The Intergalactic Medium: Overview and Selected Aspects

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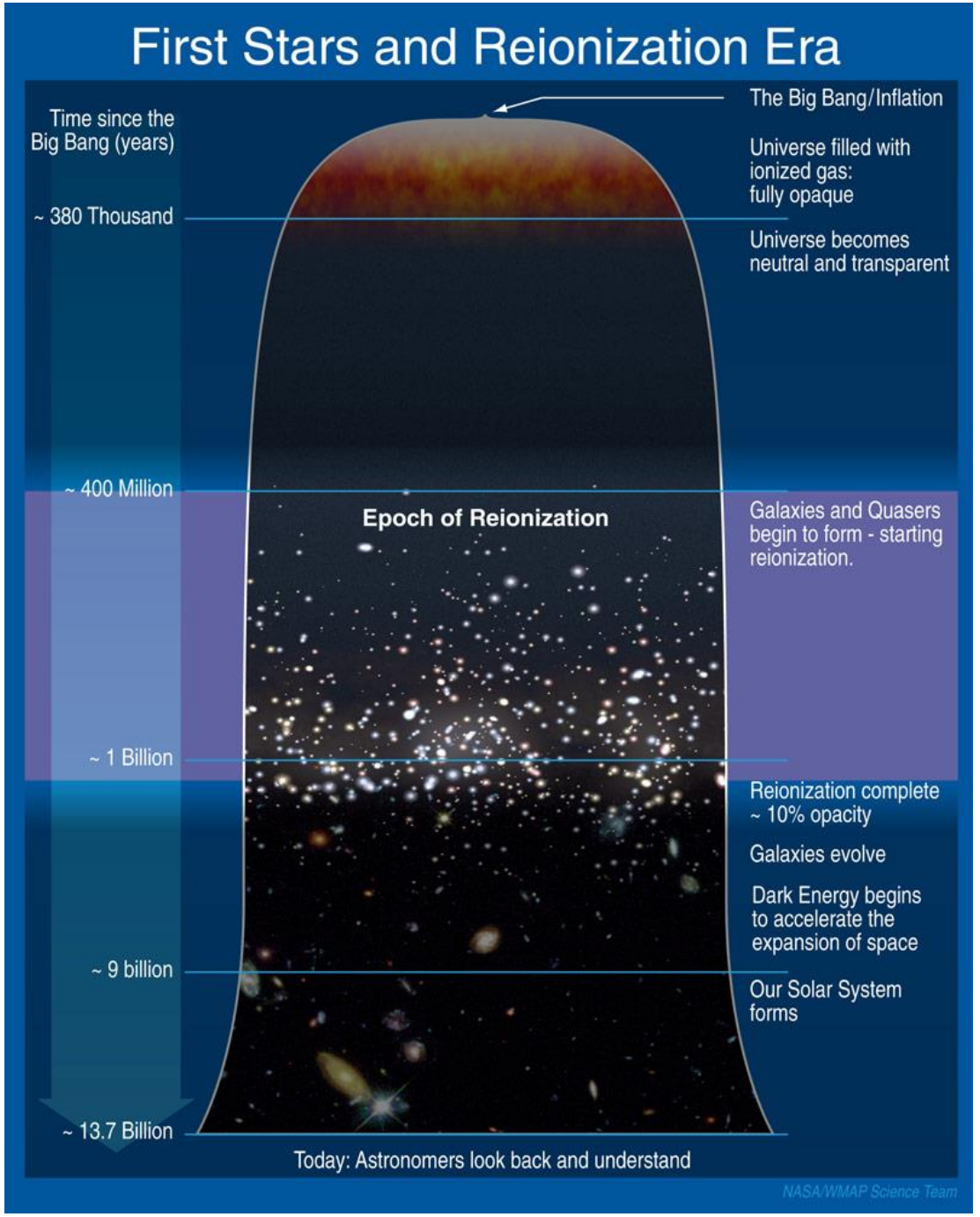
Contents

Early Universe and Reionization

- Big Bang aftermath: universe consists of ionized H and He
- $z \sim 1100$: cosmic gas cooled enough to recombine
- $z \sim 20$: the first galaxies begin to form
- $z \sim 12$ to $z \sim 6$: cosmic gas is ionized again by quasars, population III stars and supernovae



The Ly α Forest - Observations

- Ly α transitions occur in H I between the ground state and the first excited state, the rest wavelength of this spectral line is $1216\ \text{Å}$
- IGM is not completely ionized, clouds of neutral hydrogen remain between the galaxies

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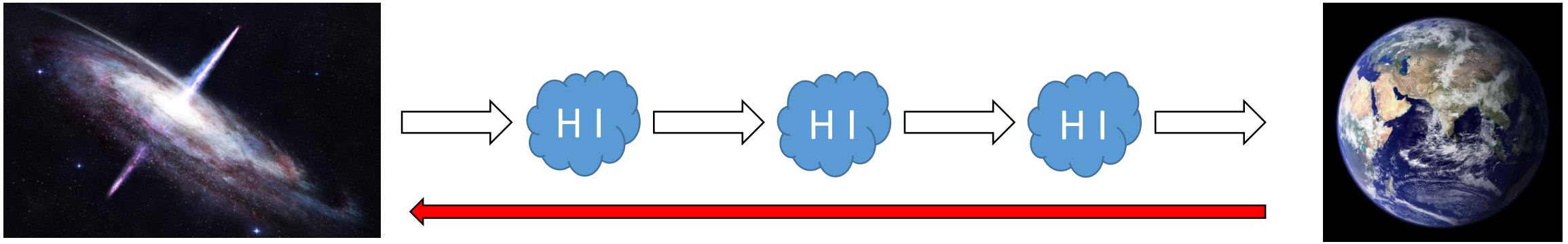
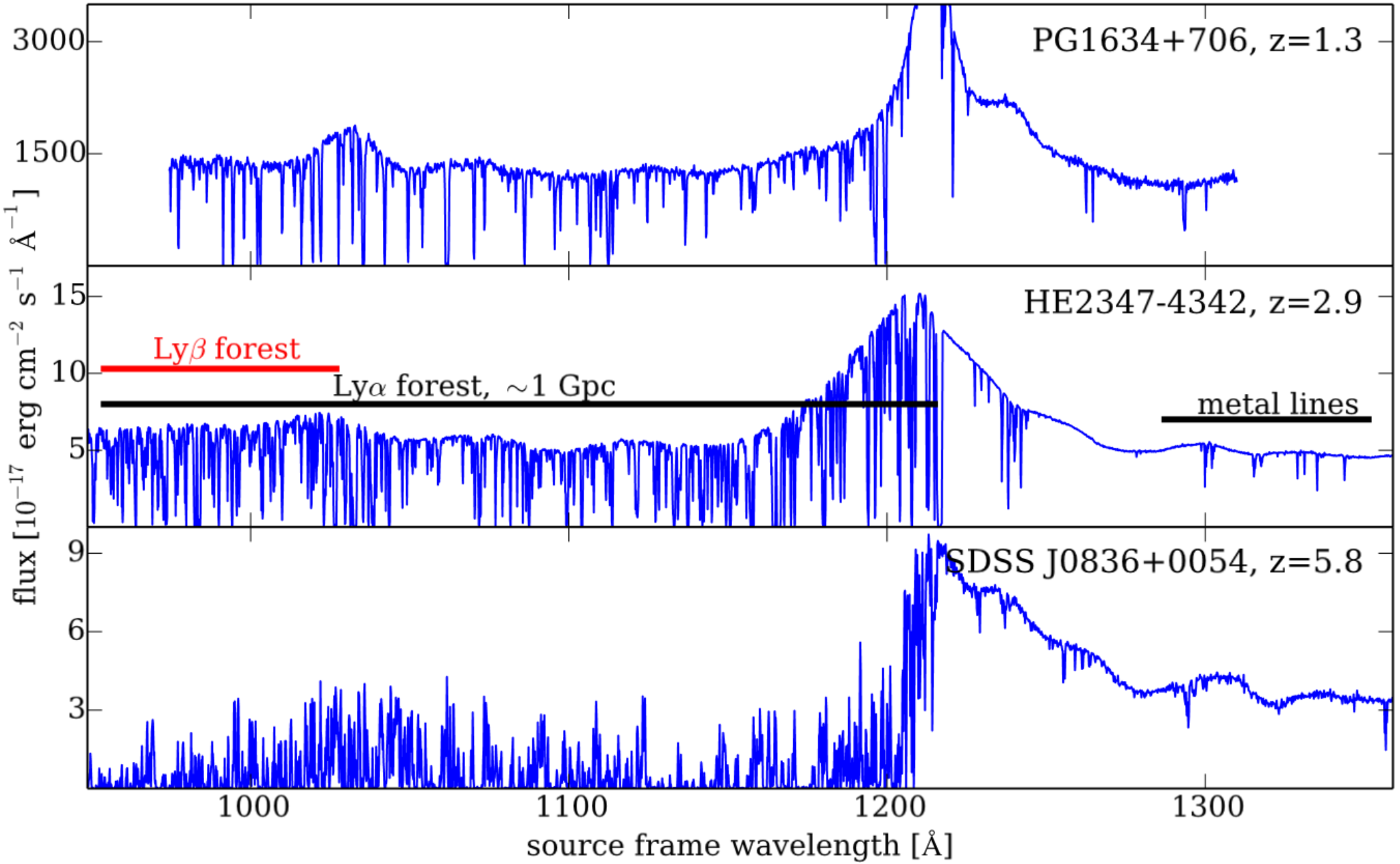
- The Ly α forest is formed in the spectrum of distant quasars, when the light of these quasars passes through multiple intergalactic H I clouds at different redshifts




PG1634+706, z=1.3
HE2347-4342, z=2.9
SDSS J0836+0054, z=5.8
Lyβ forest
Lyα forest, ∼1 Gpc
metal lines
flux [10^-17 erg cm^-2 s^-1 Å^-1]
source frame wavelength [Å]
3000
1500
15
10
5
9
6
3
1000
1100
1200
1300

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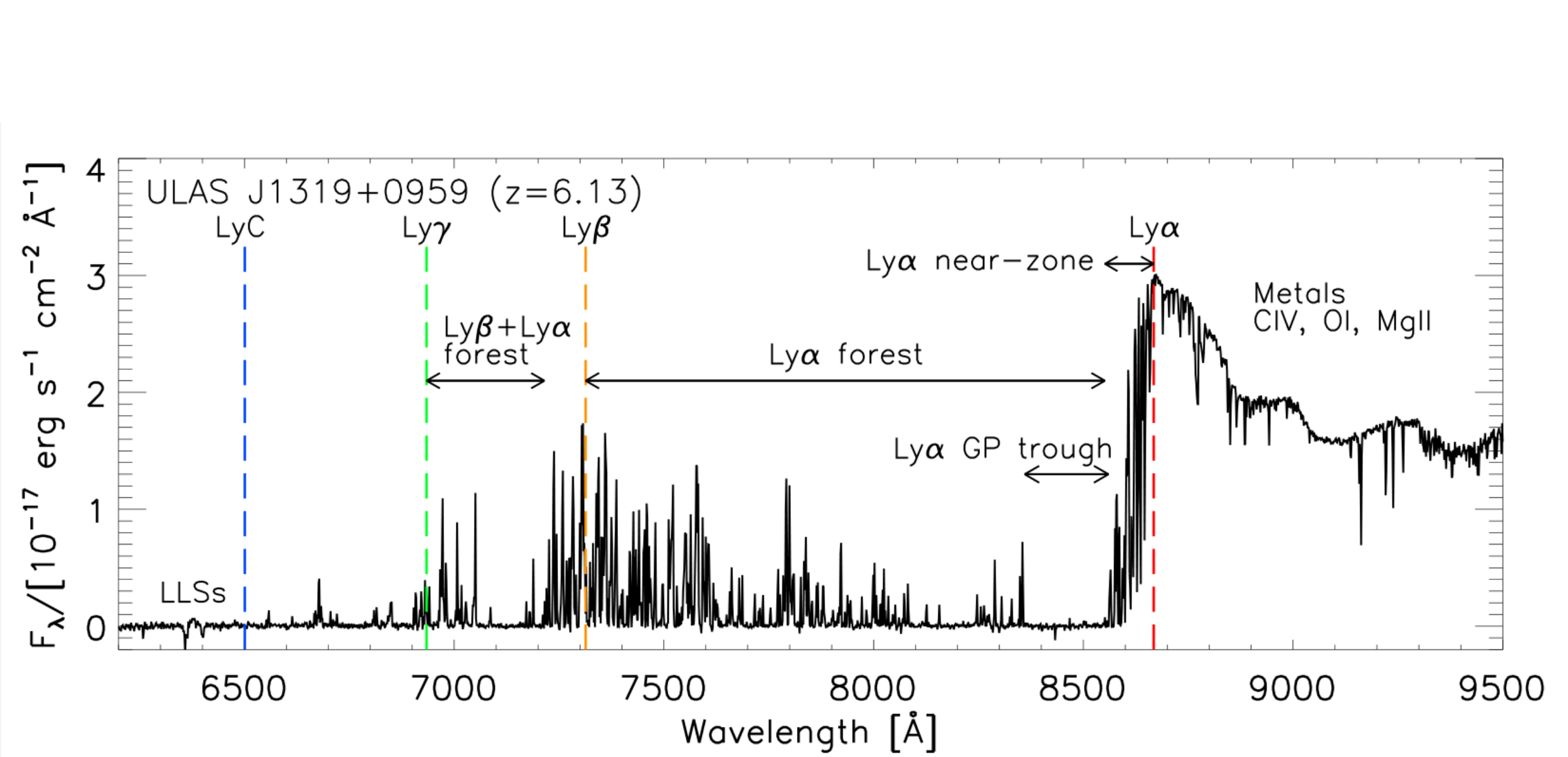
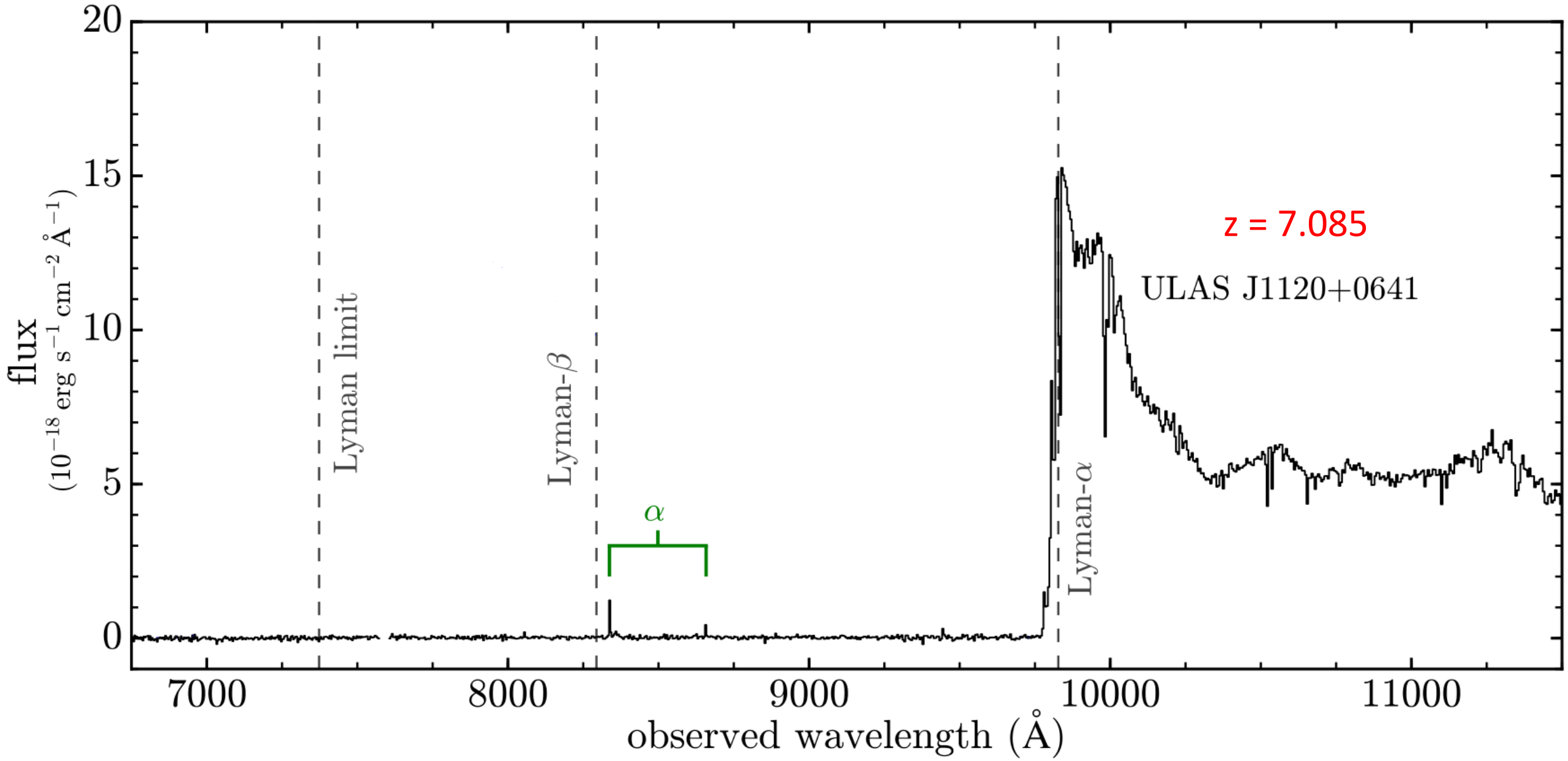
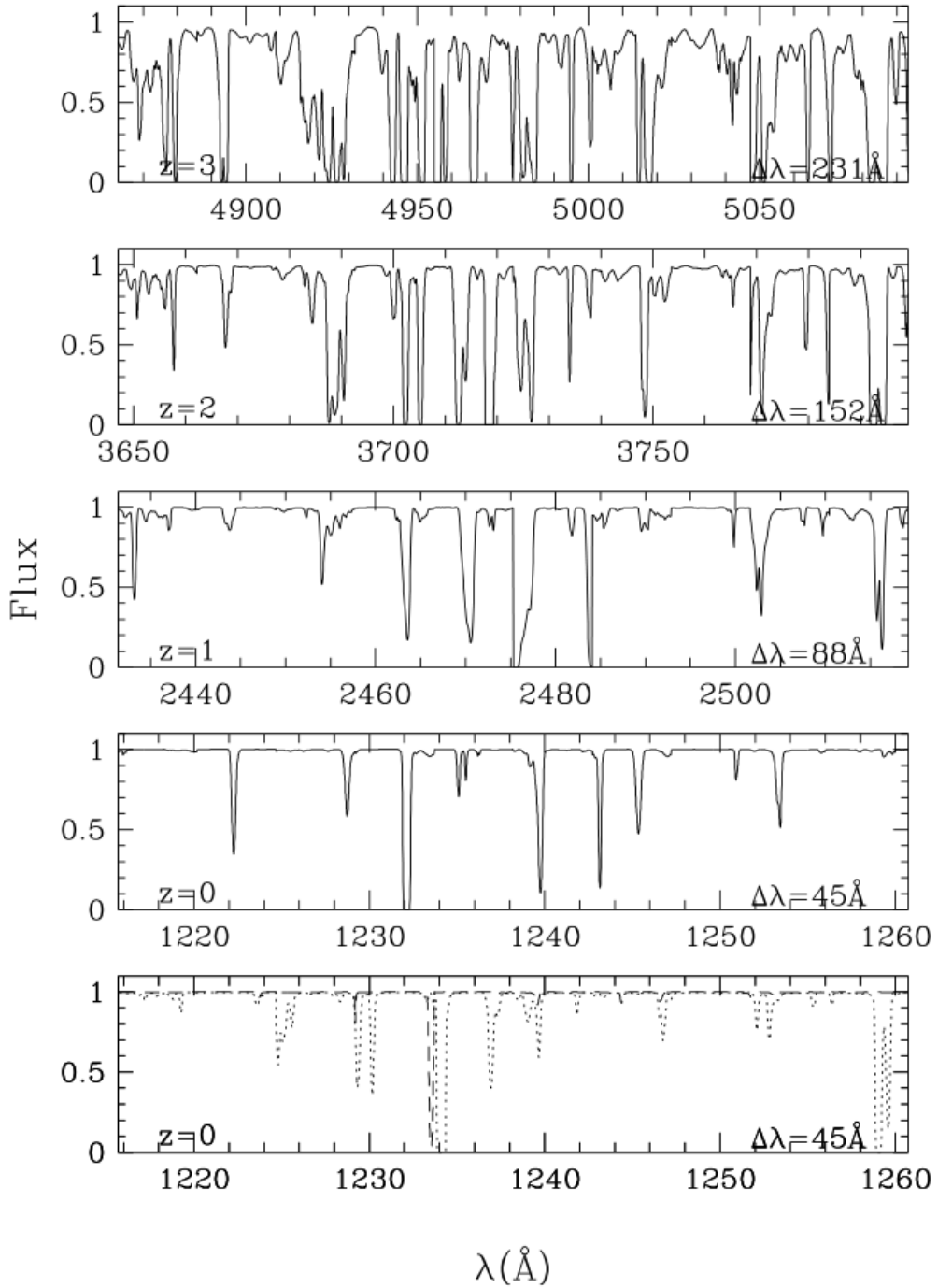
- The density of absorption lines increases with redshift, eventually resulting in a (Gunn-Peterson-)trough

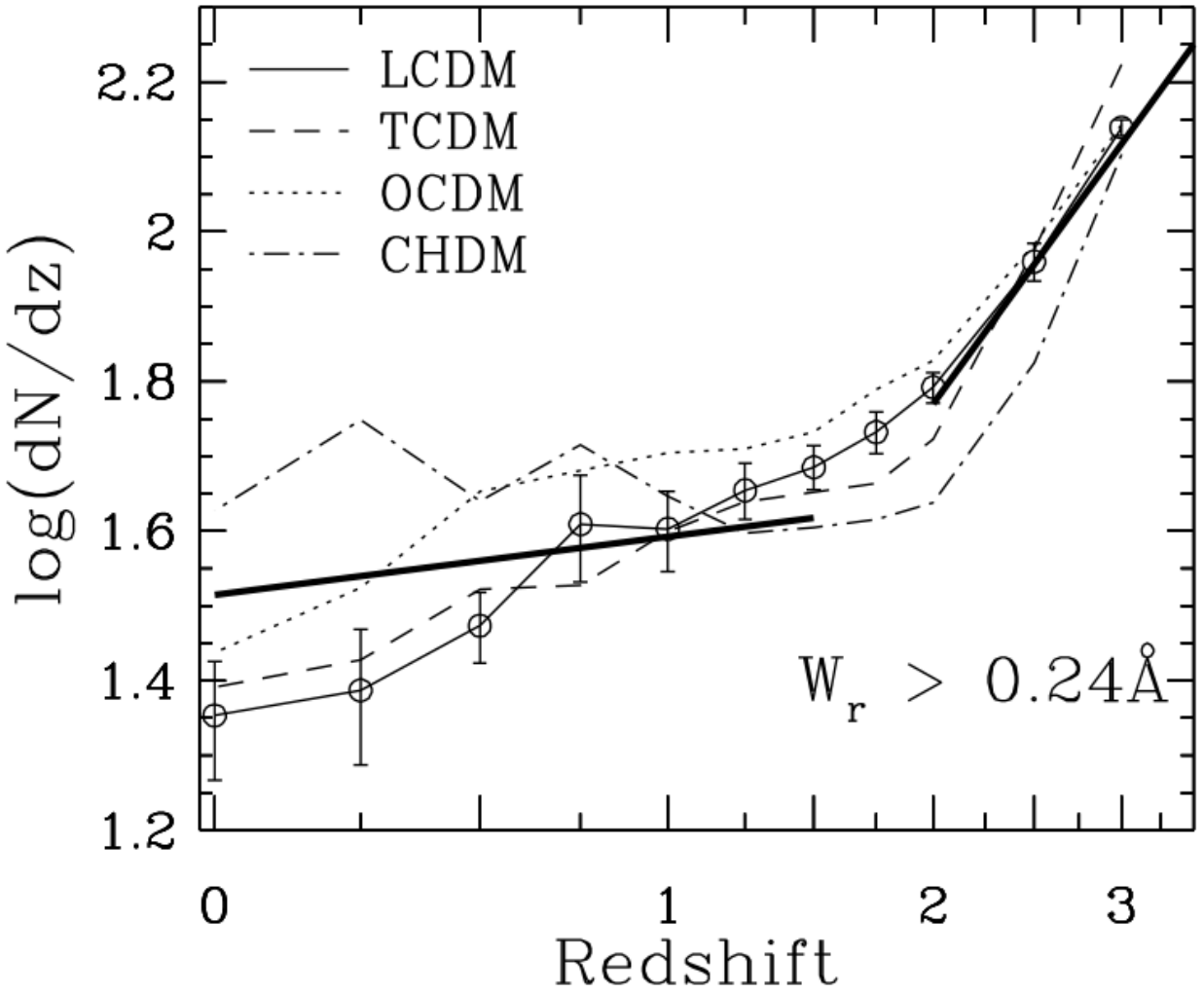

ULAS J1319+0959 (z=6.13)
LyC
Lyγ
Lyβ
Lyα
Lyα near−zone
Lyβ+Lyα forest
Lyα forest
Lyα GP trough
Metals CIV, OI, MgII
LLSs
$F_\lambda/[10^{-17}$ erg s^{-1} cm^{-2} Å$^{-1}]$
0
1
2
3
4
6500
7000
7500
8000
8500
9000
9500
Wavelength [Å]


20
15
10
5
0
flux
(10^{-18} erg s^{-1} cm^{-2} Å^{-1})
Lyman limit
Lyman-β
α
Lyman-α
z = 7.085
ULAS J1120+0641
7000
8000
9000
10000
11000
observed wavelength (Å)

The Ly α Forest - Simulations

- Davé, Hernquist and Weinberg (1999) and later Weinberg et al. (2003) succeed in using simulations, that can reproduce the Ly α forest qualitatively


Flux
z=3
Δλ=231Å
z=2
Δλ=152Å
z=1
Δλ=88Å
z=0
Δλ=45Å
z=0
Δλ=45Å
λ(Å)


LCDM
TCDM
OCDM
CHDM
log(dN/dz)
W_r > 0.24Å
Redshift

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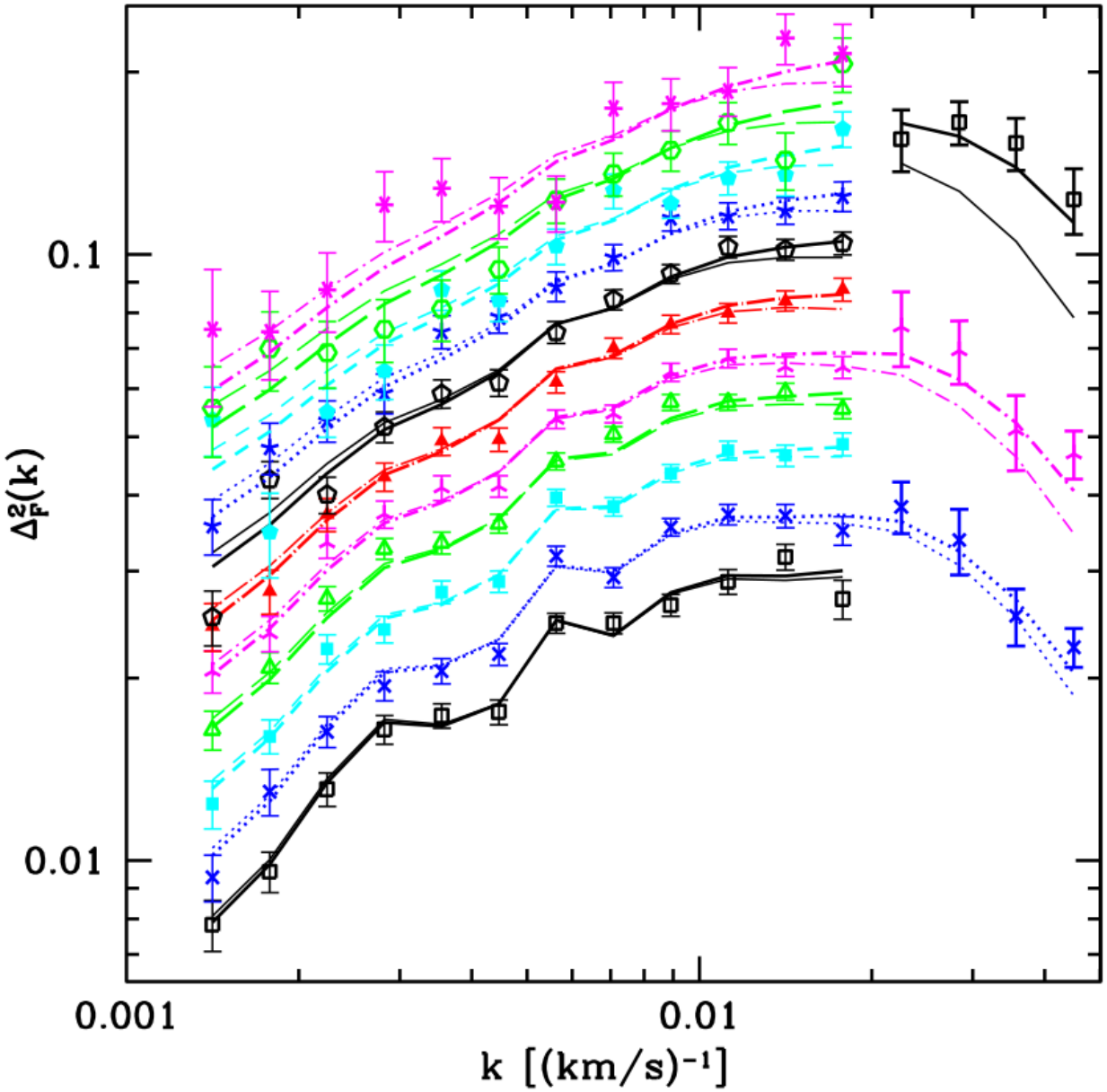
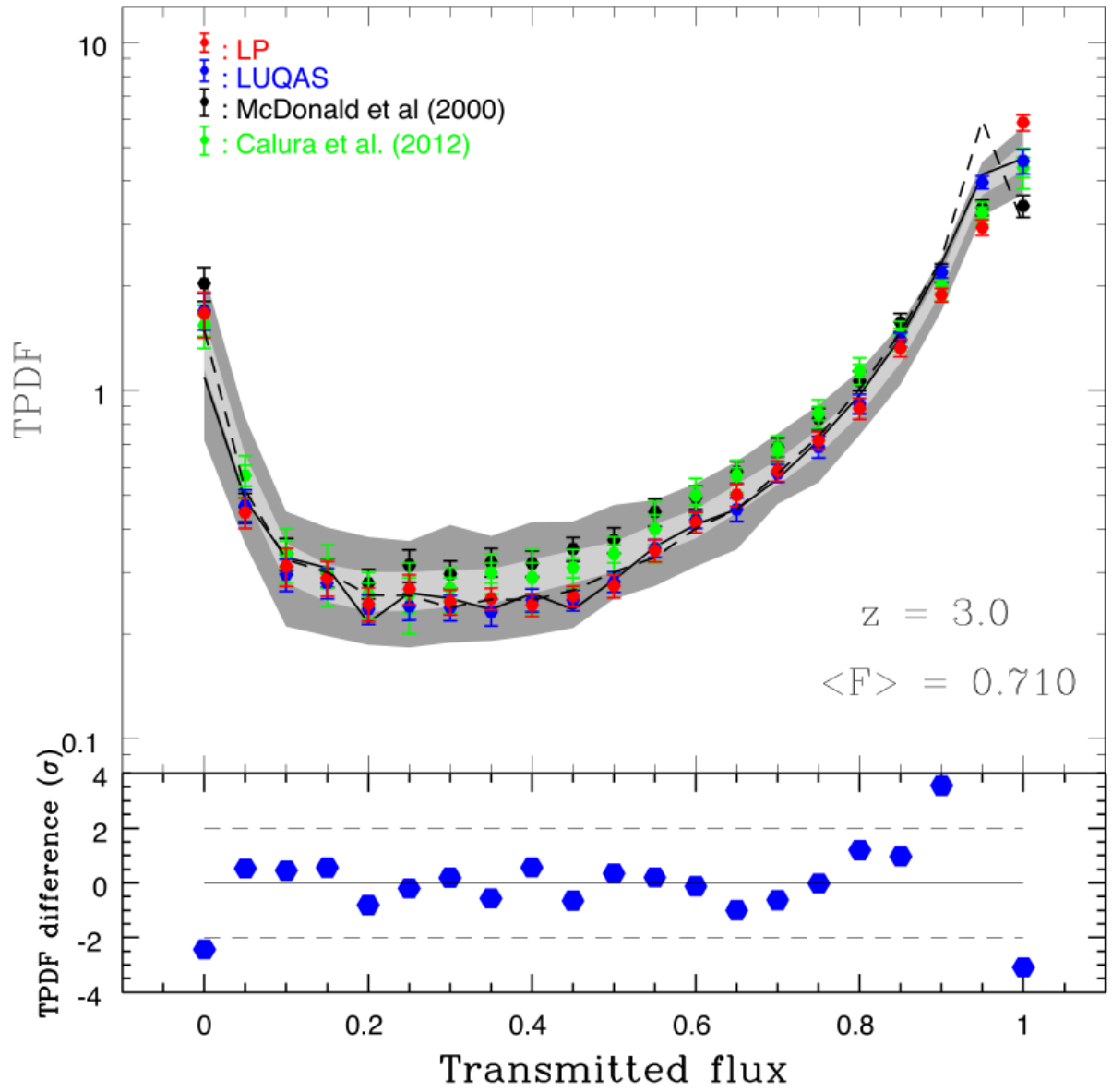

0.1
0.01
$\Delta_F^2(k)$
0.001
0.01
k [(km/s)$^{-1}$]


: LP
: LUQAS
: McDonald et al (2000)
: Calura et al. (2012)
TPDF
10
1
0.1
z = 3.0
<F> = 0.710
TPDF difference (σ)
4
2
0
-2
-4
0
0.2
0.4
0.6
0.8
1
Transmitted flux

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- Conclusion: models of the forest agree with the observations to $\sim$ 10% in the standard statistics

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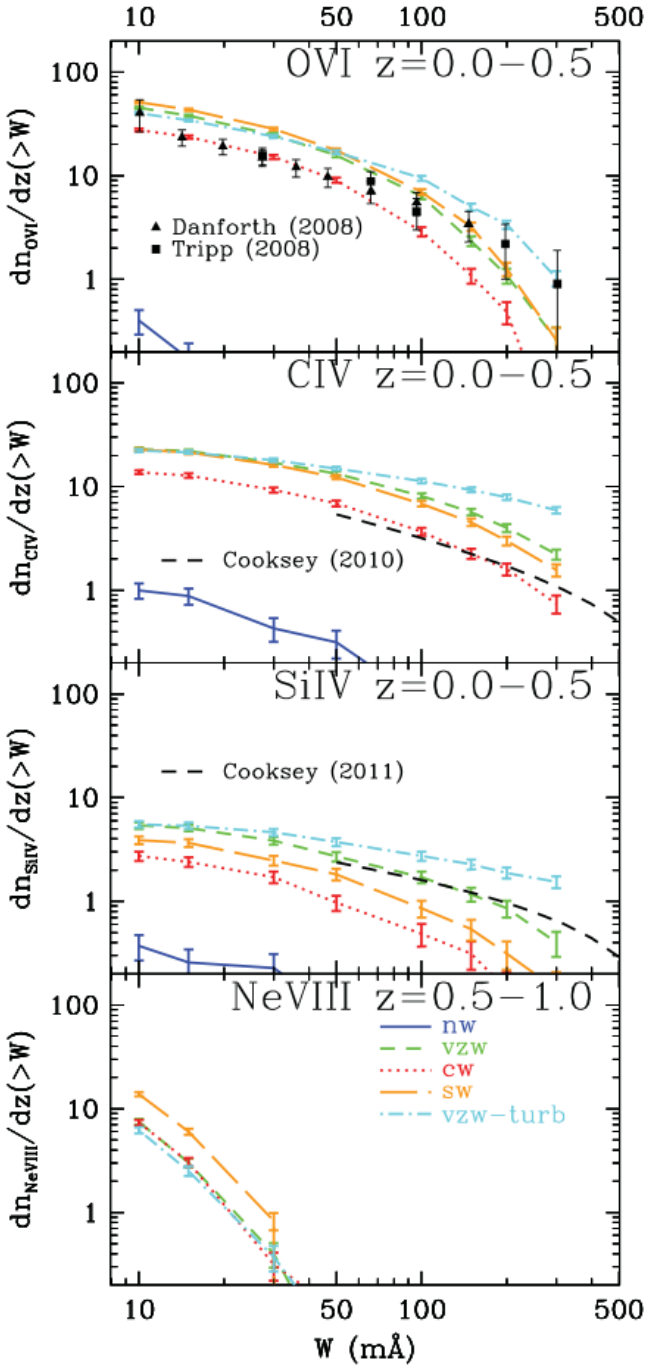
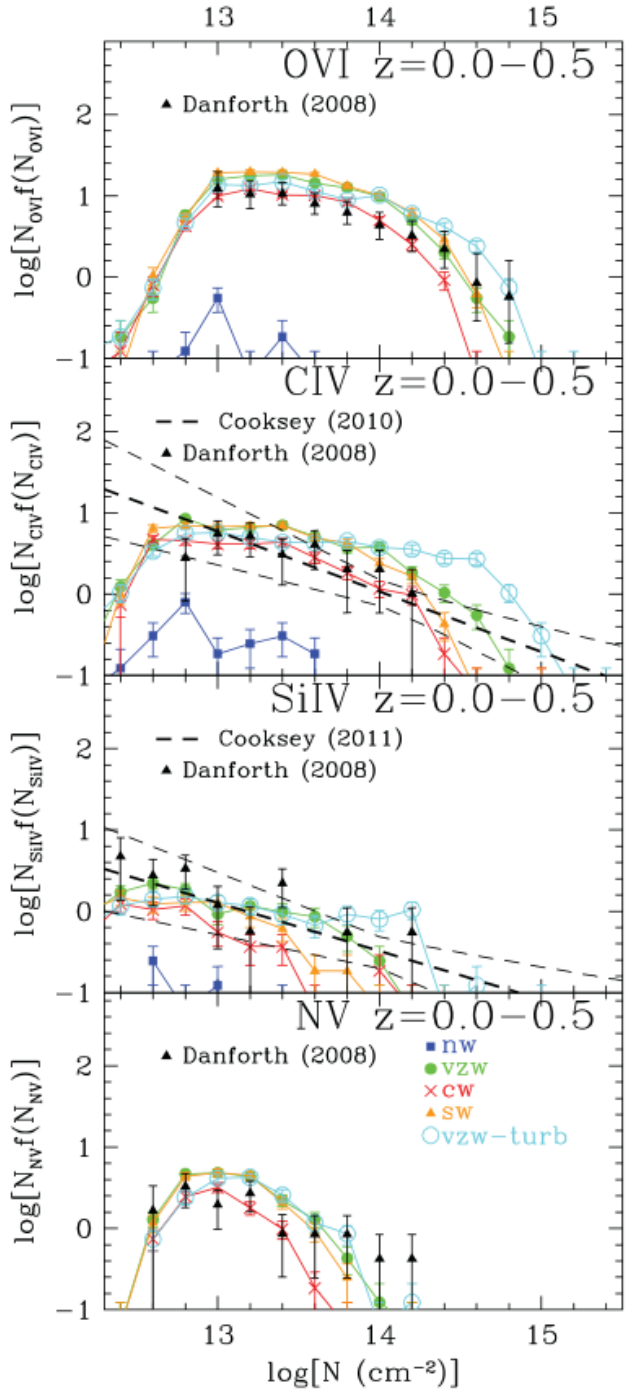
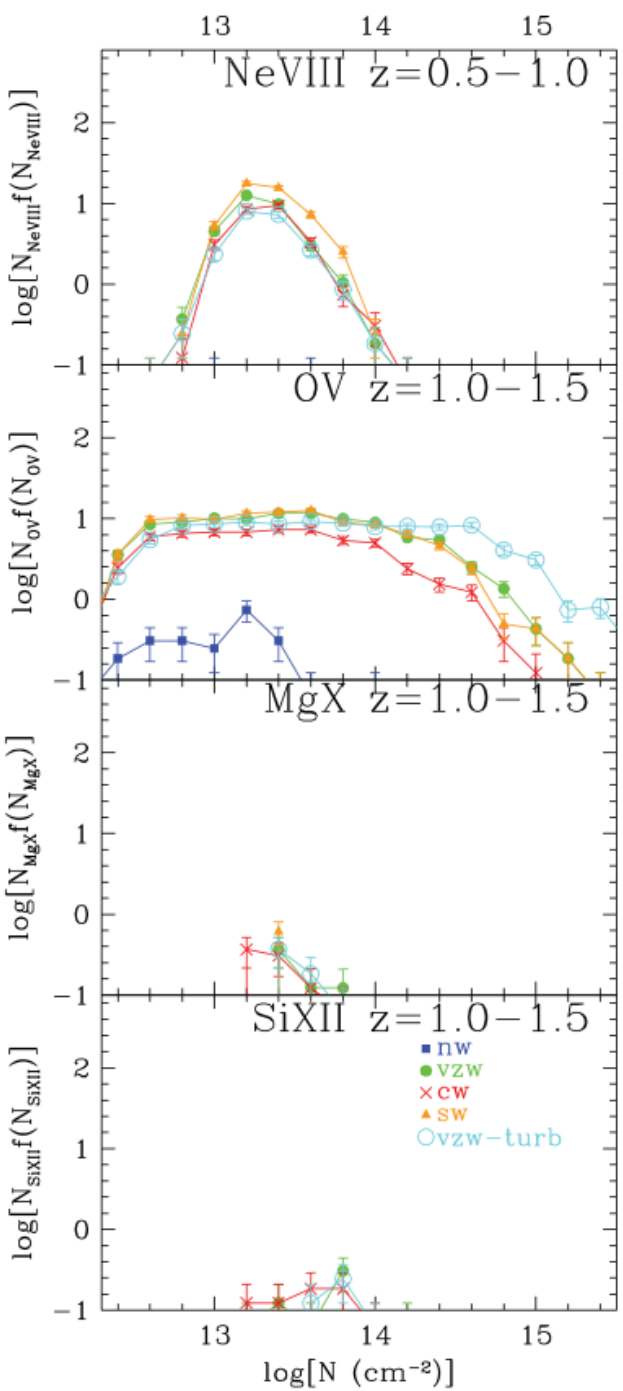
- Conclusion: models of the forest agree with the observations to $\sim 10\%$ in the standard statistics
- Possible limits of the models: low redshift region, where estimates find that only $30 \pm 10\%$ of the $z \sim 0$ gas is seen in Ly α absorption and that $\sim 10\%$ of the baryons lie within galaxies or reside as hot gas inside galaxy clusters, therefore a large fraction of baryons is “missing”

Metal Enrichment – Observation

- Stars did not only ionize the IGM, but the radiation pressure of the stars, combined with supernovae action, powered winds that enriched the IGM with metals
- Metallicity of the IGM is very sensitive to the processes of galaxy formation and evolution (galactic outflows suppress star formation and therefore metal production, but concurrently distribute metals into haloes and the IGM)


OVI z=0.0−0.5
Danforth (2008)
Tripp (2008)
CIV z=0.0−0.5
Cooksey (2010)
SiIV z=0.0−0.5
Cooksey (2011)
NeVIII z=0.5−1.0
nw
vzw
cw
sw
vzw−turb
W (mÅ)


OVI z=0.0−0.5
Danforth (2008)
CIV z=0.0−0.5
Cooksey (2010)
Danforth (2008)
SiIV z=0.0−0.5
Cooksey (2011)
Danforth (2008)
NV z=0.0−0.5
Danforth (2008)
nw
vzw
cw
sw
vzw−turb
log[N (cm⁻²)]


NeVIII z=0.5−1.0
OV z=1.0−1.5
MgX z=1.0−1.5
SiXII z=1.0−1.5
nw
vzw
cw
sw
vzw−turb
log[N (cm⁻²)]

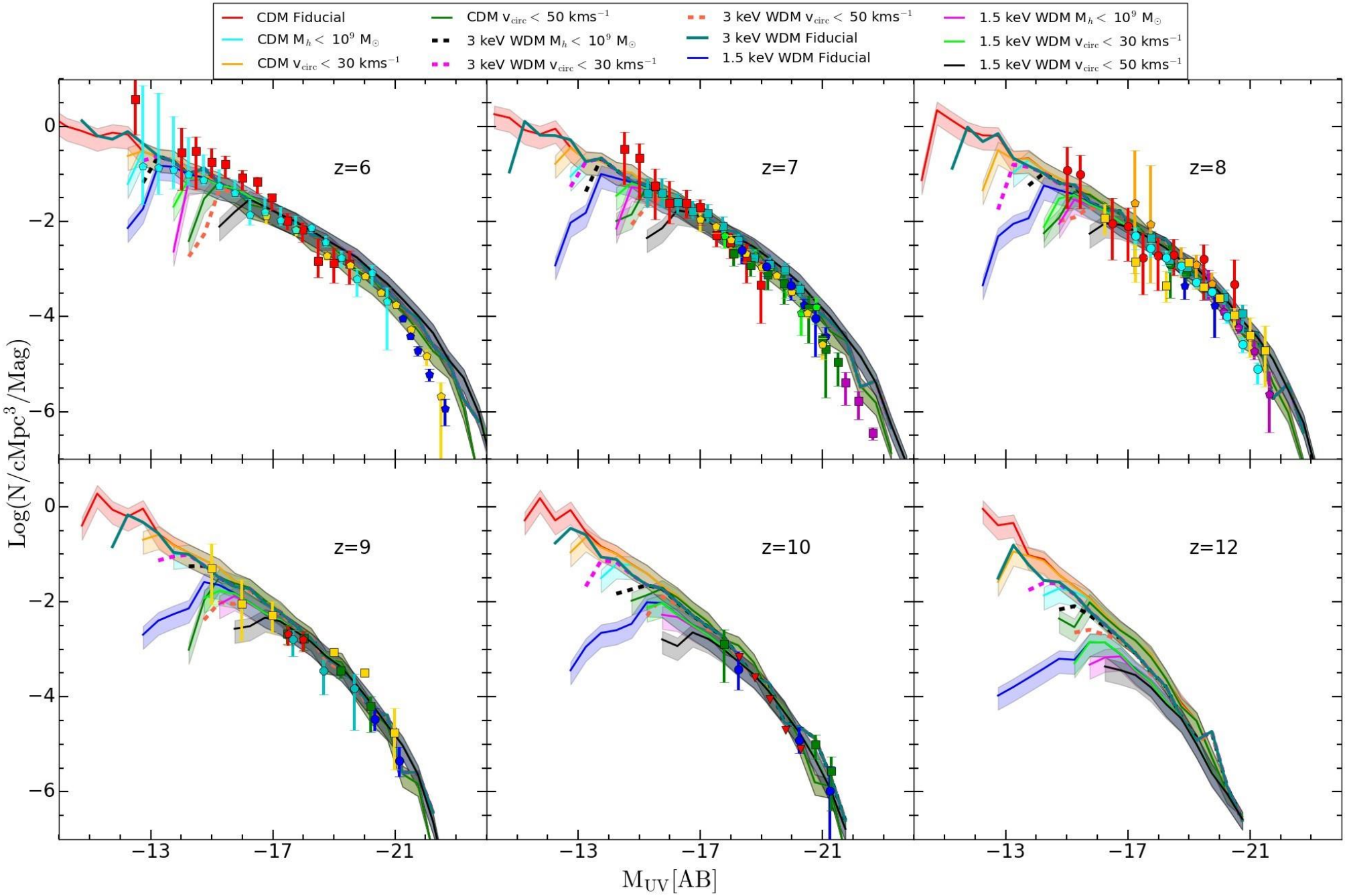
Metal Enrichment – Simulations

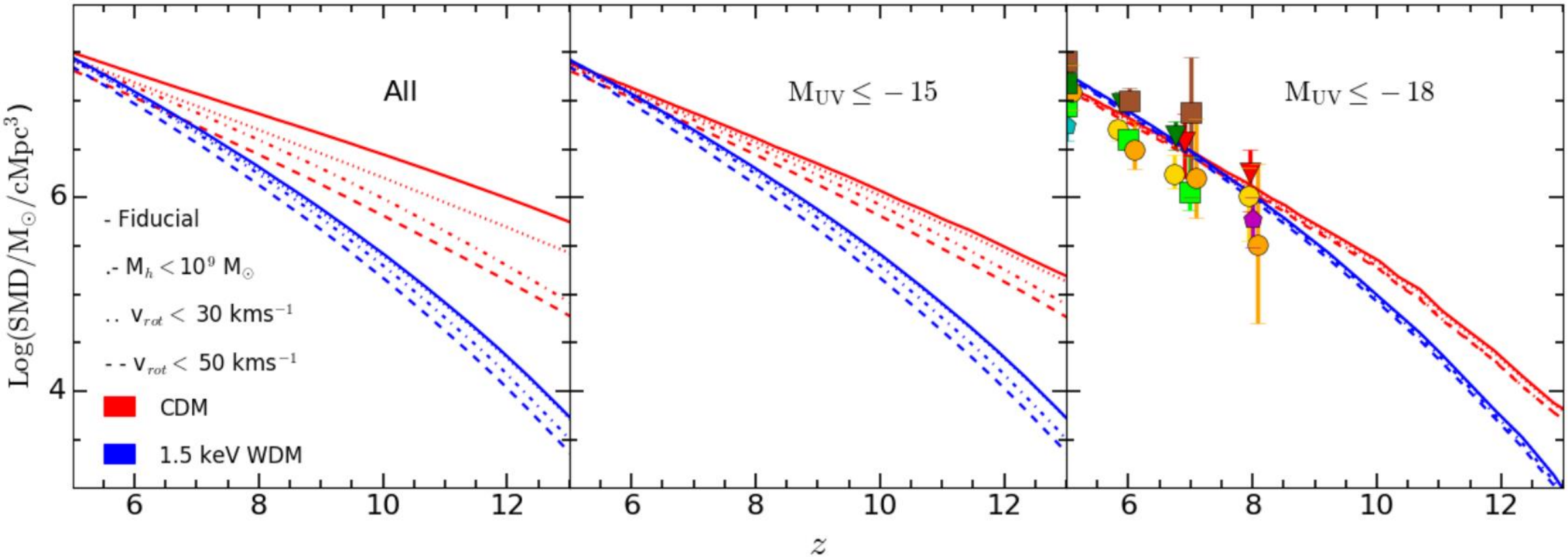
Main result of simulations done by Oppenheimer, Davé et al. (2012):

- Several simulations are compatible with current measurements, so no particular model sticks out
- The exact process of the metal enrichment depends on many parameters (such as different phases of the IGM, the strength of galactic winds etc.)
- 20% of the metals reside outside of halos at $z \sim 2$ and only 4% at $z \sim 0$ (in favoured vzw model)
- Therefore, the majority of metals today reside within galaxies, in contrast to the bulk of baryons that reside outside haloes

Metal Enrichment - Dark Matter Implications

- Bremer, Dayal and Ryan-Weber (2018) examine the constraints that the metallicity of the IGM gives for different Dark Matter cosmologies
- Idea: 1.5 keV WDM models have much less bound DM in low mass halos than CDM models, therefore these halos have lower gravitational potential, resulting in less metals produced and less metals distributed to the IGM
- The semi-analytic model Delphi (**D**ark Matter and the **e**mergence of ga**l**axies in the **e**poc**h** of re**i**onization) tracks DM and baryonic assembly of high-redshift ($z \geq 4$) galaxies


CDM Fiducial
CDM $M_h < 10^9$ $M_\odot$
CDM $v_{circ} < 30$ kms^{-1}
CDM $v_{circ} < 50$ kms^{-1}
3 keV WDM $M_h < 10^9$ $M_\odot$
3 keV WDM $v_{circ} < 30$ kms^{-1}
3 keV WDM $v_{circ} < 50$ kms^{-1}
3 keV WDM Fiducial
1.5 keV WDM Fiducial
1.5 keV WDM $M_h < 10^9$ $M_\odot$
1.5 keV WDM $v_{circ} < 30$ kms^{-1}
1.5 keV WDM $v_{circ} < 50$ kms^{-1}
z=6
z=7
z=8
z=9
z=10
z=12
Log(N/cMpc^3/Mag)
M_{UV}[AB]
0
−2
−4
−6
−13
−17
−21


All
$M_{UV} \leq -15$
$M_{UV} \leq -18$
- Fiducial
.- $M_h < 10^9$ $M_\odot$
.. $v_{rot} <$ 30 kms^{-1}
- - $v_{rot} <$ 50 kms^{-1}
CDM
1.5 keV WDM
Log(SMD/$M_\odot$/cMpc^3)
z
4
6
6
8
10
12
6
8
10
12
6
8
10
12

Metal Enrichment - Dark Matter Implications

Results of Bremer, Dayal and Ryan-Weber (2018):

- UV luminosity functions are consistent with CDM and the 3 keV and 1.5 keV models
- All models consistent with observations of stellar mass density and cosmic mass density
- Ejected gas mass densities seem to be consistent
- Problem: only bright galaxies $M_{UV} \leq -18$ well observed, need to measure magnitudes down to at least $M_{UV} = -16.5$ to distinguish between CDM and WDM
- However: older simulations by Simcoe et al. (2011) rule out all models except CDM and 3 keV WDM at $1.6\ \sigma$

Summary

- The intergalactic medium consists mostly of H I /H II, He II /He III and traces of ionized metals, which can all be identified by their absorption lines in the spectrum of quasars
- H I Ly α forest in the intermediate redshifts $z \sim 2 - 5$ is well studied and models match the observations to $\sim 10\%$
- Several models for the metal enrichment of the IGM through galactic winds proposed, none of which is fully consistent with the observations so far
- In theory, one can find constraints for the Dark Matter from measurements of the IGM metallicity and Bremer et al. (2018) suggest indeed that by combining several models and datasets along with more precise UV measurements of galaxies one might rule out all Dark Matter candidates but CDM

Open Questions

- What are the exact sources and mechanisms of reionization?
- Why is the metallicity of the IGM at $z \sim 0$ lower compared to $z \sim 2$?
- Where are the missing baryons at $z \sim 0$?
- How do galaxies interact with the IGM?

Thank you for listening!

Most important sources

- M. McQuinn. *The Evolution of the Intergalactic Medium*. Annual Review of Astronomy and Astrophysics, vol. 54, p.313-362, 2016.
- G. D. Becker, J. S. Bolton, and A. Lidz. *Reionization and high-redshift galaxies: the view from quasar absorption lines*. Publications of the Astronomical Society of Australia, Volume 32, id.e045 29 pp., 2015.
- R. Dave and L. Hernquist. *The Low Redshift Lyman Alpha Forest in Cold Dark Matter Cosmologies*. The Astrophysical Journal, Volume 511, Issue 2, pp. 521-545., 1999.
- B. D. Oppenheimer, R. Dave, et al. *The intergalactic medium over the last 10 billion years - II. Metal-line absorption and physical conditions*. Monthly Notices of the Royal Astronomical Society, Volume 420, Issue 1, pp. 829-859, 2012.
- Jonas Bremer, Pratika Dayal, and Emma Ryan-Weber. *Probing the nature of Dark Matter through the metal enrichment of the intergalactic medium*. MNRAS, Volume 477, Issue 2, p.2154-2163, 2018.