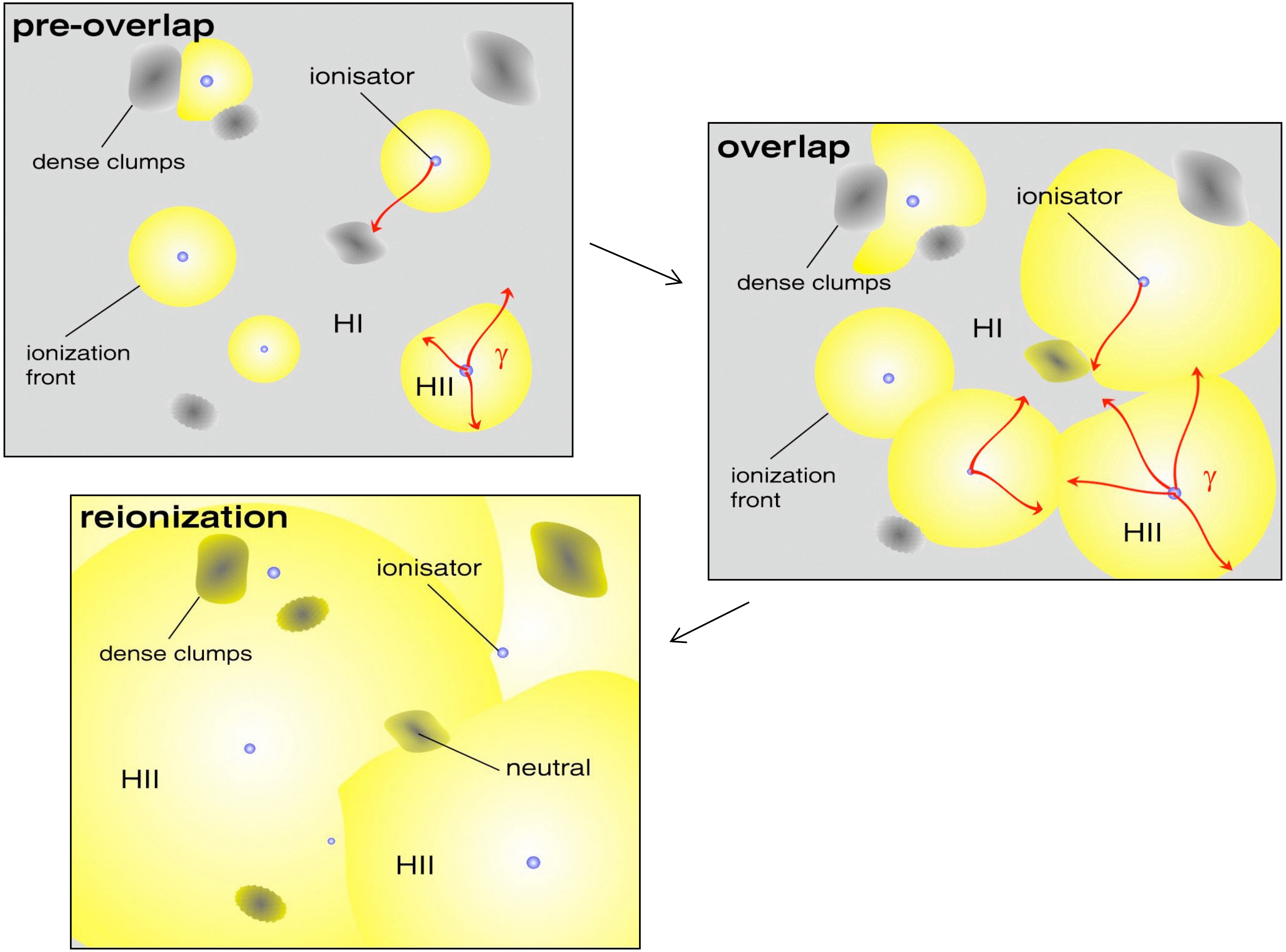
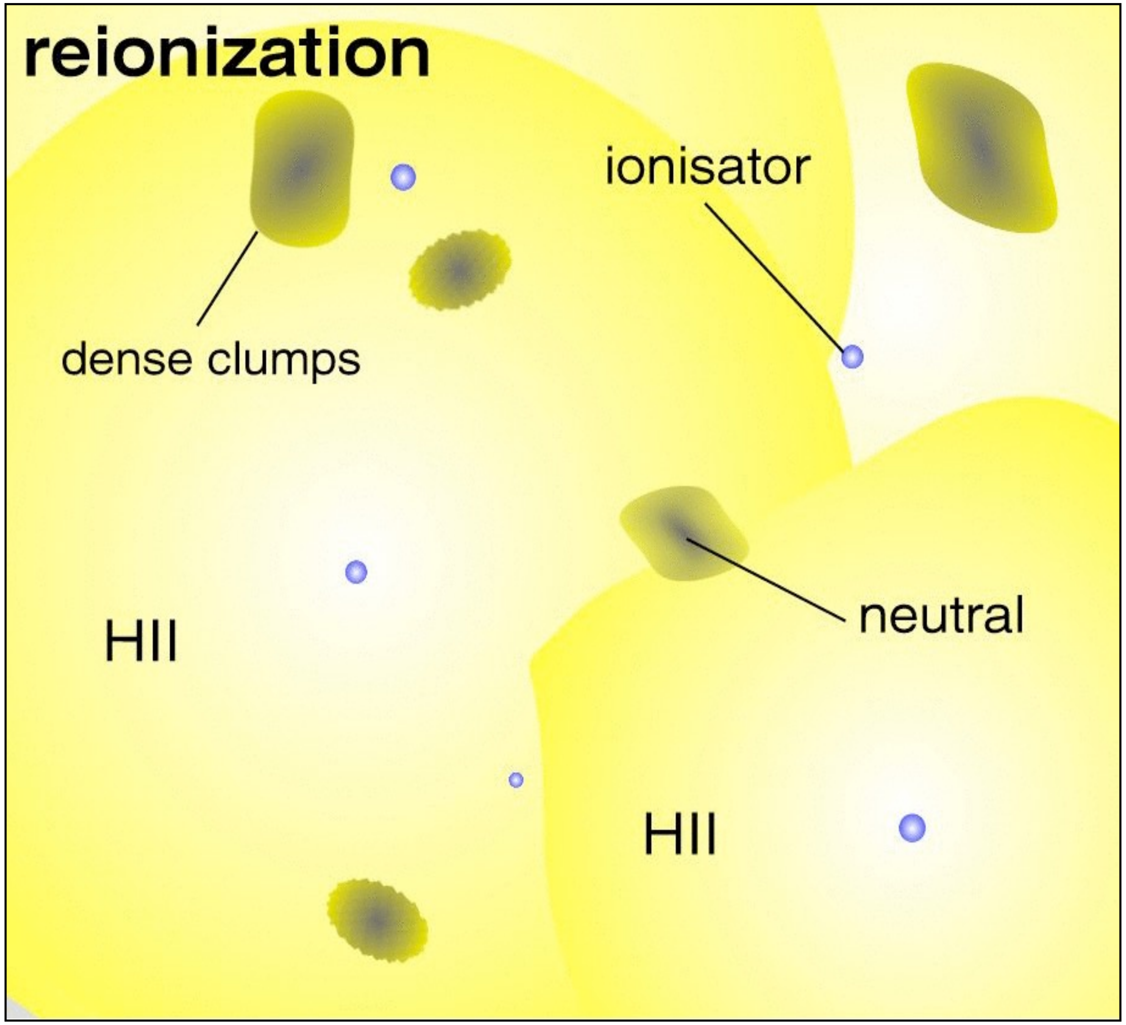


- reionising the Universe – movie

(R. Kaehler, M. Alvarez & T. Abel, 2020)

- <u>reionising the Universe – the UV background</u>

eventually there will be a homogenous UV background filling the Universe!



- reionising the Universe – the UV background

THE ASTROPHYSICAL JOURNAL, 461:20–37, 1996 April 10

RADIATIVE TRANSFER IN A CLUMPY UNIVERSE. II. THE ULTRAVIOLET EXTRAGALACTIC BACKGROUND

FRANCESCO HAARDT[1,2,3] AND PIERO MADAU[1]
Received 1995 June 1; accepted 1995 October 18

ABSTRACT

The integrated ultraviolet flux arising from QSOs and/or hot, massive stars in metal-producing young galaxies is likely responsible for maintaining the intergalactic diffuse gas and the Lyα forest clouds in a highly ionized state. The spectrum and intensity of such UV background have generally been obtained by modeling the reprocessing due to intervening material as a pure photoelectric absorption process. However, owing to the emission from radiative recombinations within the absorbing clouds, a photoionized clumpy medium could contribute substantially to the metagalactic flux. In other words, QSO absorption-line systems are sources, not just sinks of ionizing photons.

We present a detailed calculation of the propagation of AGN-like ionizing radiation through the intergalactic space. We model the ionization state of absorbing clouds, and show that the universe will be more opaque above 4 Ry than previously estimated. Singly ionized helium in Lyα forest clouds and Lyman-limit systems is found to be very efficient in reprocessing soft X-ray, helium-ionizing photons into ultraviolet, hydrogen-ionizing ones. We demonstrate that a significant fraction of the absorbed primary photons (emitted, e.g., by quasar sources) will be reradiated by the photoionized gas through Lyα line emission, two-photon continuum, and recombination continuum radiation.

In the light of new data and recent studies, we also reassess the contribution of the QSOs observed in optical surveys to the UV extragalactic background, and find that the stochastic reprocessing of quasar Lyman continuum radiation by hydrogen and helium along the line of sight will significantly affect the amplitude, spectral shape, and fluctuation properties of the metagalactic flux. In a scenario in which QSOs are the primary source of ionizing photons in the universe, the integrated H I Lyα emission at $z = 0$ from photoionized Lyα clouds and Lyman limit systems is found to be at a level of less than 5% of current observational limits on the far-UV extragalactic radiation flux. We show that J_{912} increases from $\approx 10^{-23}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at the present epoch to $\approx 5 \times 10^{-22}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at $z = 2.5$. The attenuated direct quasar emission plus recombination radiation from intergalactic gas appear to provide enough hydrogen-ionizing photons to satisfy the proximity effect at large redshift. The He II/H I ratio in the diffuse intergalactic medium and the Lyα clouds increases from ≈ 25 at $z = 0$ to ≈ 45 at $z = 2.5$, to decrease again below 30 for $z \gtrsim 4.5$. The spectrum of the ionizing background at high redshift is shown to have a hump at energies below 40.8 eV due to redshift-smeared He II Lyα line and two-photon continuum emission. We propose that observations of low-ionization species such as O II in metal-line absorption systems may be able to test the presence of such a prominent feature in the UV background spectrum. We also note that, if the metagalactic flux is dominated by QSOs, the suggested steep decline of their ionizing emissivity beyond $z \sim 4$ should produce an increase in the observed rate of incidence of Lyα forest clouds at these redshifts relative to an extrapolation from the intermediate-z regime, as observed by Williger et al. (1994).

Subject headings: cosmology: theory — diffuse radiation — intergalactic medium — quasars: absorption lines — radiative transfer

1. INTRODUCTION

The existence of a uniformly distributed intergalactic medium (IGM), which contains the bulk of the baryonic matter of the universe in most models of structure formation, is predicted as a product of primordial nucleosynthesis. The hydrogen component of this IGM must have been highly ionized by $z \sim 5$, as the flux decrement observed on the blue side of the Lyα emission line of neutral hydrogen in the spectra of high-redshift QSOs appears entirely consistent with the blanketing by discrete absorption lines along the line of sight (Steidel & Sargent 1987; Giallongo et al. 1994). It is widely believed (but see, e.g., Sciama 1993) that the integrated ultraviolet flux arising from QSOs and/or hot, massive stars in metal-producing young galaxies is responsible for maintaining the intergalactic diffuse gas and the Lyα forest clouds in a highly ionized state. Such UV background may also be responsible for the ionization of the metal-rich QSO absorption systems (Steidel 1990; Vogel & Reimers 1993) and of the hydrogen clouds located in the galactic halo (Fransson & Chevalier 1985; Ferrara & Field 1994), and for producing the sharp edges of H I disks observed in nearby spiral galaxies (Bochkarev & Sunyaev 1977; Maloney 1993; Corbelli & Salpeter 1993; Dove & Shull 1994). Photoionization by UV radiation may also inhibit the collapse of small-mass galaxies (Dekel & Rees 1987; Efstathiou 1992).

The *Hubble Space Telescope* (*HST*) Faint Object Camera (FOC) detection of redshifted He II 304 Å absorption in the spectrum of the $z = 3.29$ quasar Q0302−003 (Jakobsen et

[1] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.
[2] Department of Astronomy & Astrophysics, Institute of Theoretical Physics, University of Göteborg & Chalmers University of Technology, 412 96 Göteborg, Sweden.
[3] ISAS/SISSA, via Beirut 2-4, 34014 Trieste, Italy.

first quantitative calculations can be found in Haardt & Madau (1996)

- reionising the Universe – the UV background

image credit: Andrea Maccio (in the foreground...)

Haardt & Madau in the background

first quantitative calculations can be found in Haardt & Madau (1996)

- reionising the Universe – first stars? first galaxies?

but what exactly are the sources?

- reionising the Universe – first stars:
  - are very massive
  - should have zero metalicities

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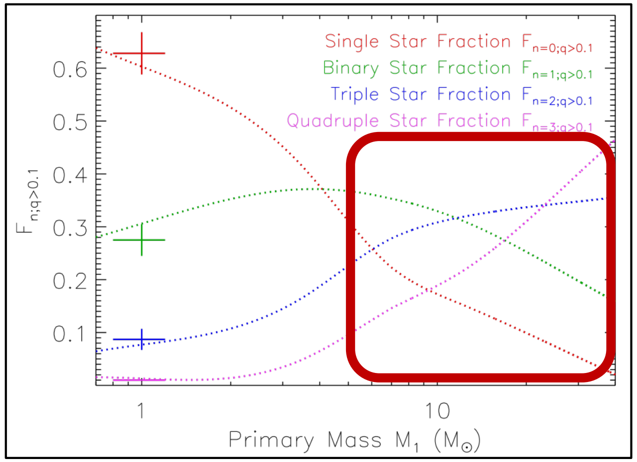
massive stars are primarily forming in pairs



Moe et al. (2017)

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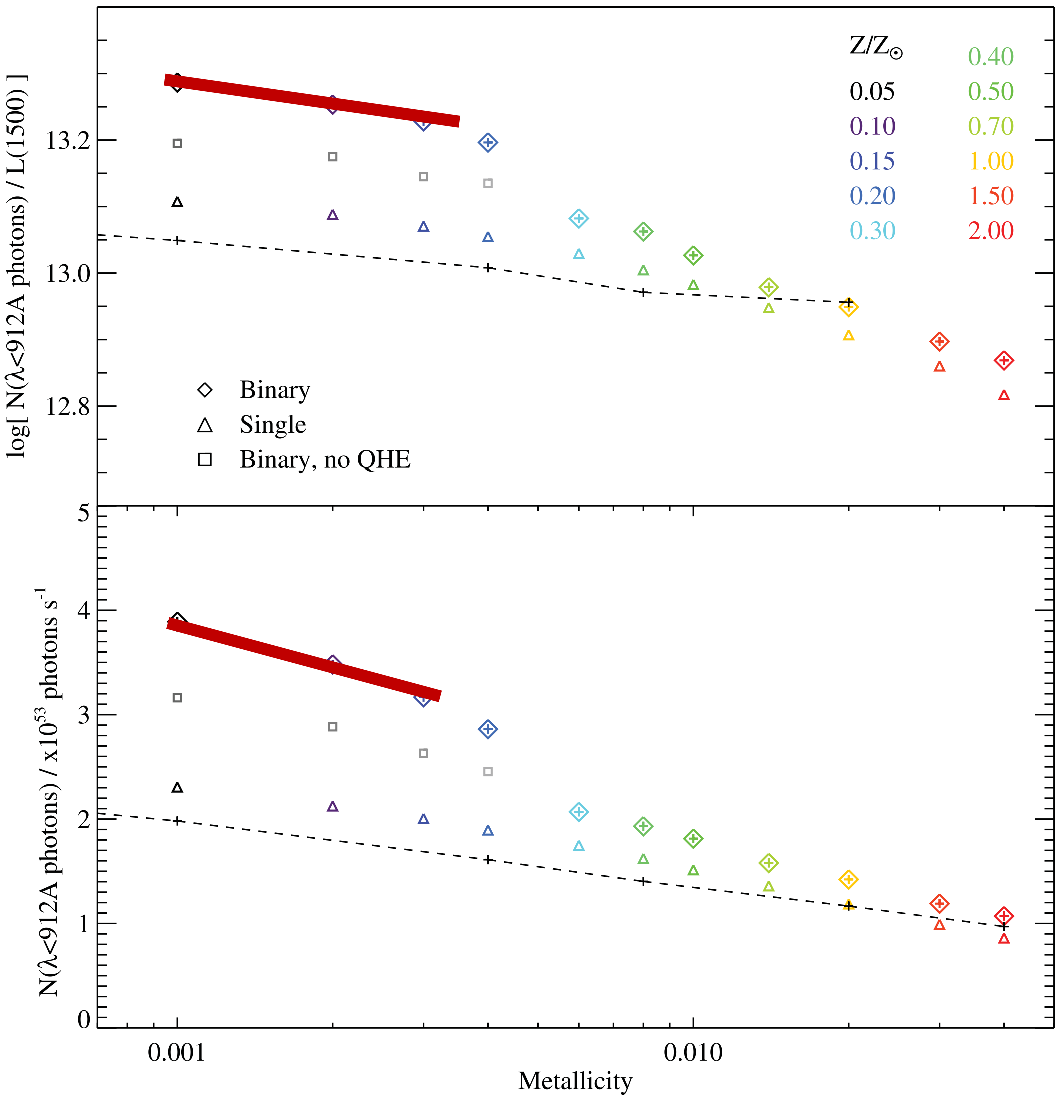
low-metalicity binaries emit far more photons



Stanway et al. (2016)

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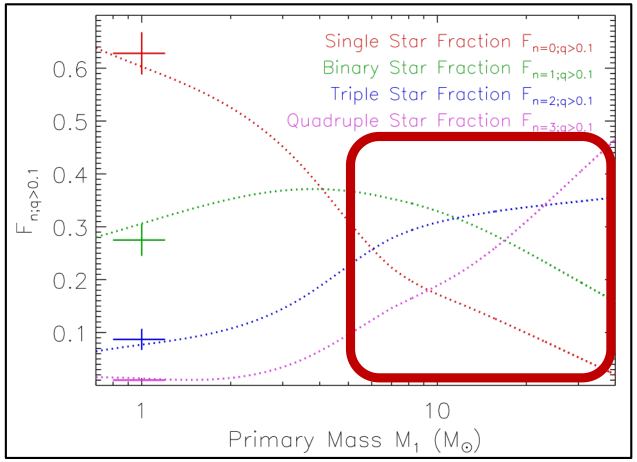
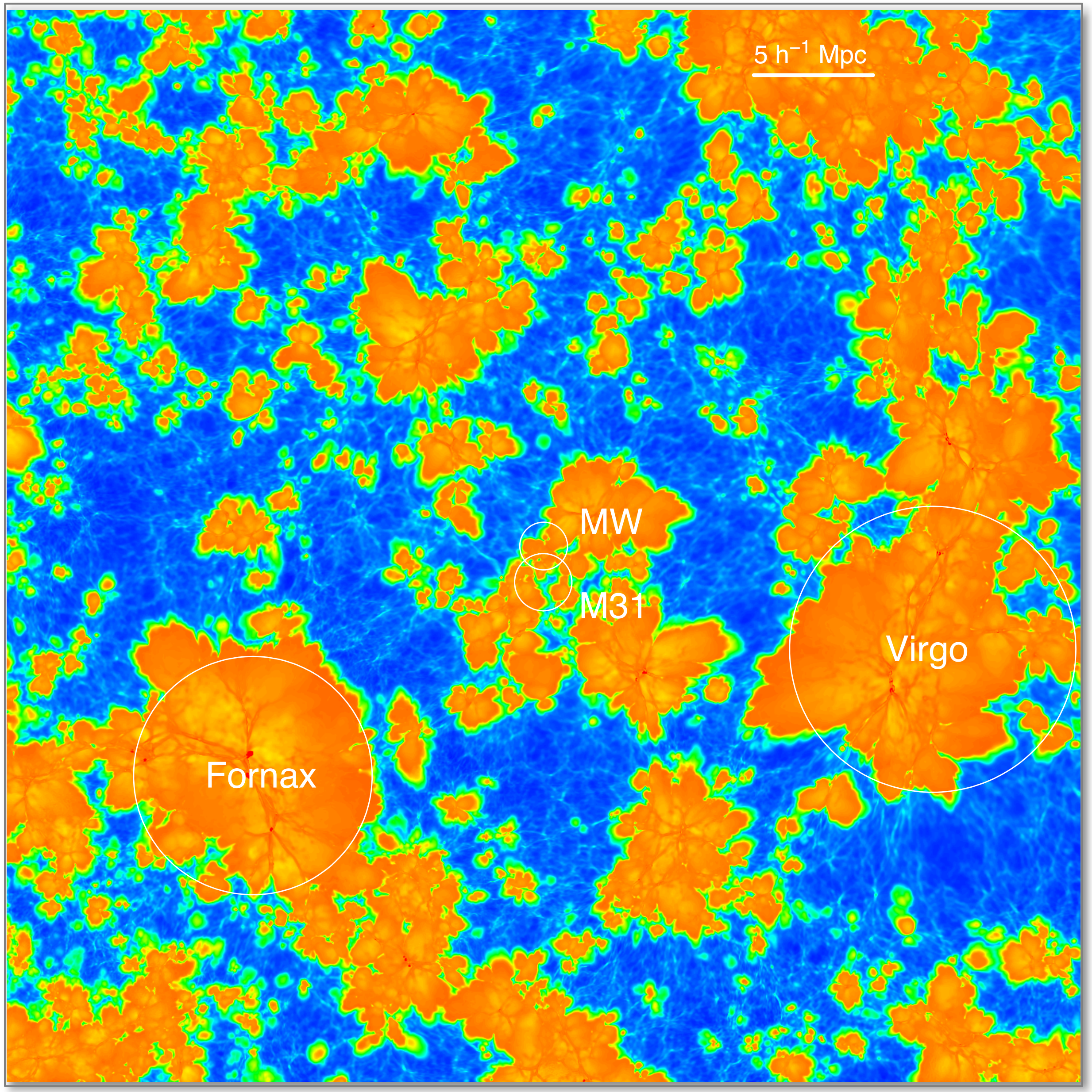
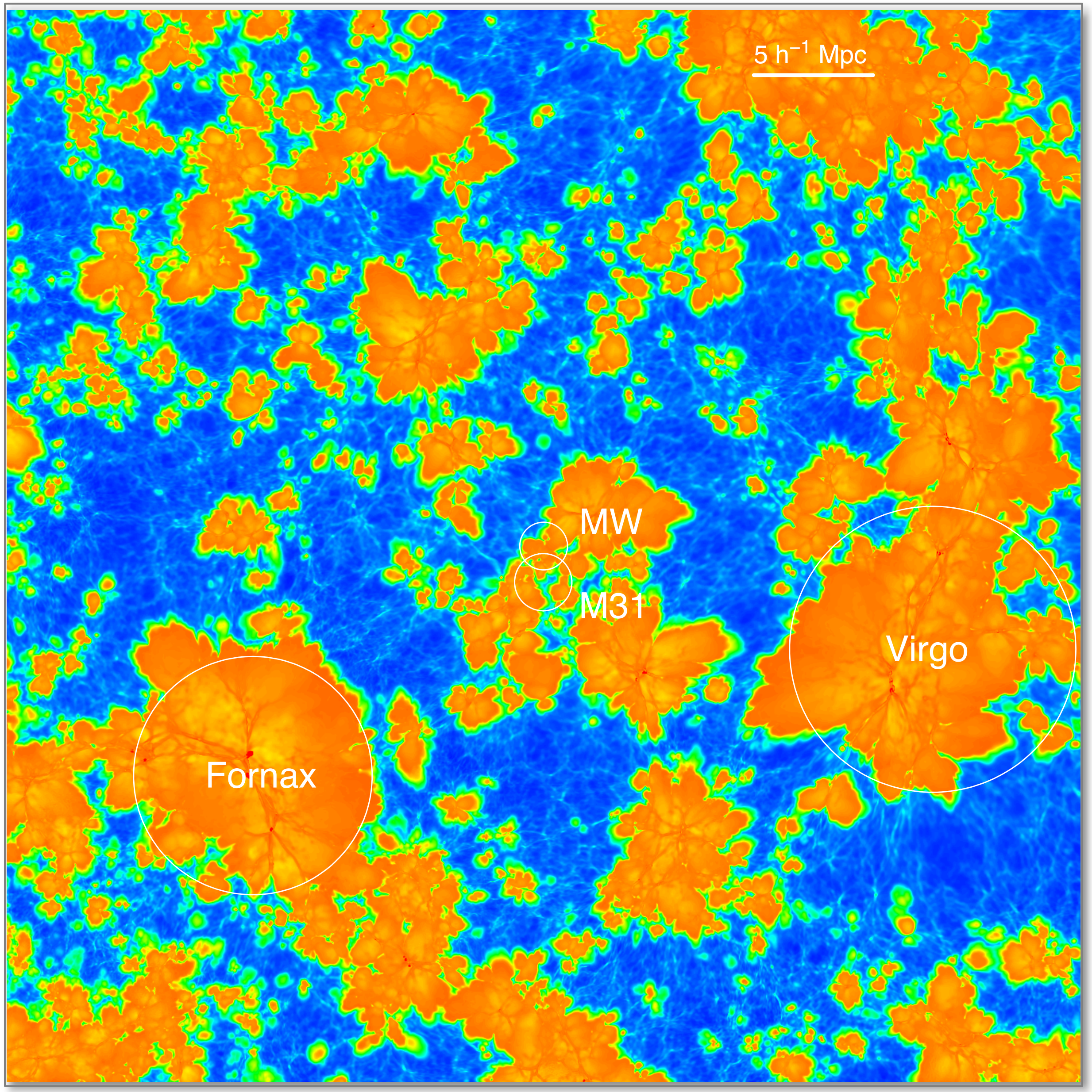


Moe et al. (2017)

- reionising the Universe – (first) galaxies



- <u>reionising the Universe - Cosmic Dawn simulation</u> (Ocvirk et al. 2016)



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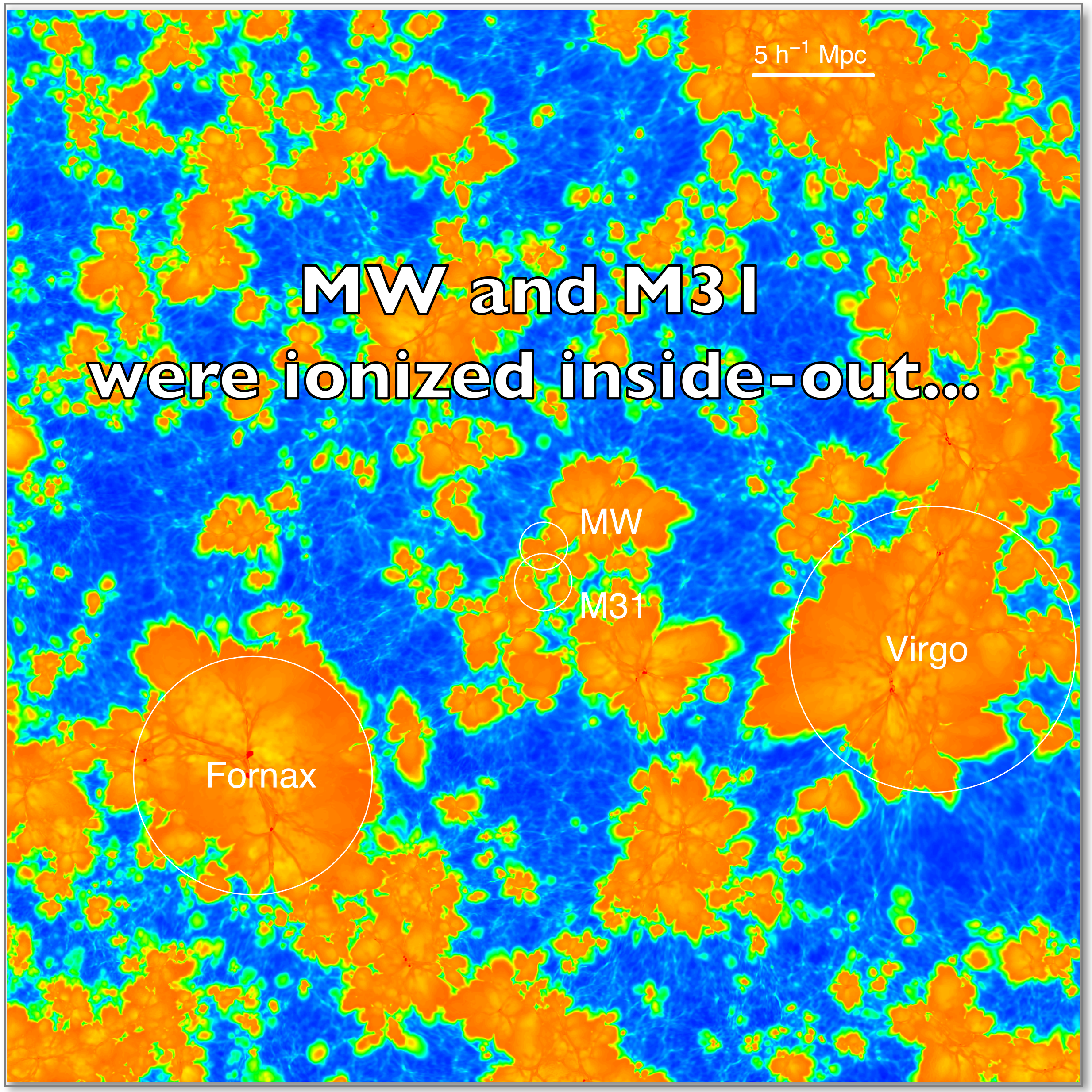

- the Ly-α forest
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- **the warm-hot intergalactic medium**

Cosmic Baryon Census at $z<0.5$

	absolute	relative
	$\Omega_b h^2$	$\Omega_b / \Omega_b^{Plank}$
Stars in galaxies	0.0015 ± 0.0004	$(7 \pm 2)\%$

(Nicastro et al. 2018)

Ω_b, baryon density; Ω_b^{Plank}, total baryon density measured by the Planck satellite.

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Galaxies' hot disks/haloes	0.0011 ± 0.0007	$(5 \pm 3)\%$

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(Nicastro et al. 2018)

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where are the missing baryons?

Hydrogen

$T < 10^5$K

neutral hydrogen atoms:
• absorption of background photons
• emission via 21cm 'spin-flip'

10^7K $< T$

fully ionised hydrogen atoms:
• emission of X-rays (electrons)

Note: 10^5K $\sim$ 13.6eV

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cosmological simulations to the rescue!

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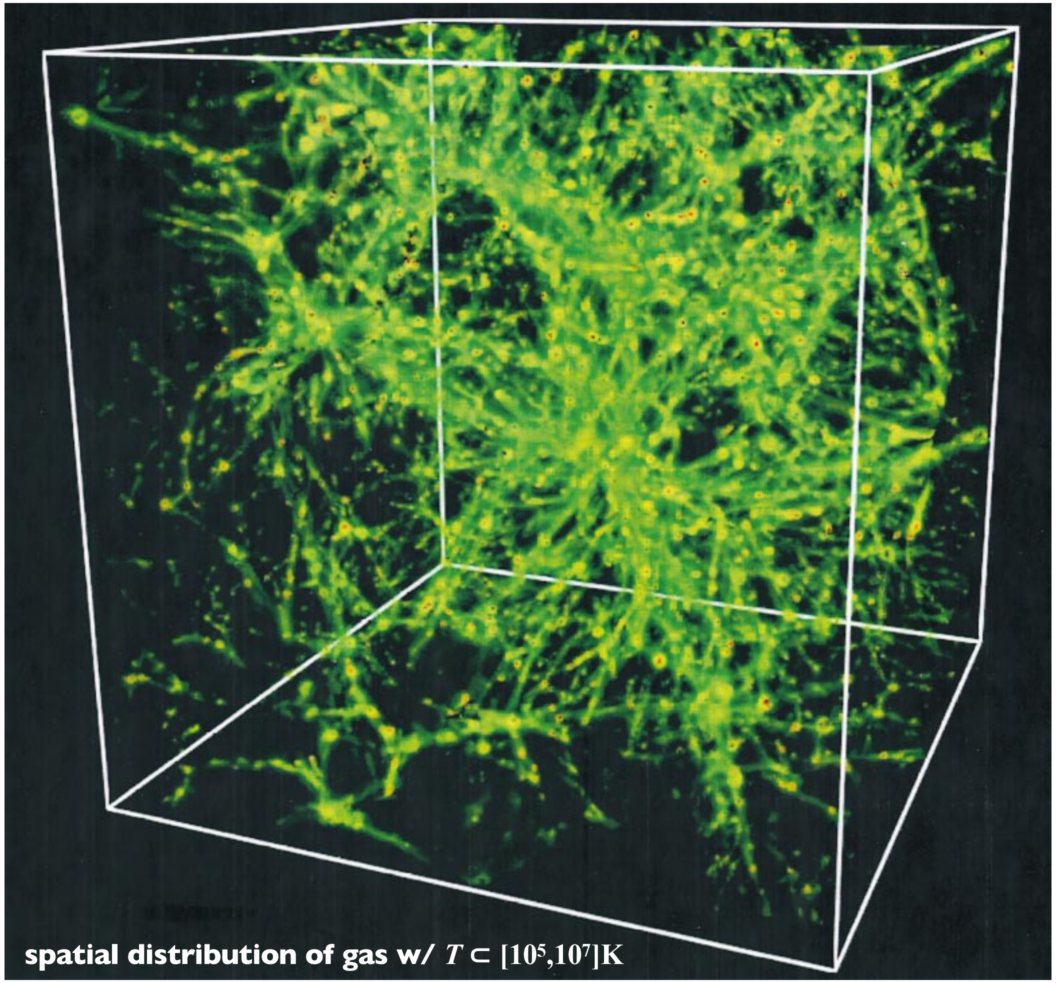
...but where to look for them?

possibly hidden in filamentary structure of the Universe*
(Cen & Ostriker 1999)

*based upon performing full physics cosmological simulations and simply looking for them...

Cosmological Simulations



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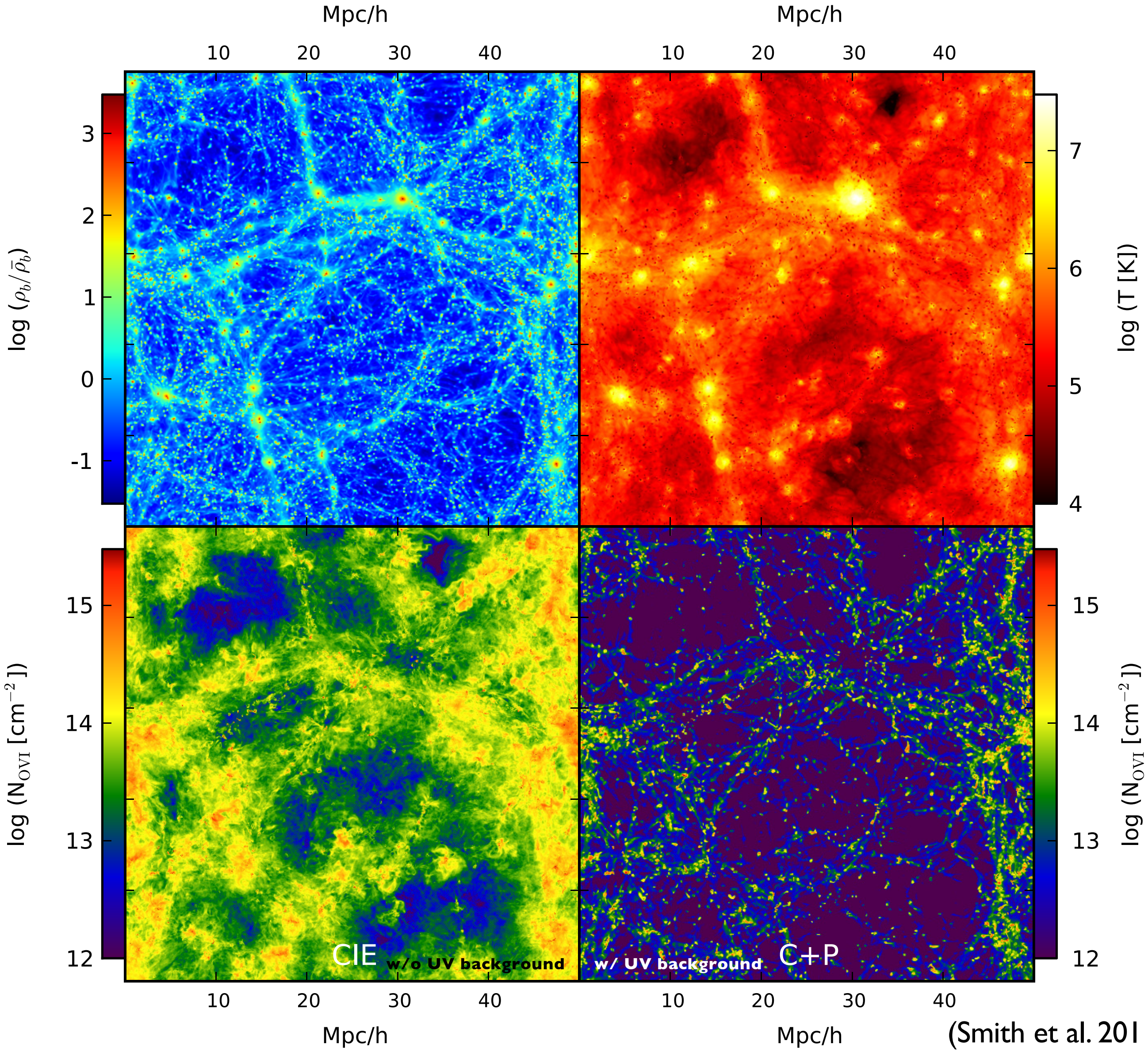
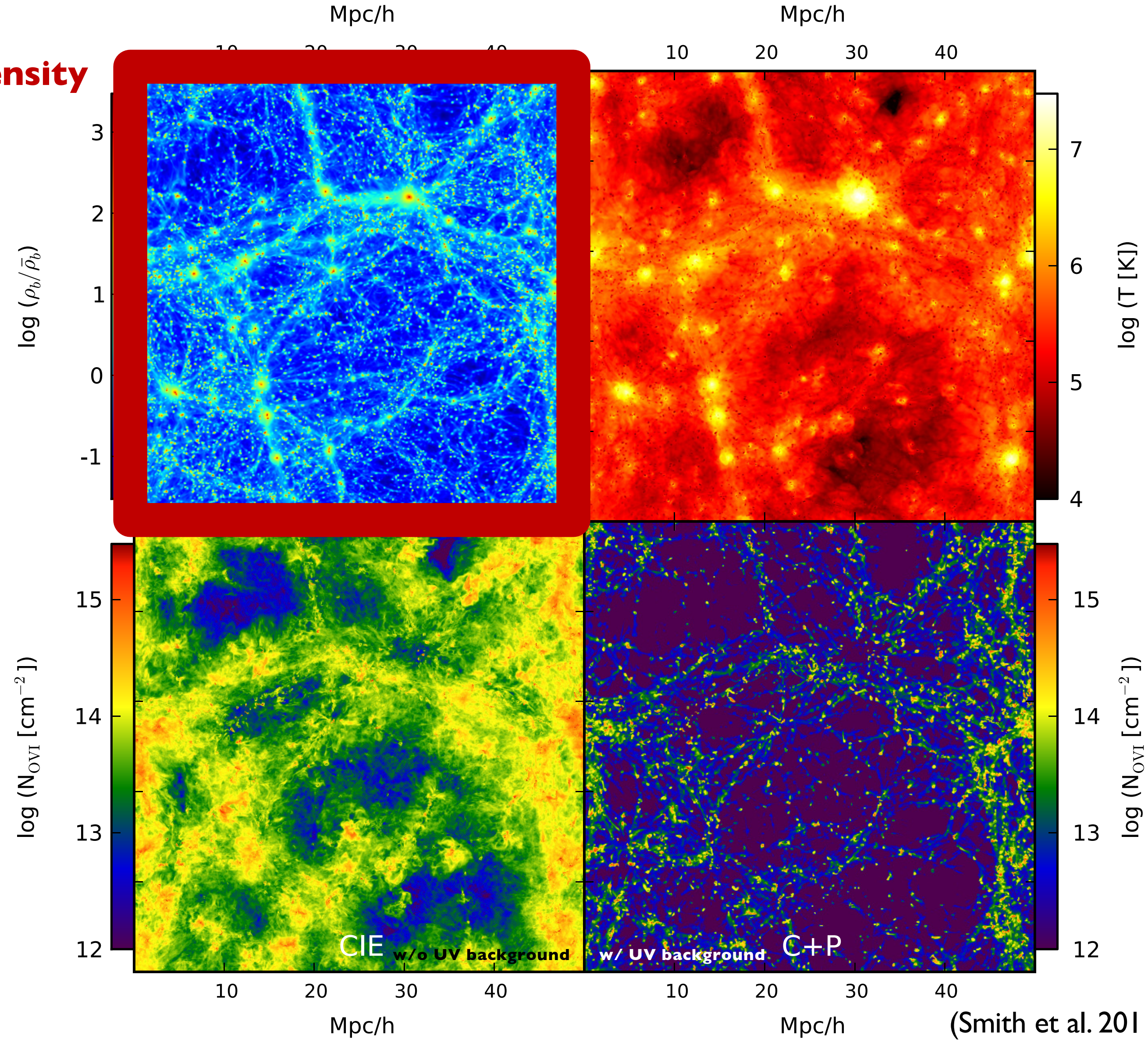


(Smith et al. 2011)

Cosmological Simulations

baryon density



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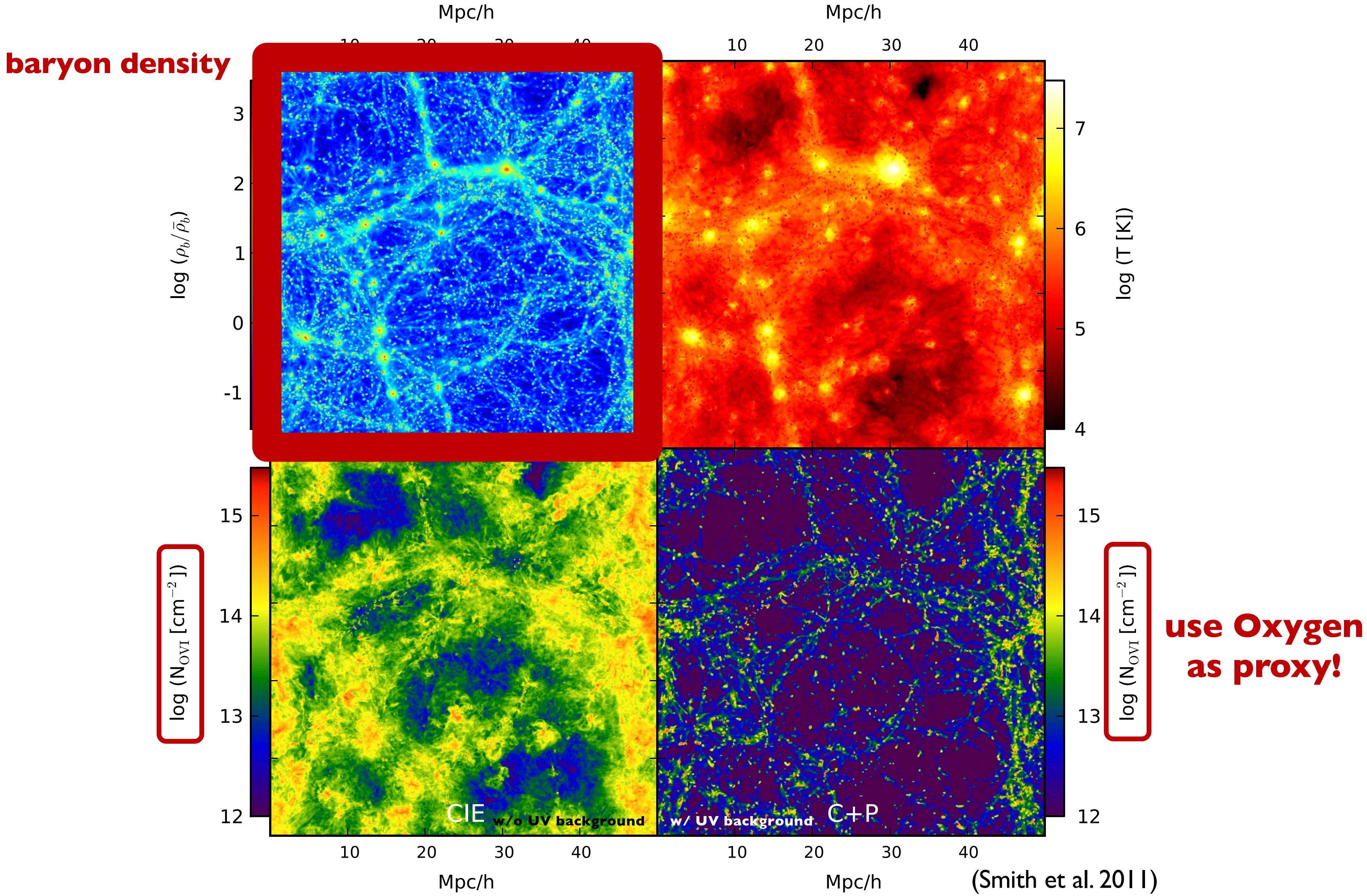

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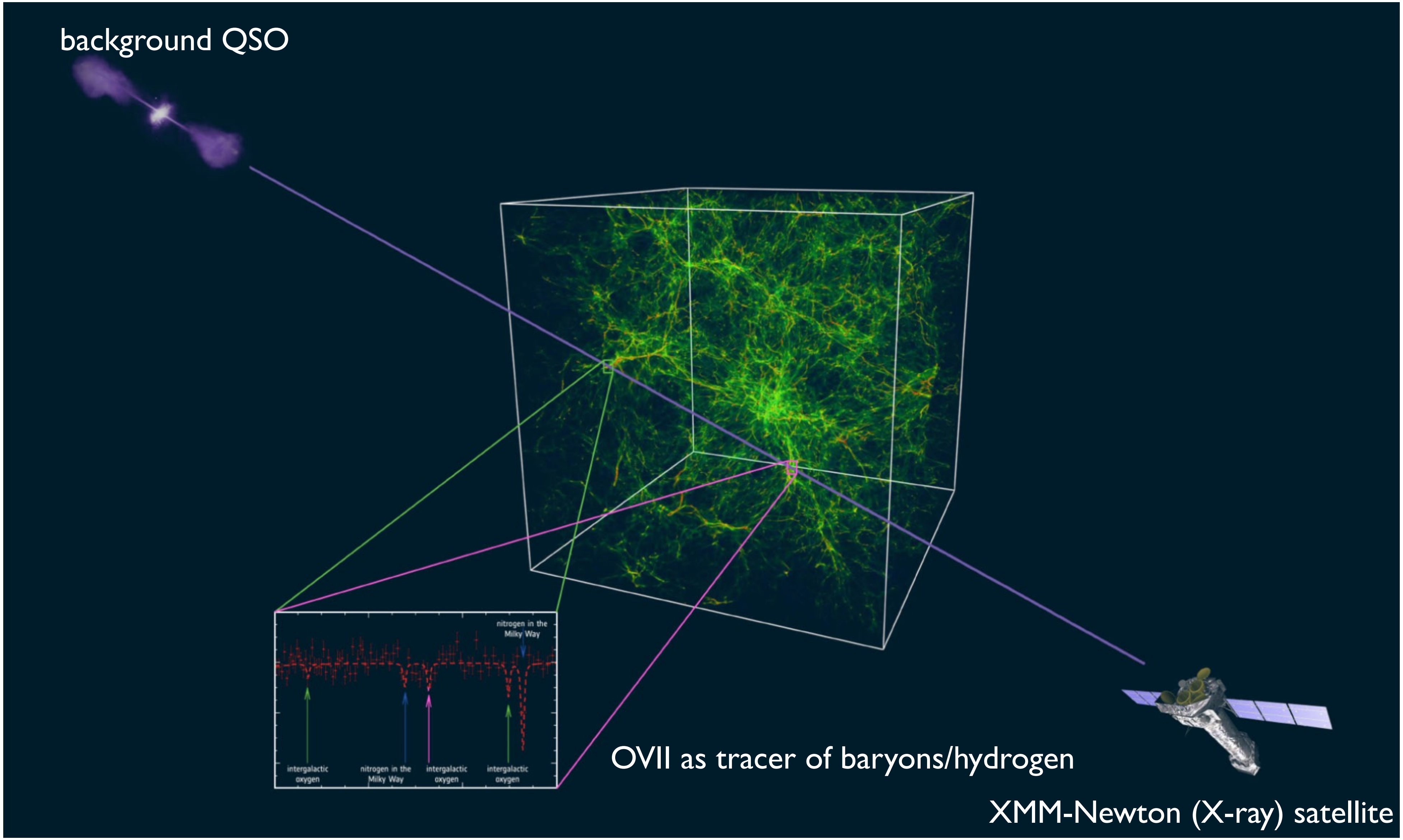
background QSO
nitrogen in the Milky Way
intergalactic oxygen
nitrogen in the Milky Way
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OVII as tracer of baryons/hydrogen
XMM-Newton (X-ray) satellite

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WHIM with 10^5 K $\leq T < 10^{5.7}$ K	$0.0033^{+0.0018}_{-0.0009}$	$15^{+8}_{-4}\%$
WHIM with $10^{5.7}$ K $\leq T < 10^{6.2}$ K	>0.002 and <0.009	$>9\%$ and $<40\%$
Total	>0.013 and <0.026	$>59\%$ and $<118\%$

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the missing baryons have been found!?

- the Ly-a forest
- cosmic reionisation
- the warm-hot intergalactic medium

- the Ly-a forest

  → study spatial distribution of neutral hydrogen clouds

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