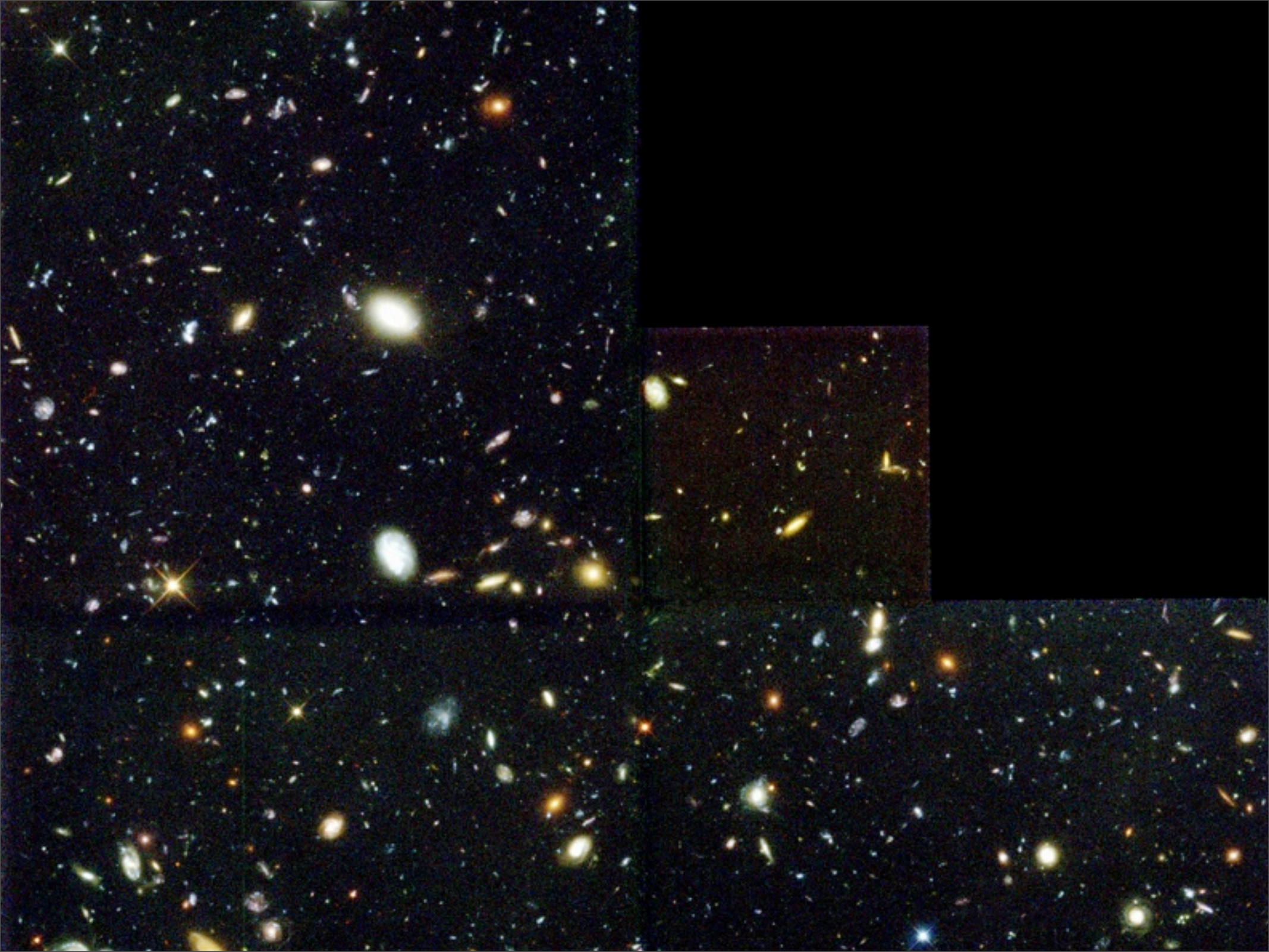
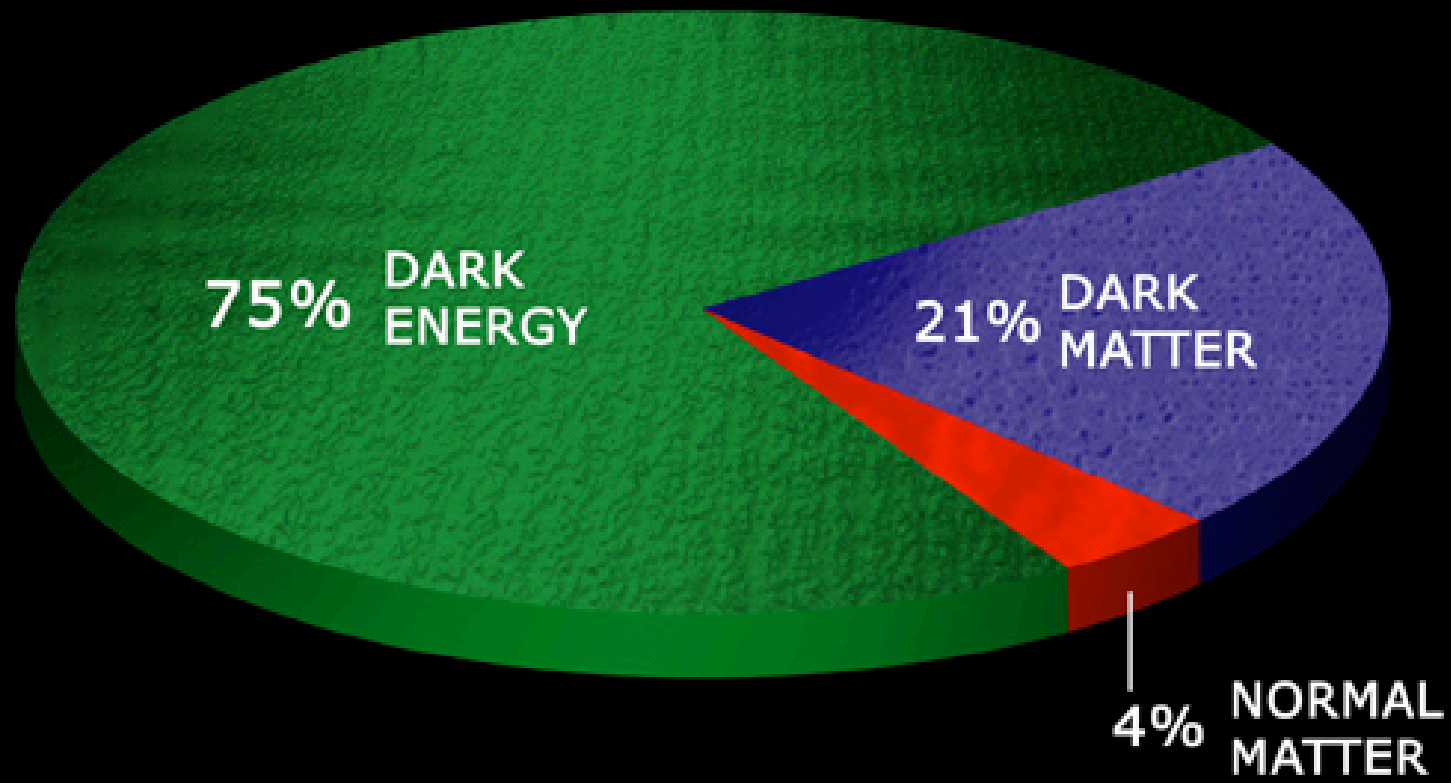


The intergalactic medium

3 sessions:

1. What do we expect to see?
2. What do we see?
3. What can we learn from the IGM?
4. Examples as home work

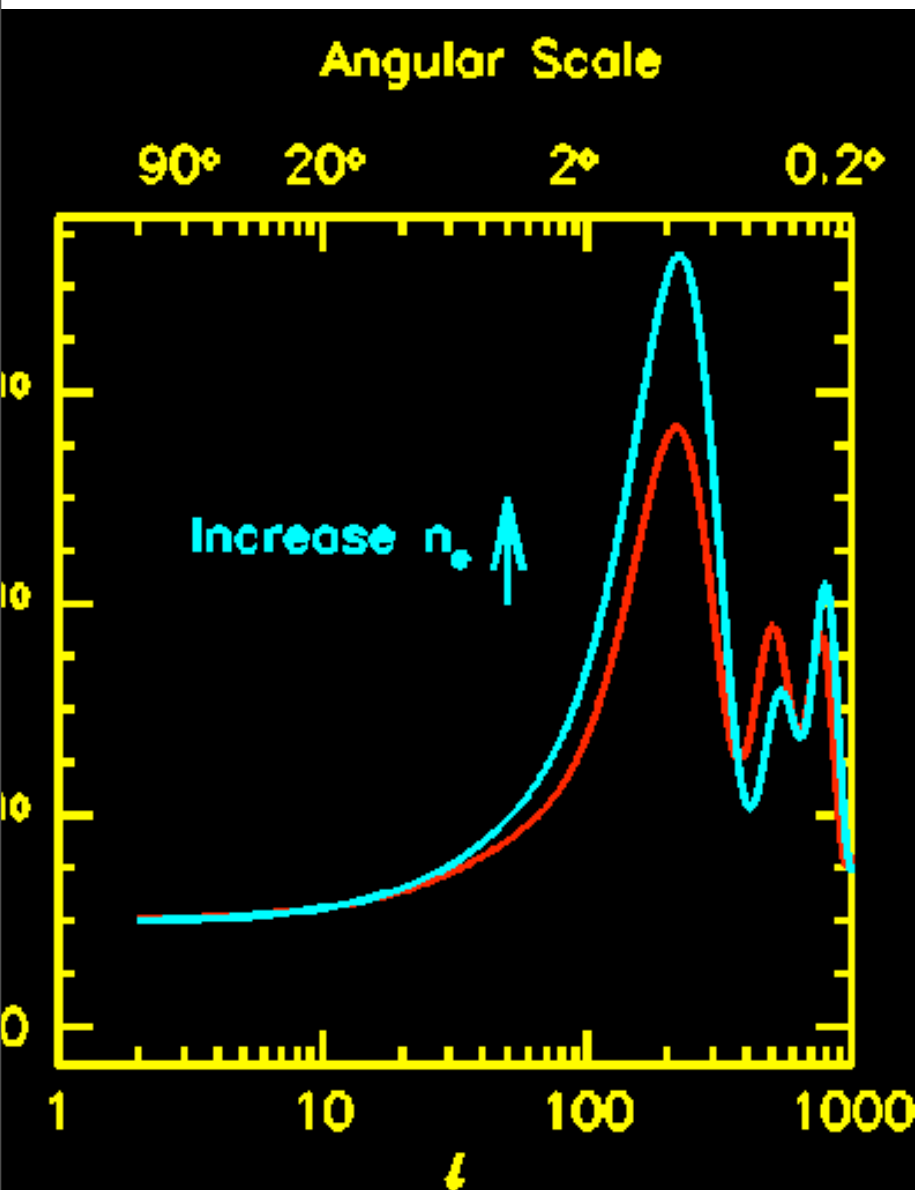




How do we know the baryon density?

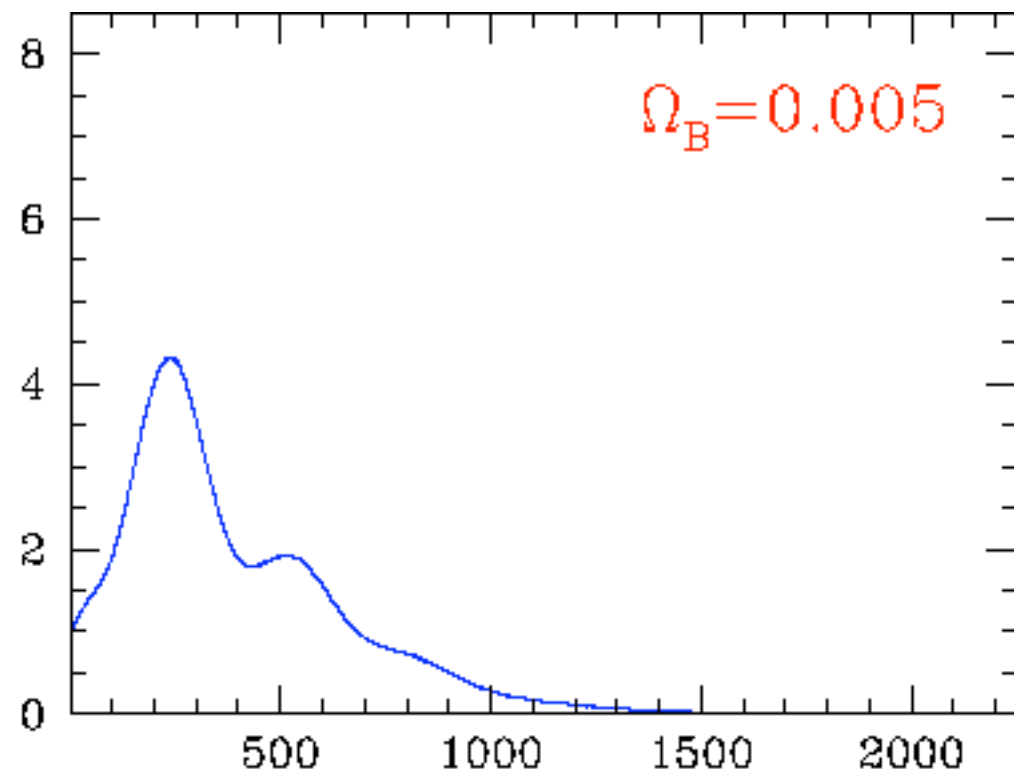
How do we know baryon density?

- CMB
- BBN
- Clusters

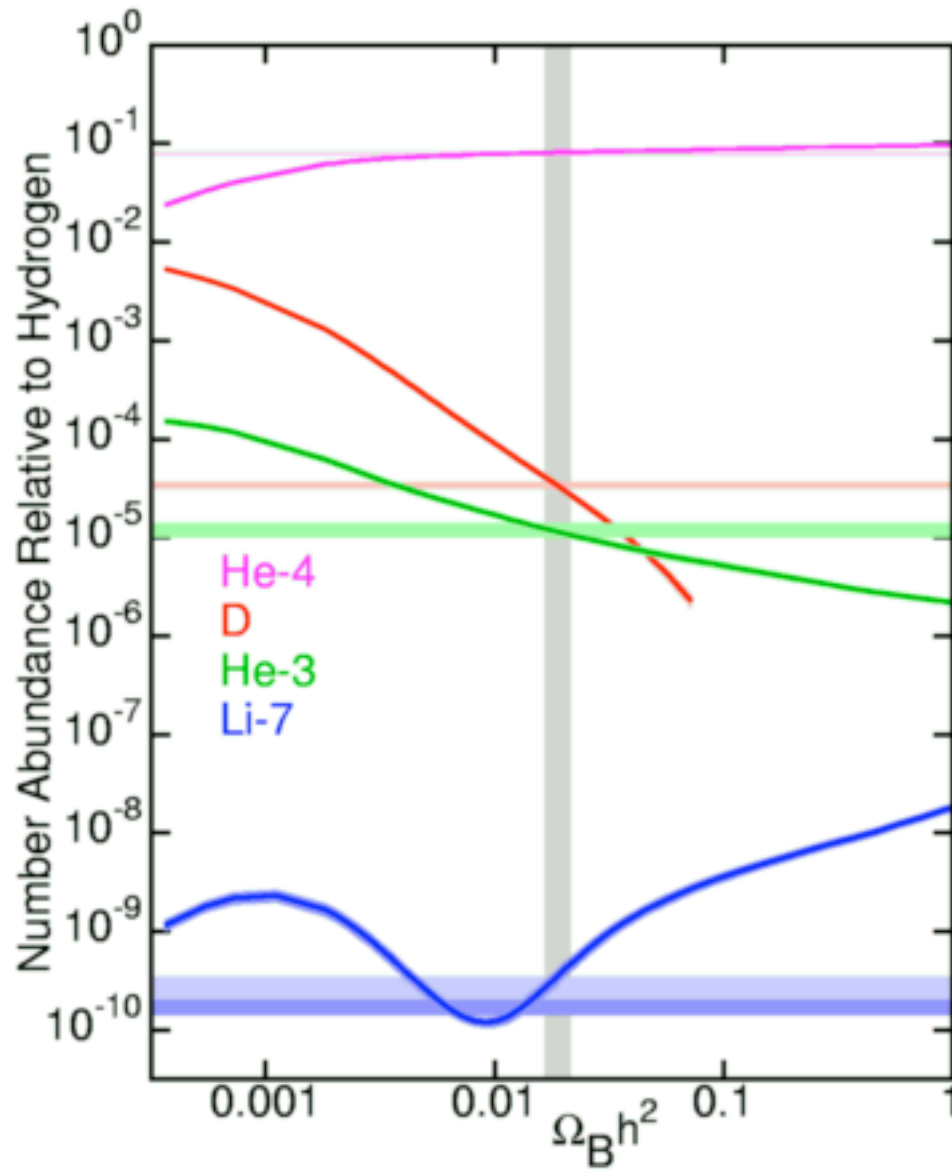


WMAP

$l(l+1)C_l$ (Power)



Wayne Hu



BBN

How do we know how many baryons are in stars?

Where are the baryons?

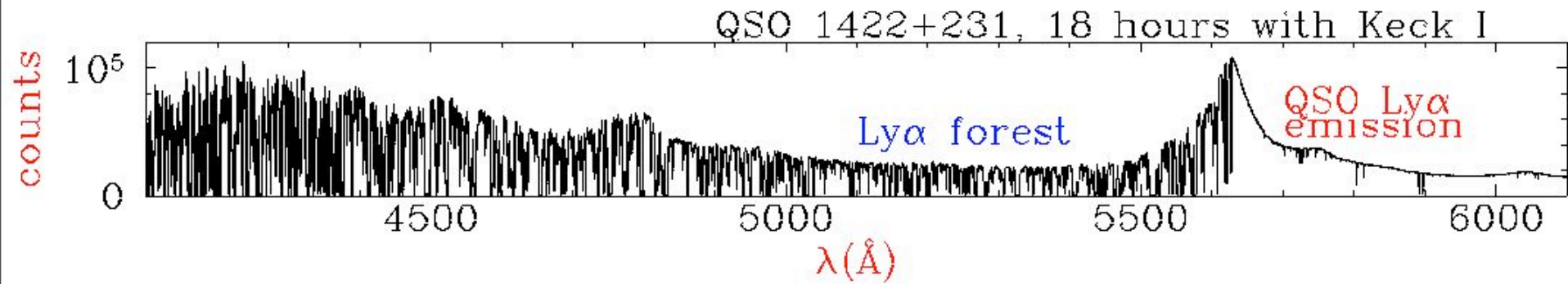
Table 3. The Baryon Budget

Component	Central	Maximum	Minimum	Grade ^a
Observed at $z \approx 0$:				
1 stars in spheroids	$0.0026h_{70}^{-1}$	$0.0043h_{70}^{-1}$	$0.0014h_{70}^{-1}$	A
2 stars in disks	$0.00086h_{70}^{-1}$	$0.00129h_{70}^{-1}$	$0.00051h_{70}^{-1}$	A-
3 stars in irregulars	$0.000069h_{70}^{-1}$	$0.000116h_{70}^{-1}$	$0.000033h_{70}^{-1}$	B
4 neutral atomic gas	$0.00033h_{70}^{-1}$	$0.00041h_{70}^{-1}$	$0.00025h_{70}^{-1}$	A
5 molecular gas	$0.00030h_{70}^{-1}$	$0.00037h_{70}^{-1}$	$0.00023h_{70}^{-1}$	A-
6 plasma in clusters	$0.0026h_{70}^{-1.5}$	$0.0044h_{70}^{-1.5}$	$0.0014h_{70}^{-1.5}$	A
7a warm plasma in groups	$0.0056h_{70}^{-1.5}$	$0.0115h_{70}^{-1.5}$	$0.0029h_{70}^{-1.5}$	B
7b cool plasma	$0.002h_{70}^{-1}$	$0.003h_{70}^{-1}$	$0.0007h_{70}^{-1}$	C
7' plasma in groups	$0.014h_{70}^{-1}$	$0.030h_{70}^{-1}$	$0.0072h_{70}^{-1}$	B
8 sum (at $h = 70$ and $z \simeq 0$)	0.021	0.041	0.007	...
Gas components at $z \approx 3$:				
9 damped absorbers	$0.0015h_{70}^{-1}$	$0.0027h_{70}^{-1}$	$0.0007h_{70}^{-1}$	A-
10 Lyman- α forest clouds	$0.04h_{70}^{-1.5}$	$0.05h_{70}^{-1.5}$	$0.01h_{70}^{-1.5}$	B
11 intercloud gas (HeII)	...	$0.01h_{70}^{-1.5}$	$0.0001h_{70}^{-1}$	B
Abundances of:				
12 deuterium	$0.04h_{70}^{-2}$	$0.054h_{70}^{-2}$	$0.013h_{70}^{-2}$	A
13 helium	$0.010h_{70}^{-2}$	$0.027h_{70}^{-2}$		A
14 Nucleosynthesis	$0.020h_{70}^{-2}$	$0.027h_{70}^{-2}$	$0.013h_{70}^{-2}$...

^aConfidence of evaluation, from A (robust) to C (highly uncertain)

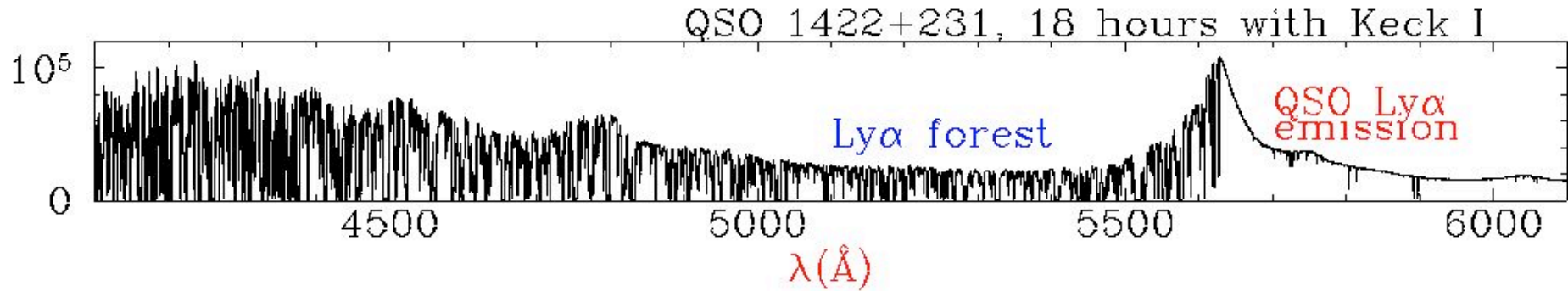
Let's do a simple case: a homogeneous Universe

QSO 1422+231



or: where did we go wrong?

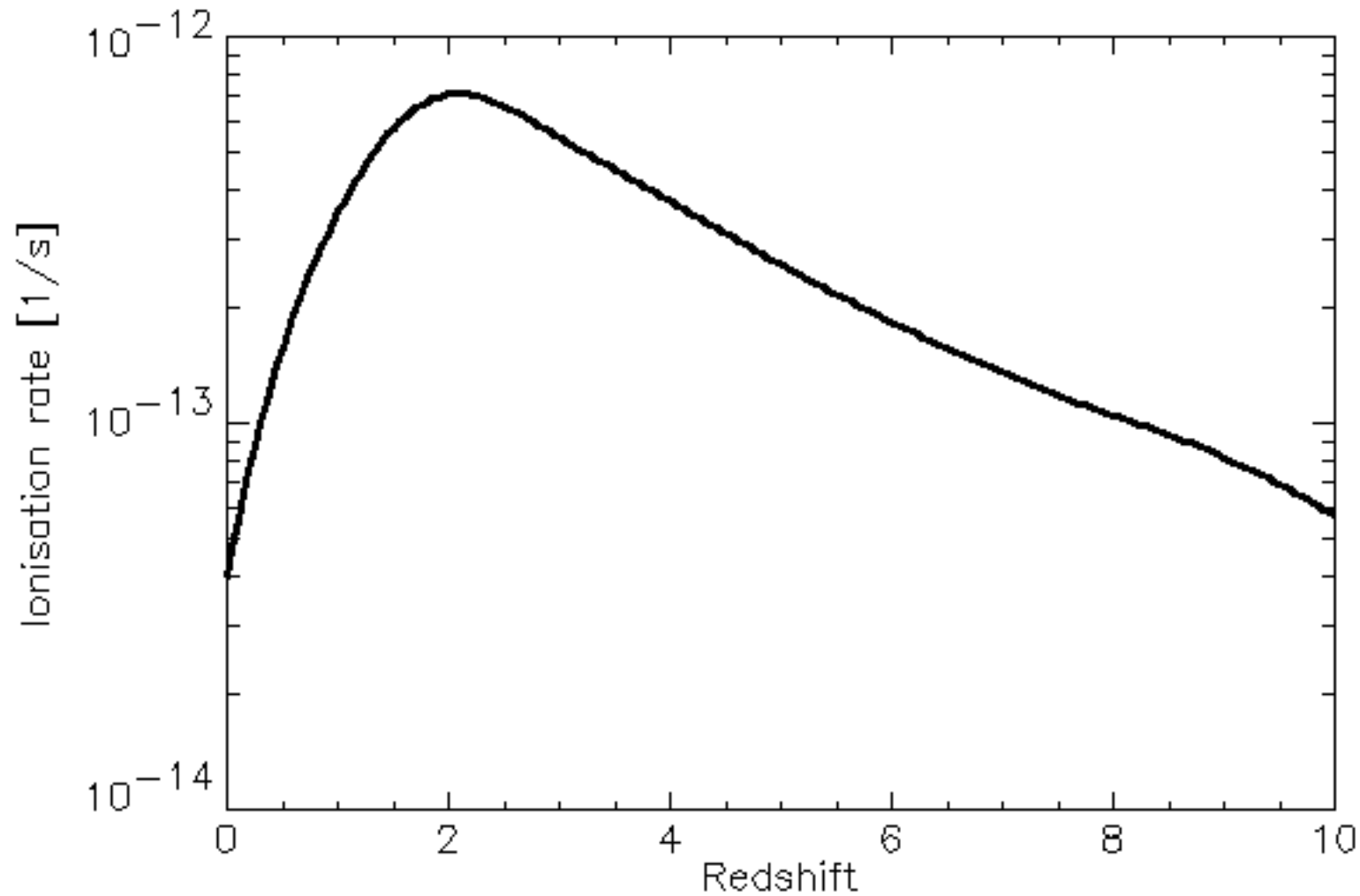
QSO 1422+231



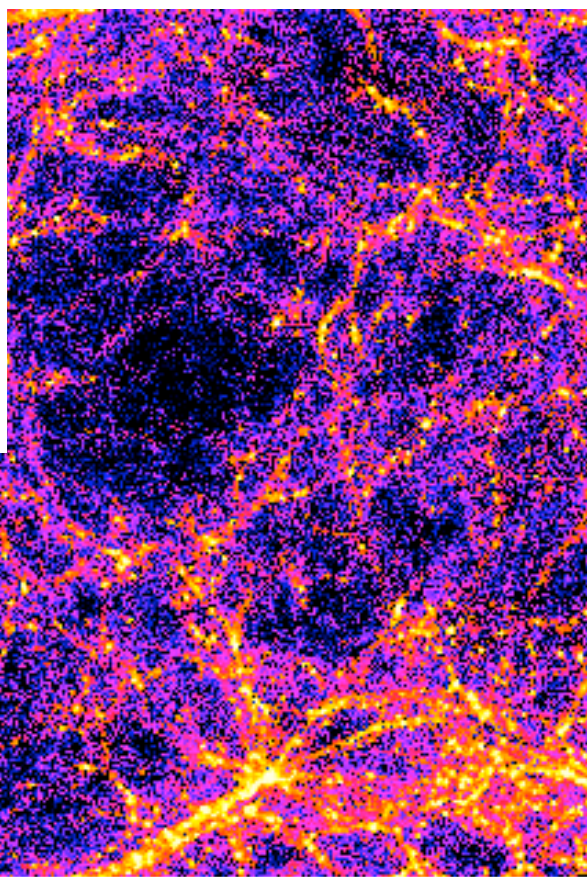
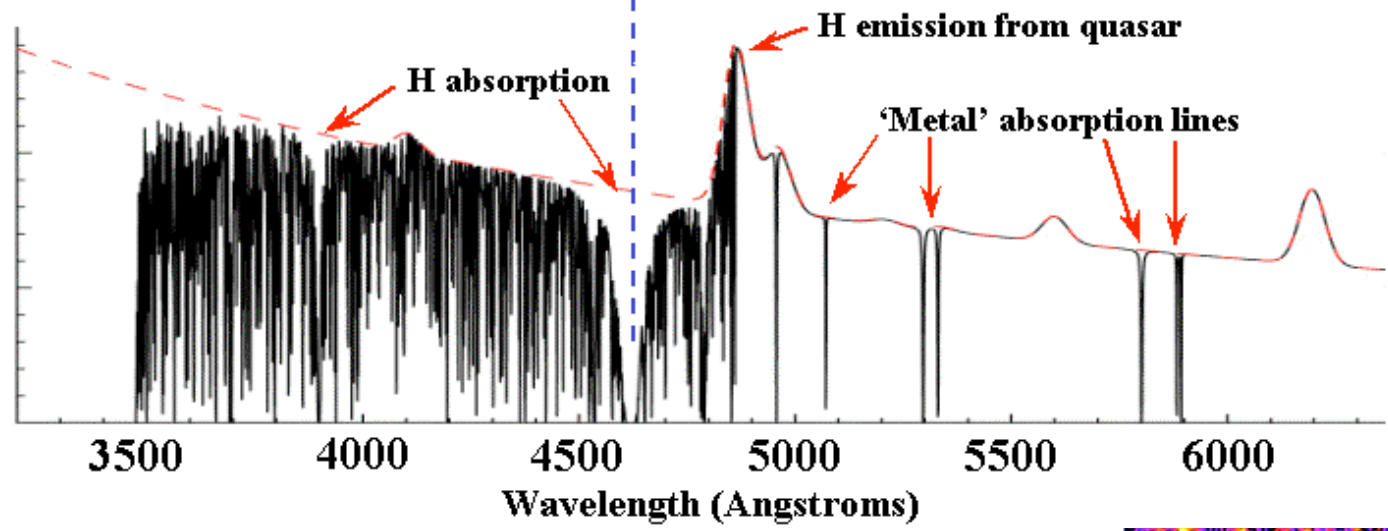
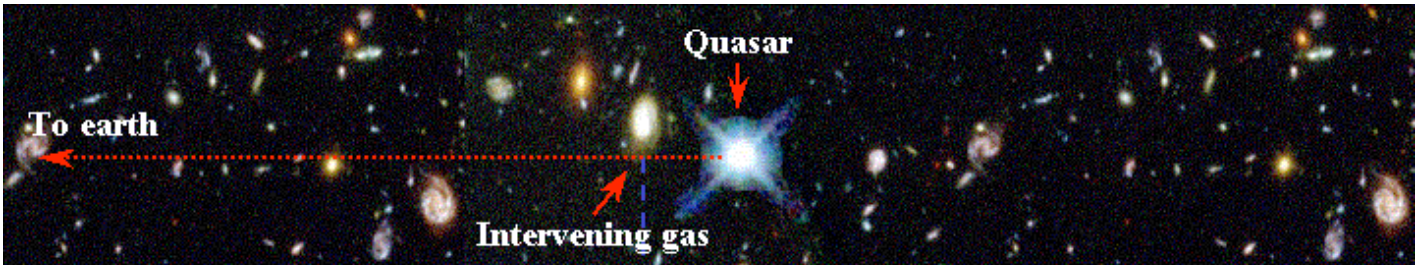
Things to consider:

- Is there a Lyman-beta forest? Where?
- Is there a Balmer-alpha forest? Where?
- How about Helium?

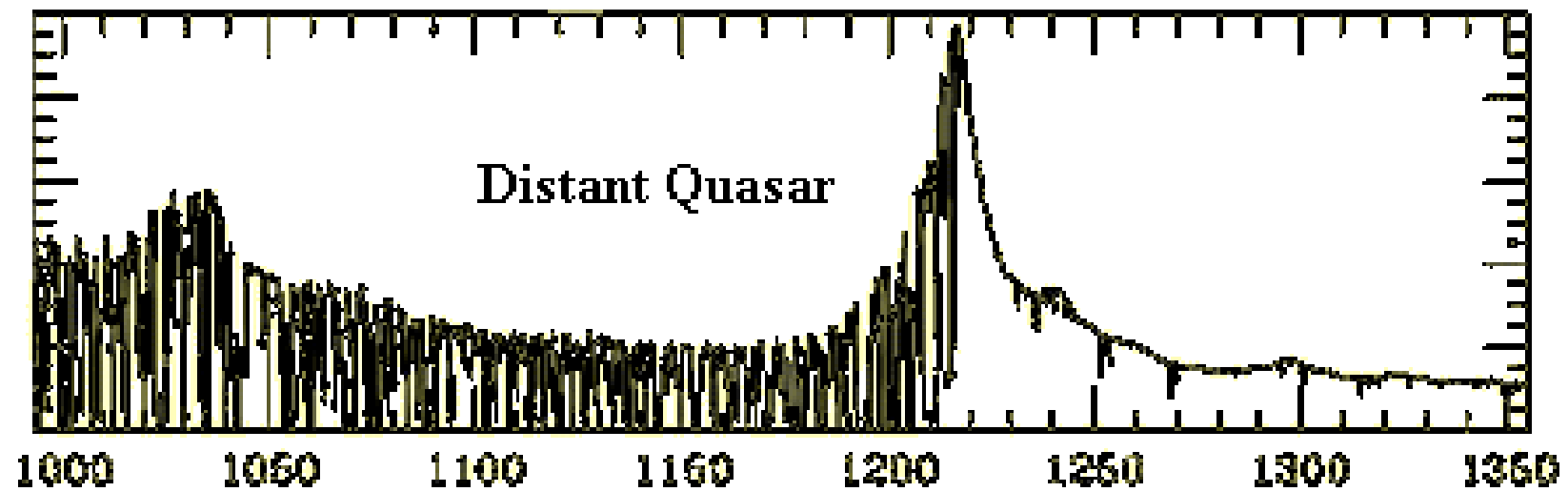
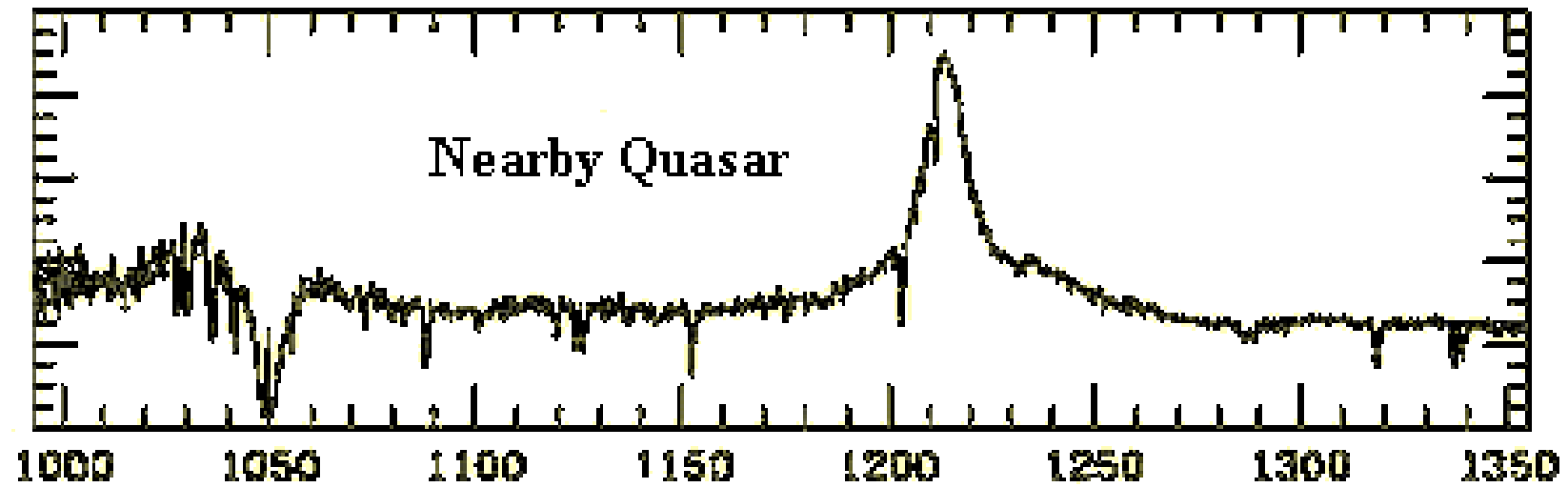
The IGM is highly ionized



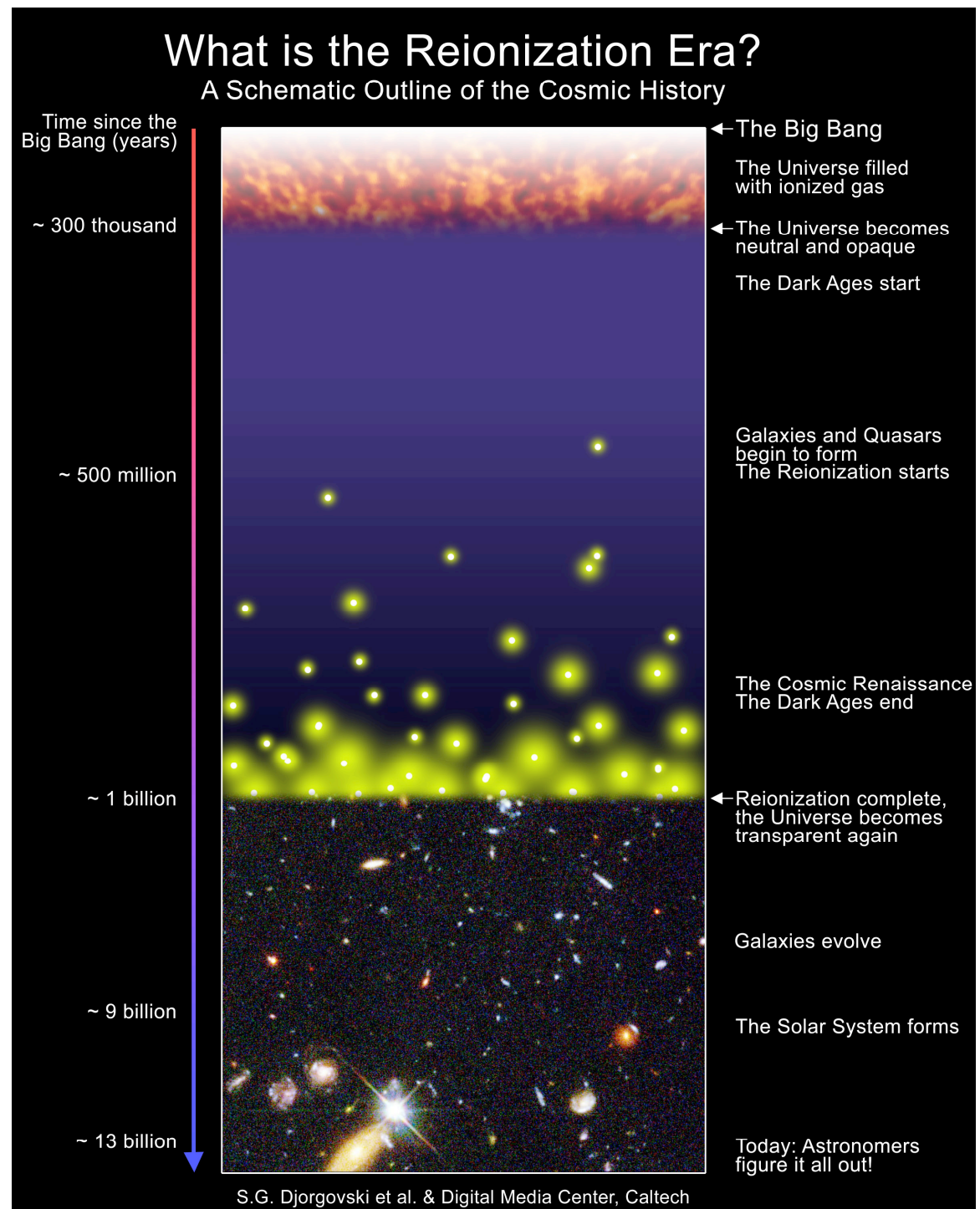
Ionization rate from gals
& QSOs as computed by
Haardt & Madau



Filaments and galaxies will produce more absorption than low-density IGM

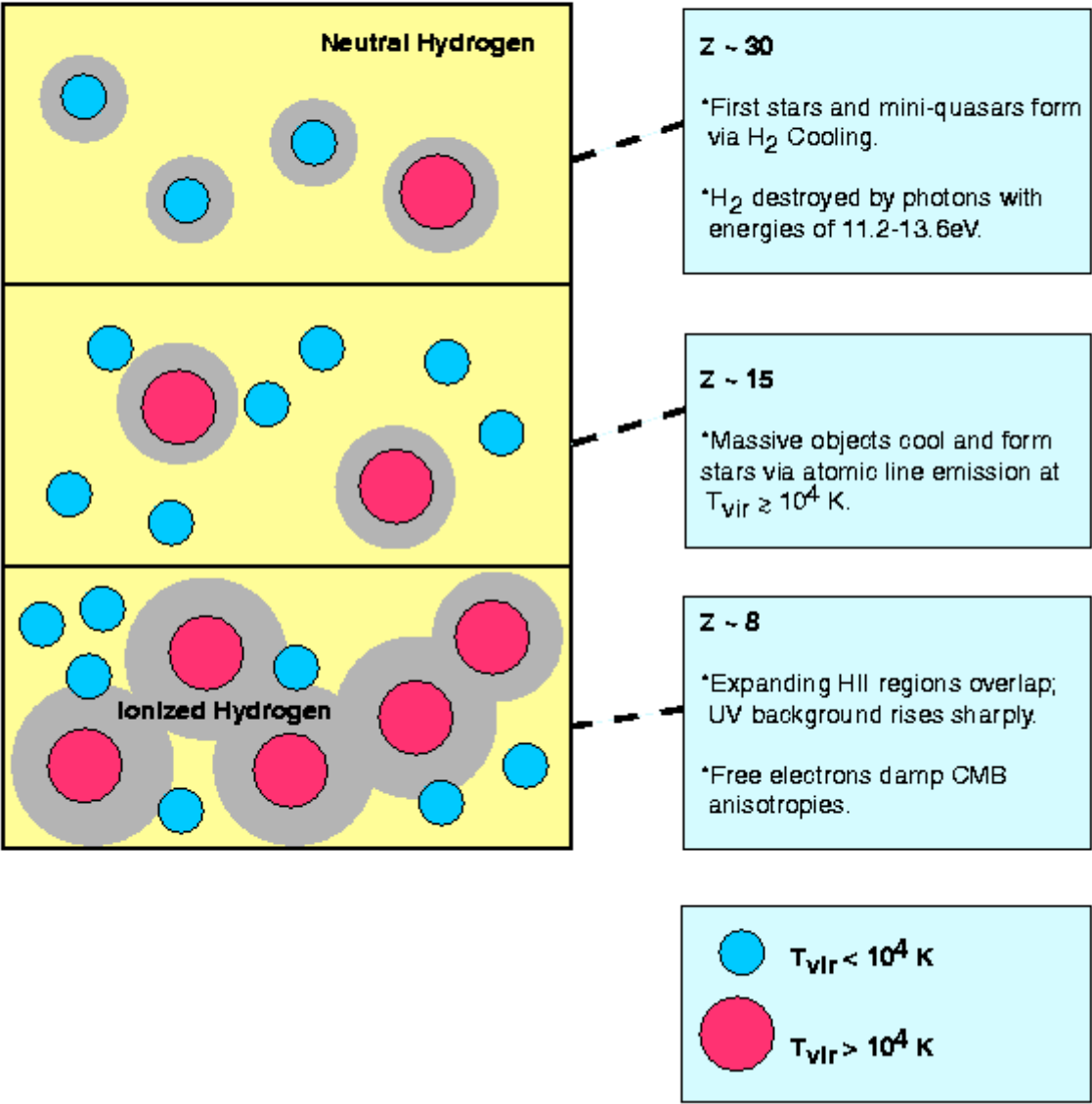


Reionization



REIONIZATION OF THE UNIVERSE

Three stages



Pre-overlap



Overlap



Post-overlap

Open Questions:

When did it happen: f_{HI} vs. z

$z \sim 6$: late

$z \sim 15$: early

Extended or phase transition?

How did reionization proceed:

Homogeneous or large scatter? (f_{HI}) vs. z

Topology of overlap; f_{HI} vs.

What did it: (stars, gal, qso) vs. z

AGN?

Star formation?

Decay particles?

Observational goals

Map the evolution and spatial distribution of ionization state

Find highest redshift galaxies and quasars: source of reionization

What Ionized the Universe?

Reionization Budget

$$\dot{N}_{ion} \propto \rho_{912\text{\AA}}^L f_{esc} C_{IGM}$$

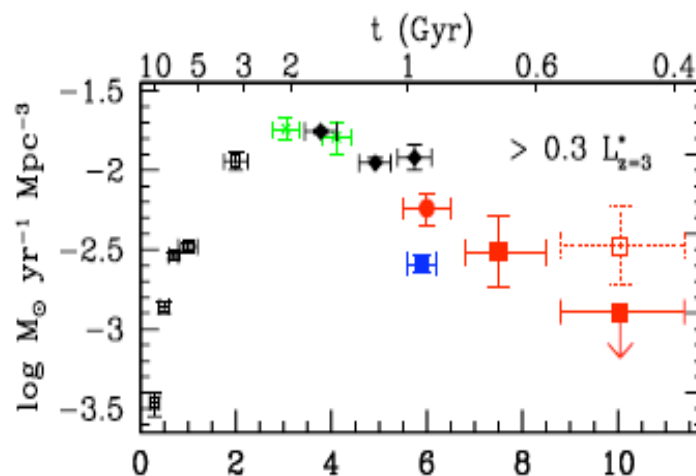
- Early Pop III stars
- “Normal” galaxies
- AGN

Depends on:

- Luminosity density:
 - Detailed LF and IMF
- Escape fraction of ionizing photons to the IGM:
 - Quasar: $f_{esc} \sim 1$
- Galaxies??
- Clumpiness of the IGM

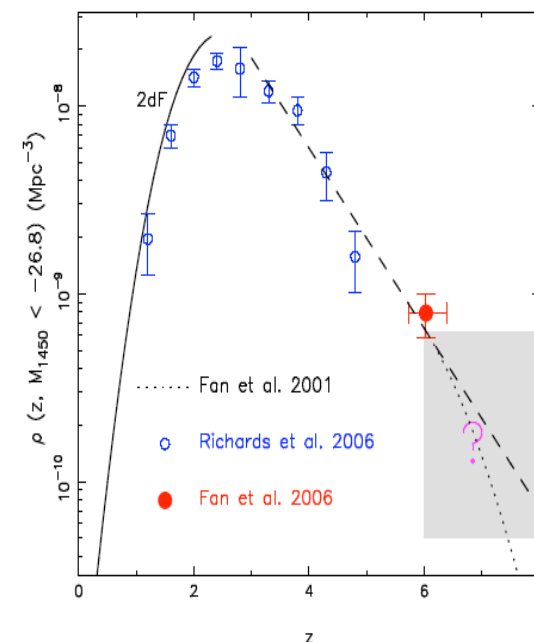
Can quasars do it? *Not likely*

- Too few quasars unless QLF remains to be steep to AGN luminosity
- Extra constraints from X-ray background



Density of quasars

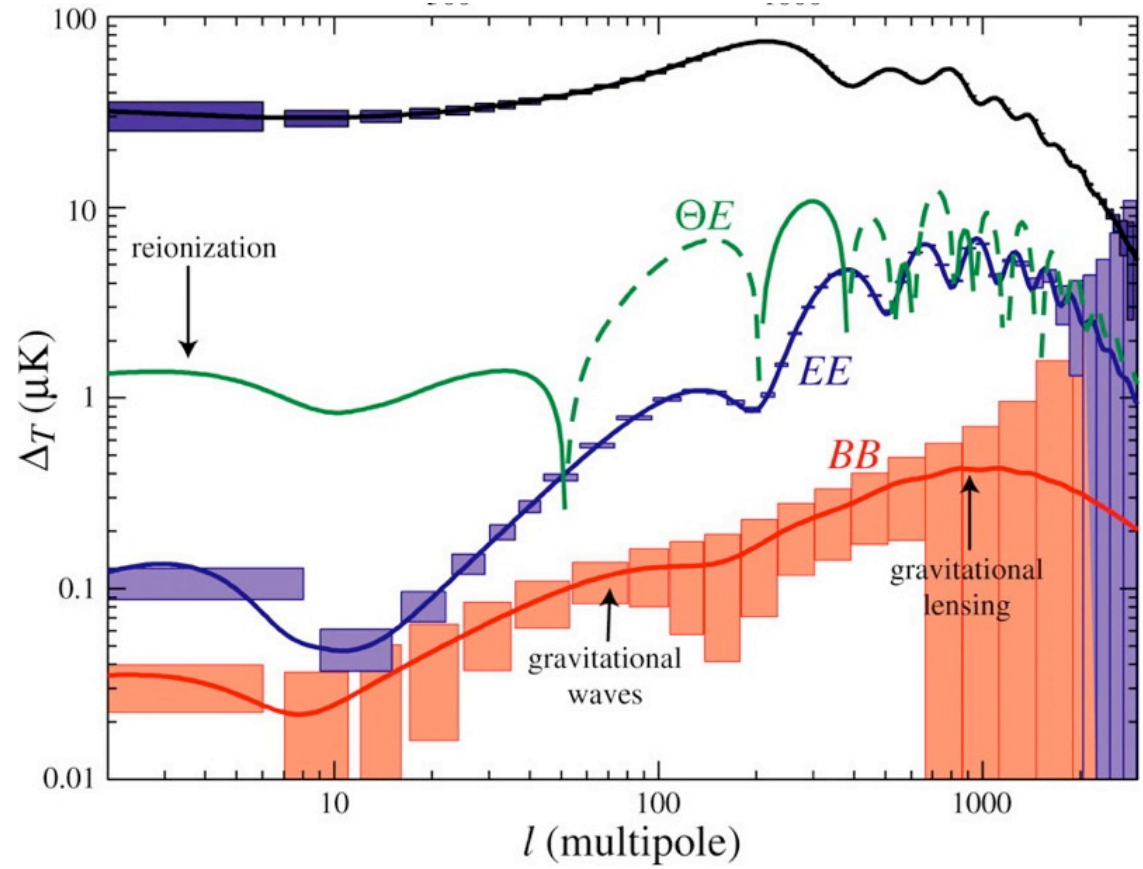
SFR of galaxies



What do we know about Reionization?

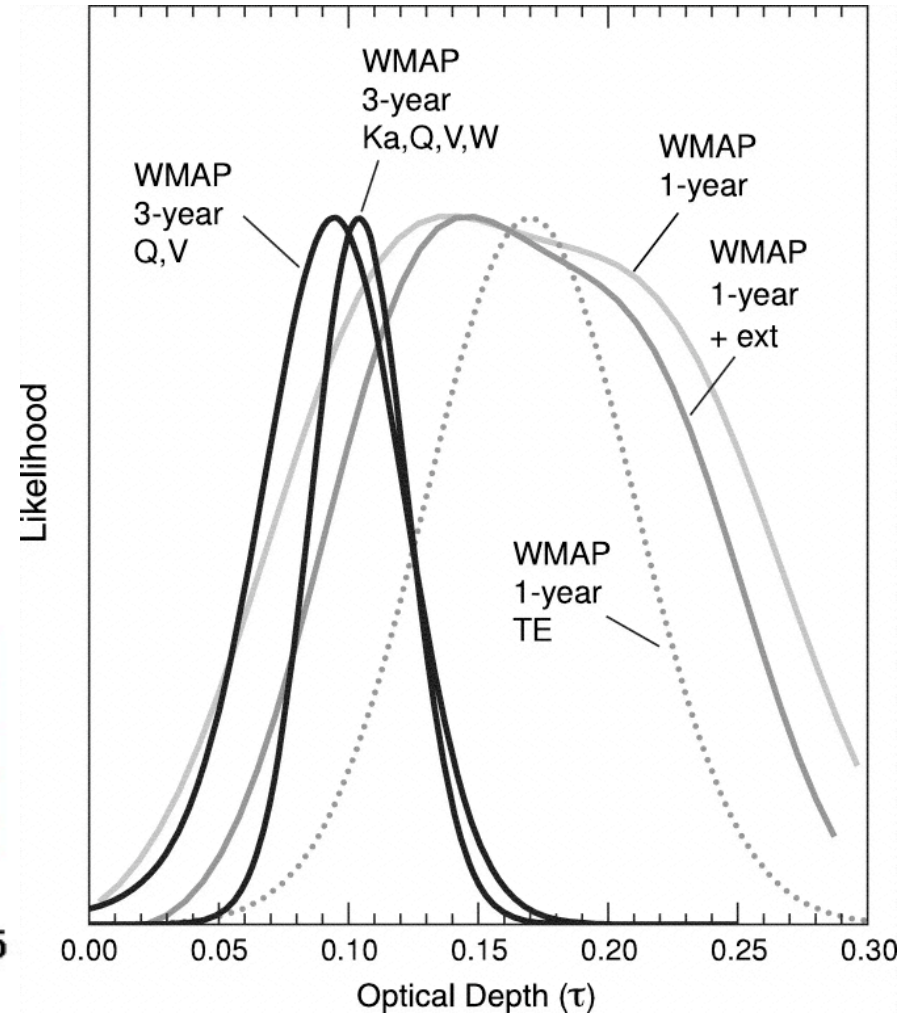
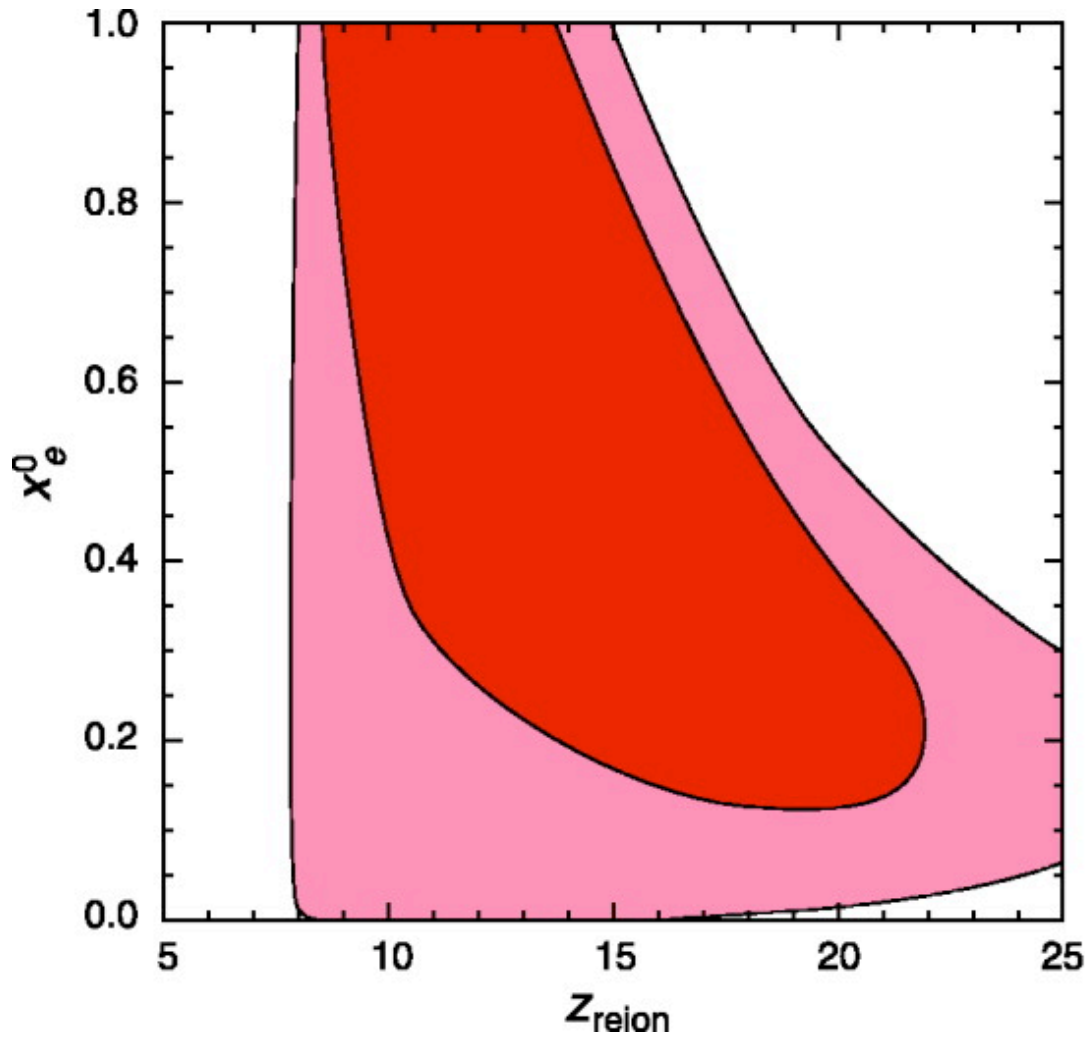
Free-electrons post recombination may scatter CMB photons from different patches towards the observer.

This introduces correlations between temperature and polarization of CMB photons

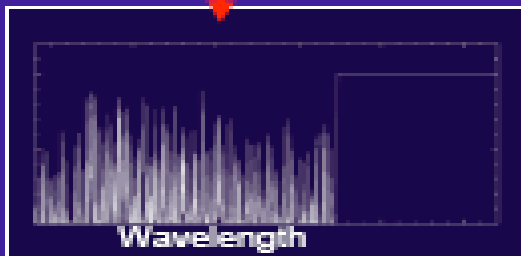
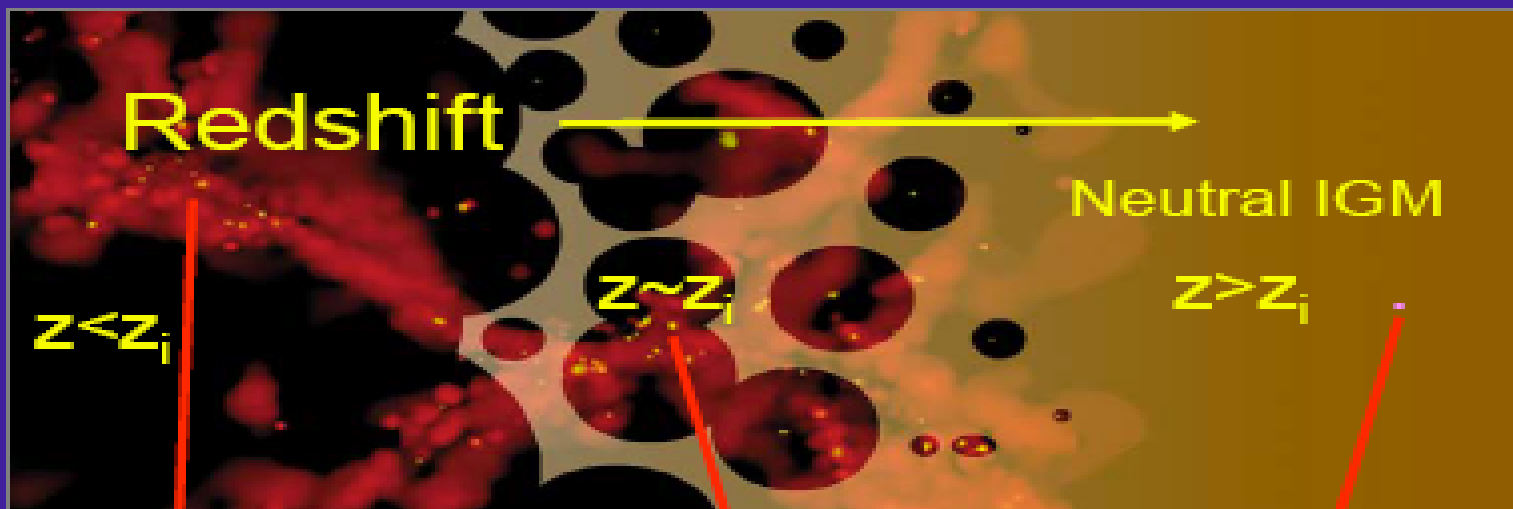


Wayne Hu

WMAP



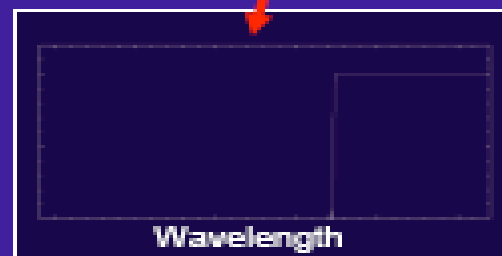
Page et al., Spergel et al. 2006



Lyman Forest Absorption



Patchy Absorption



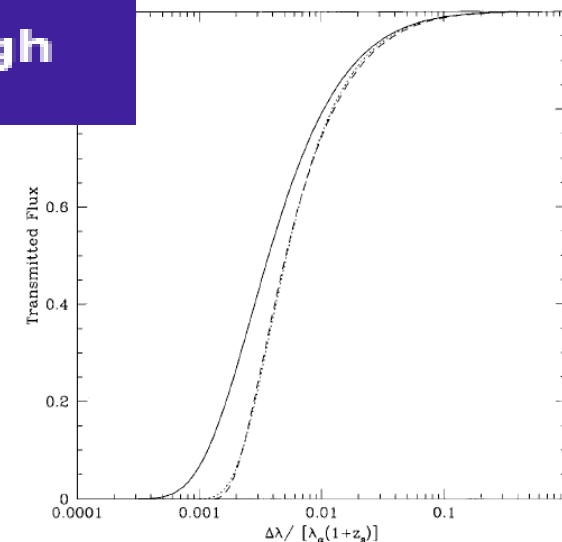
Black Gunn-Peterson trough

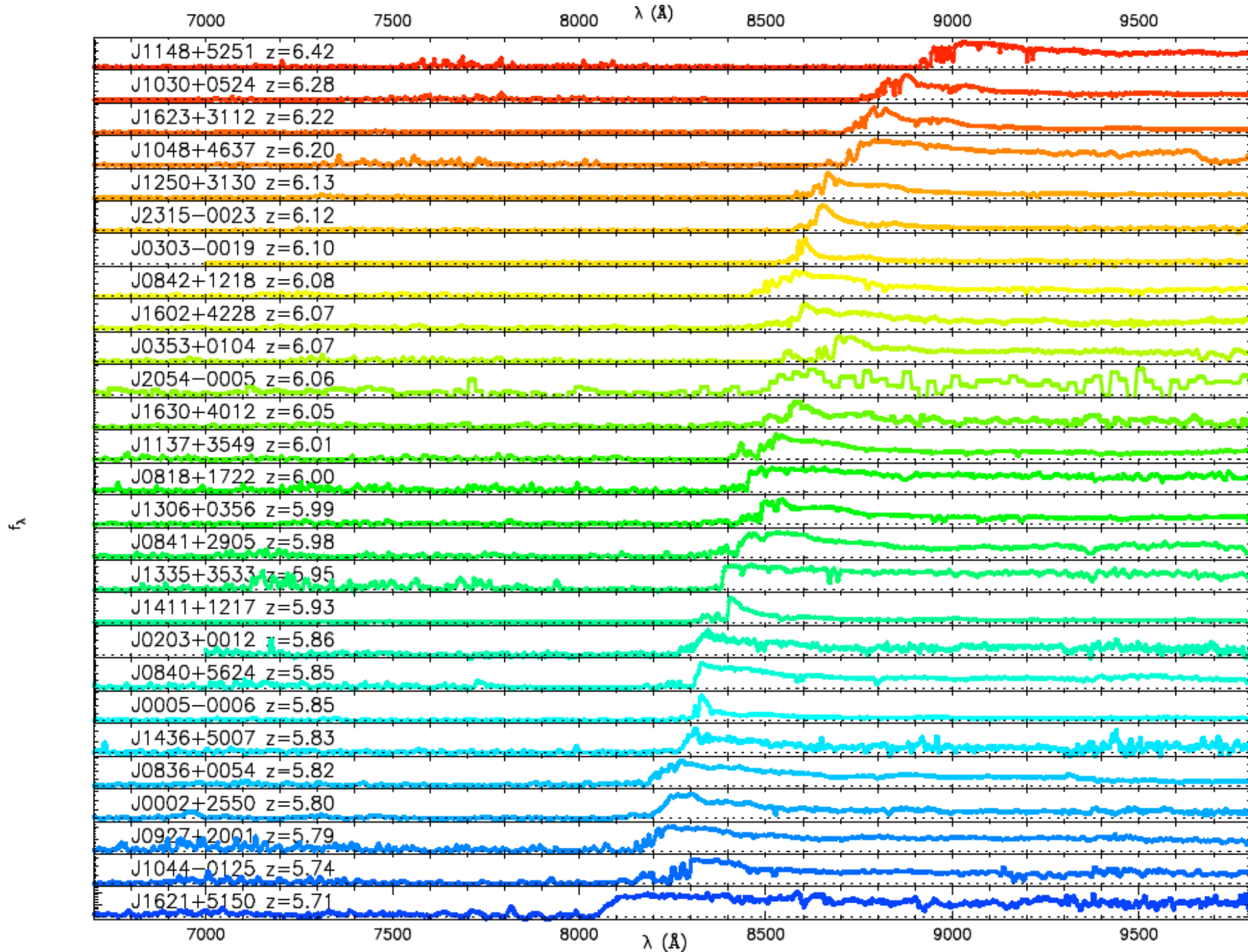
Classical G-P (1965) effect: $\tau_{GP} \sim 10^5 (n_{HI} / n_H)$

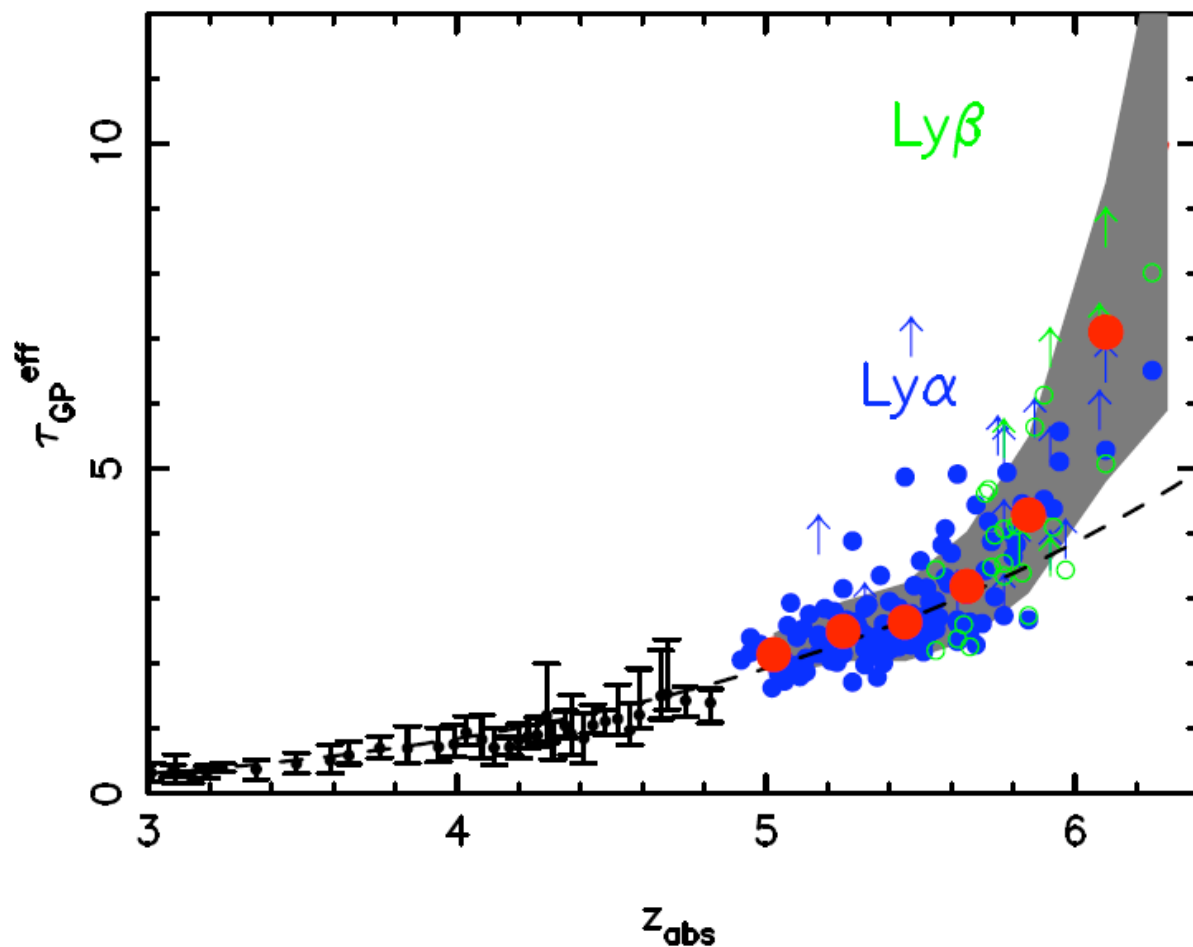
- Saturates at low neutral fraction

G-P damping wing (Miralda-Escude 1998)

- Sensitive to neutral IGM
- Attenuates off-resonance transmissions







Optical depth evolution accelerated

- $z < 5.7$: $\sim (1+z)^{4.5}$
- $z > 5.7$: $\sim (1+z)^{11}$

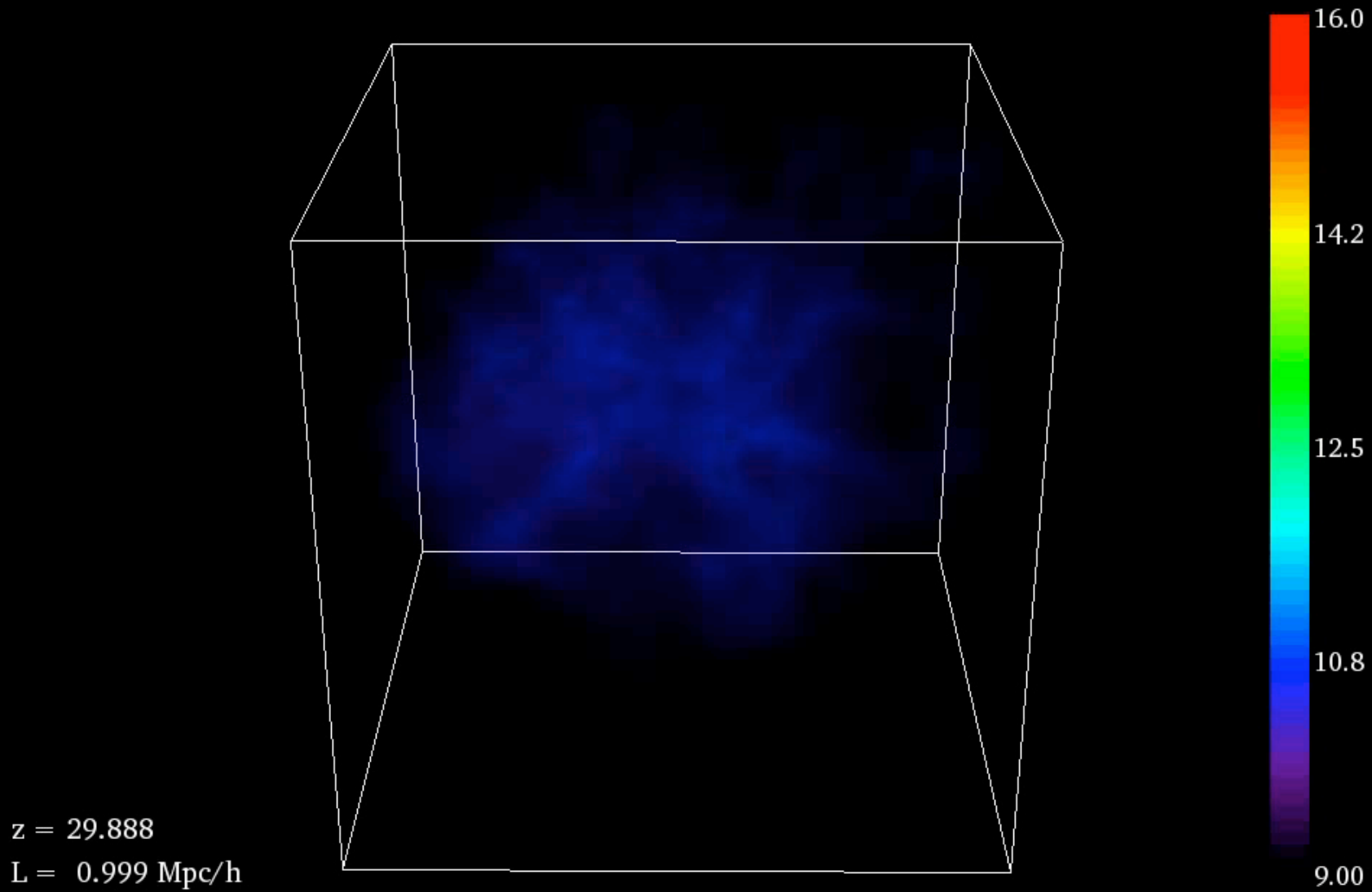
End of reionization?

Evolution of neutral fraction

- $f_{\text{HI}} > 10^{-3} - 10^{-2}$ at $z=6$
- Order of magnitude increase from $z \sim 5$
- G-P absorption saturates; needs more sensitive tests

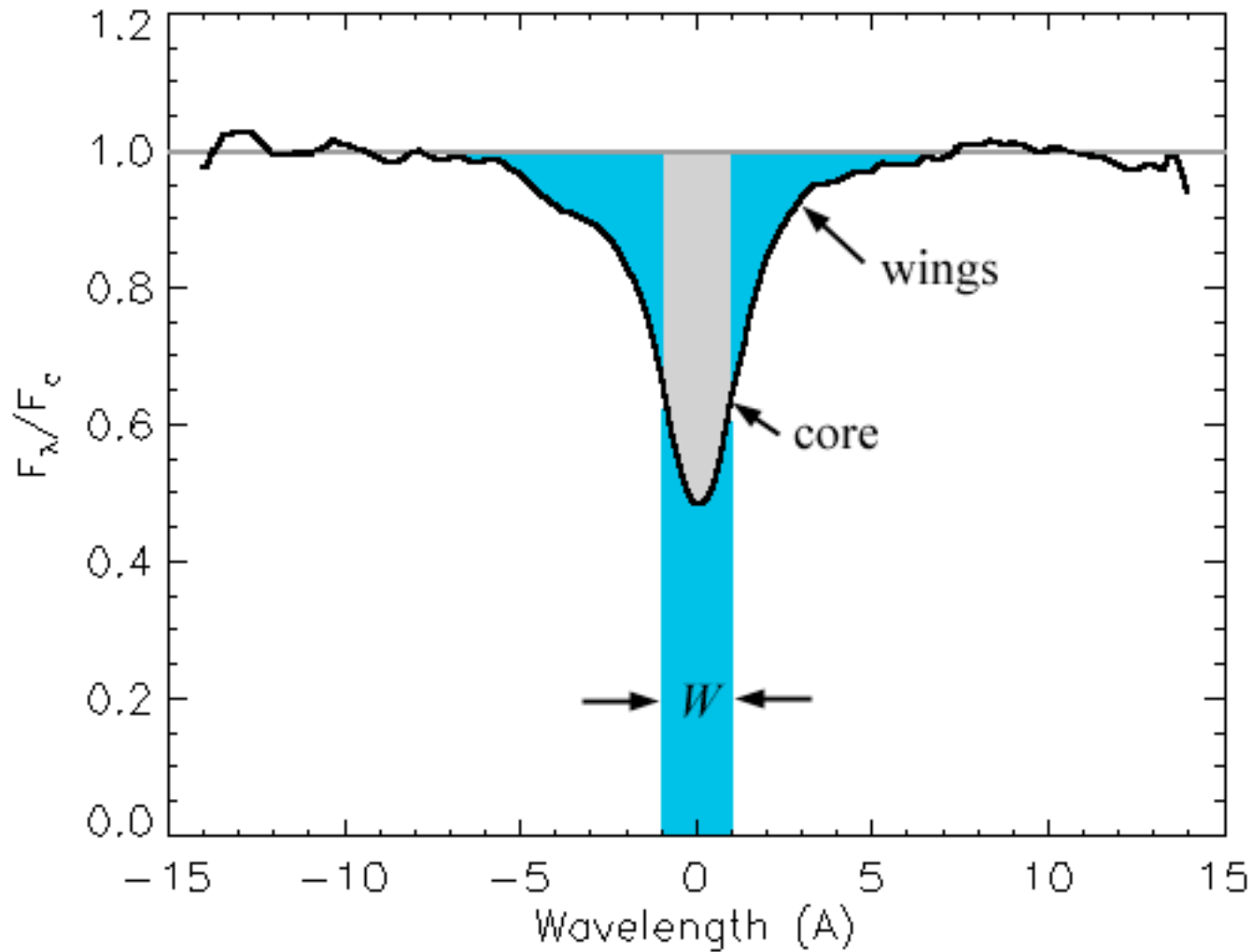
Dwarf galaxy with GIMIC/OWLS code

$\log(\text{Gas density})$ in $[\text{Msun}/h / (\text{Mpc}/h)^3]$



Simulation of dwarf galaxy formation

Characterizing lines: Equivalent width



Curve of growth: see [Michael Richmond's page](#)

Equivalent width

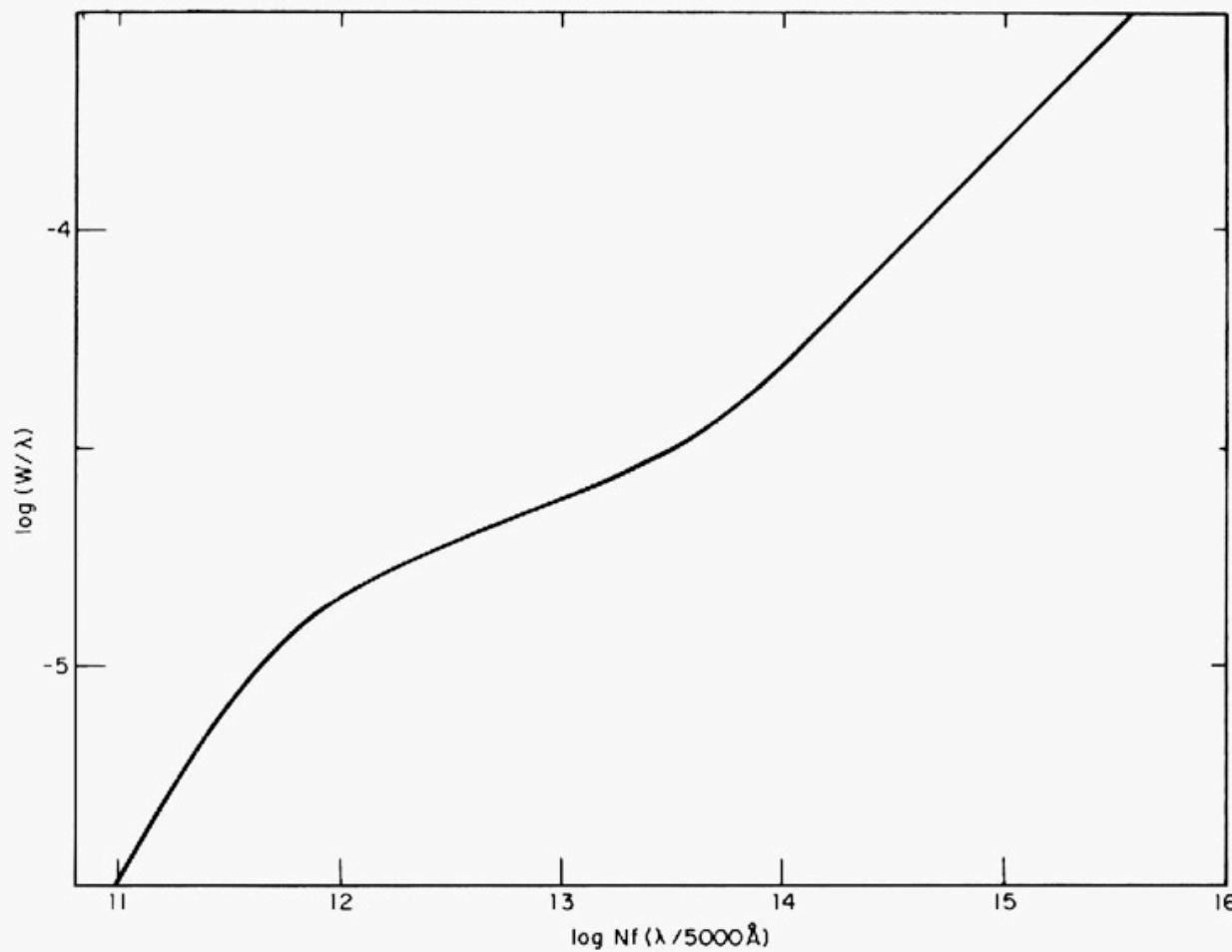
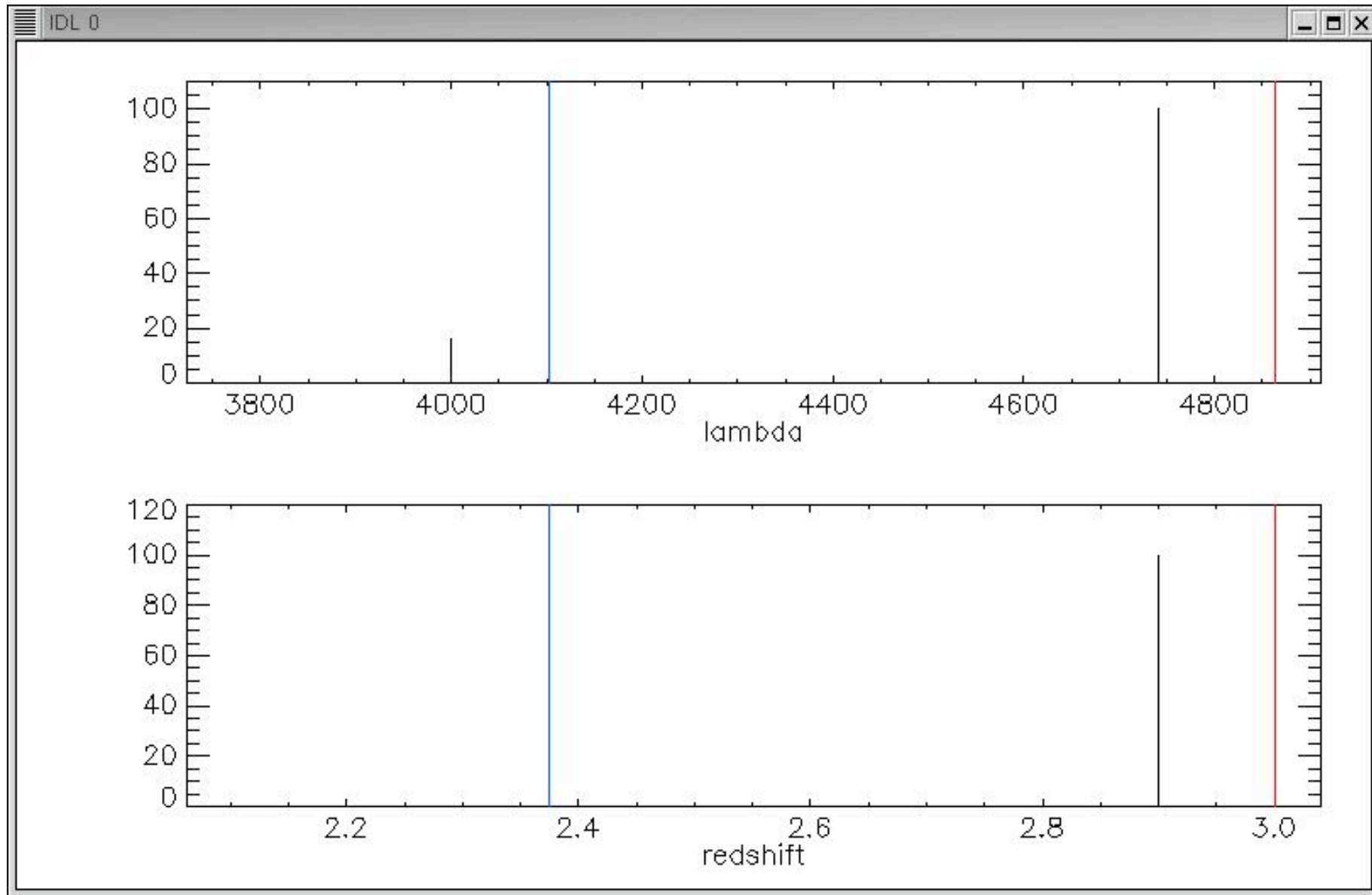
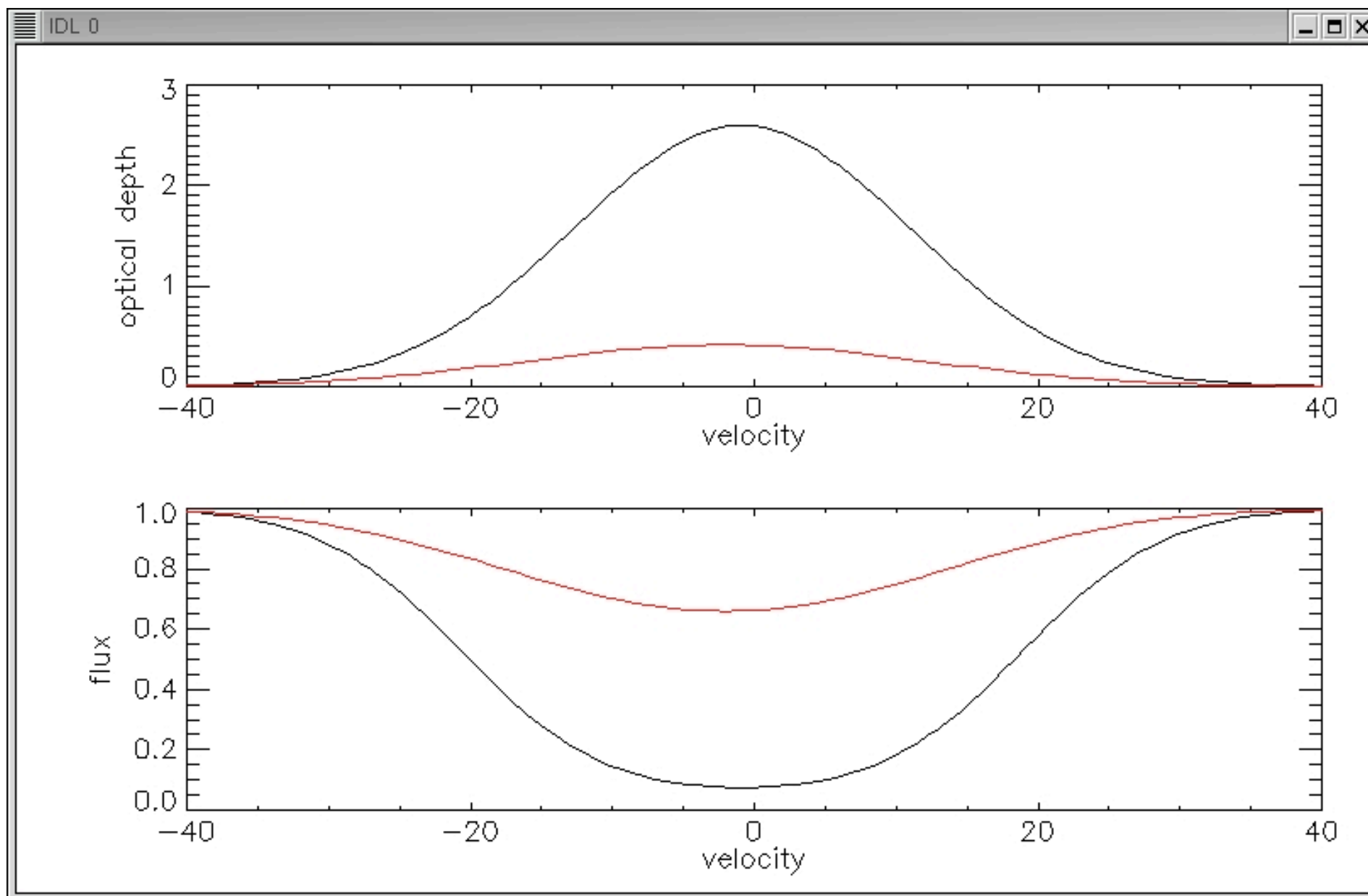


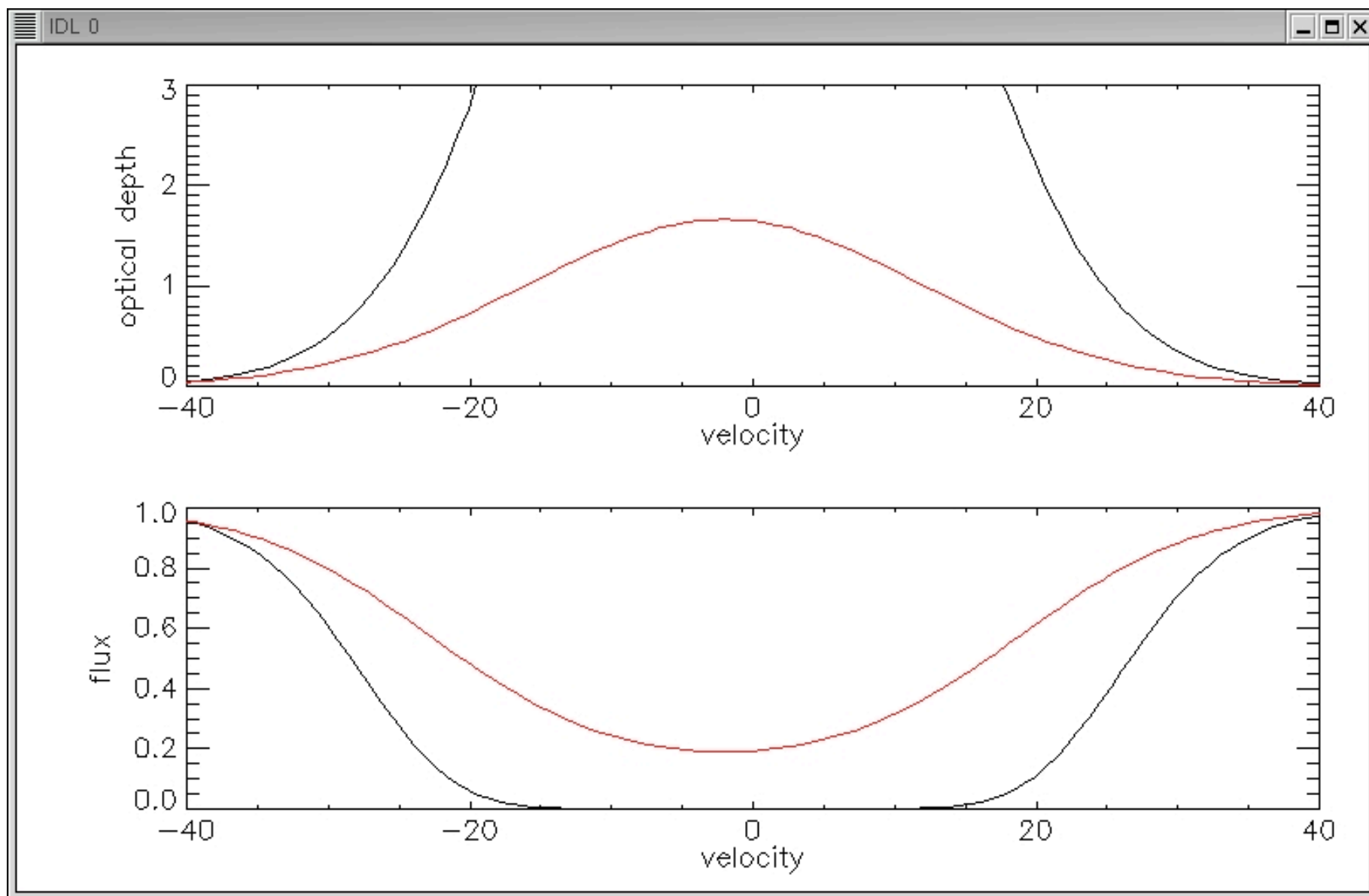
Figure 9.22 A general curve of growth for the Sun. (Figure from Aller, *Atoms, Stars, and Nebulae*, Revised Edition, Harvard University Press, Cambridge, MA, 1971.)

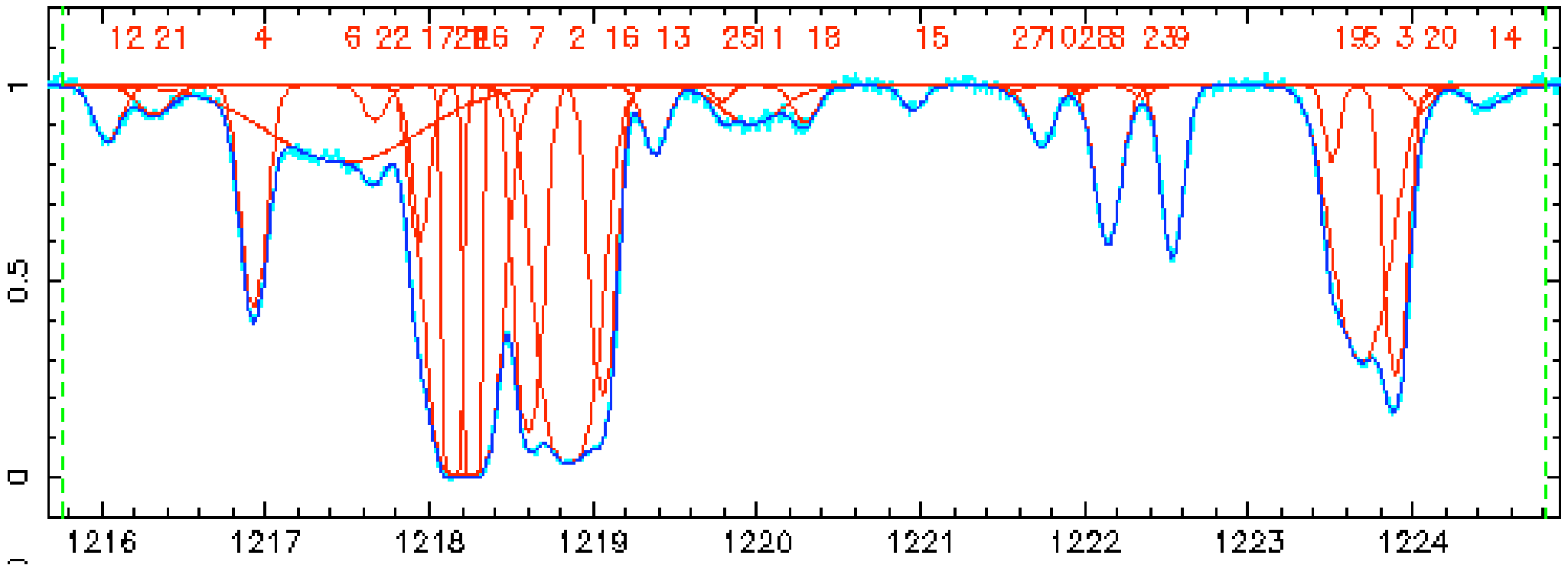
Column density

Build your own QSO:









Line-fitting with vpf

What can we learn from IGM?

- Effect of galaxies/QSOs on IGM
- He-forest
- Temperature evolution of IGM

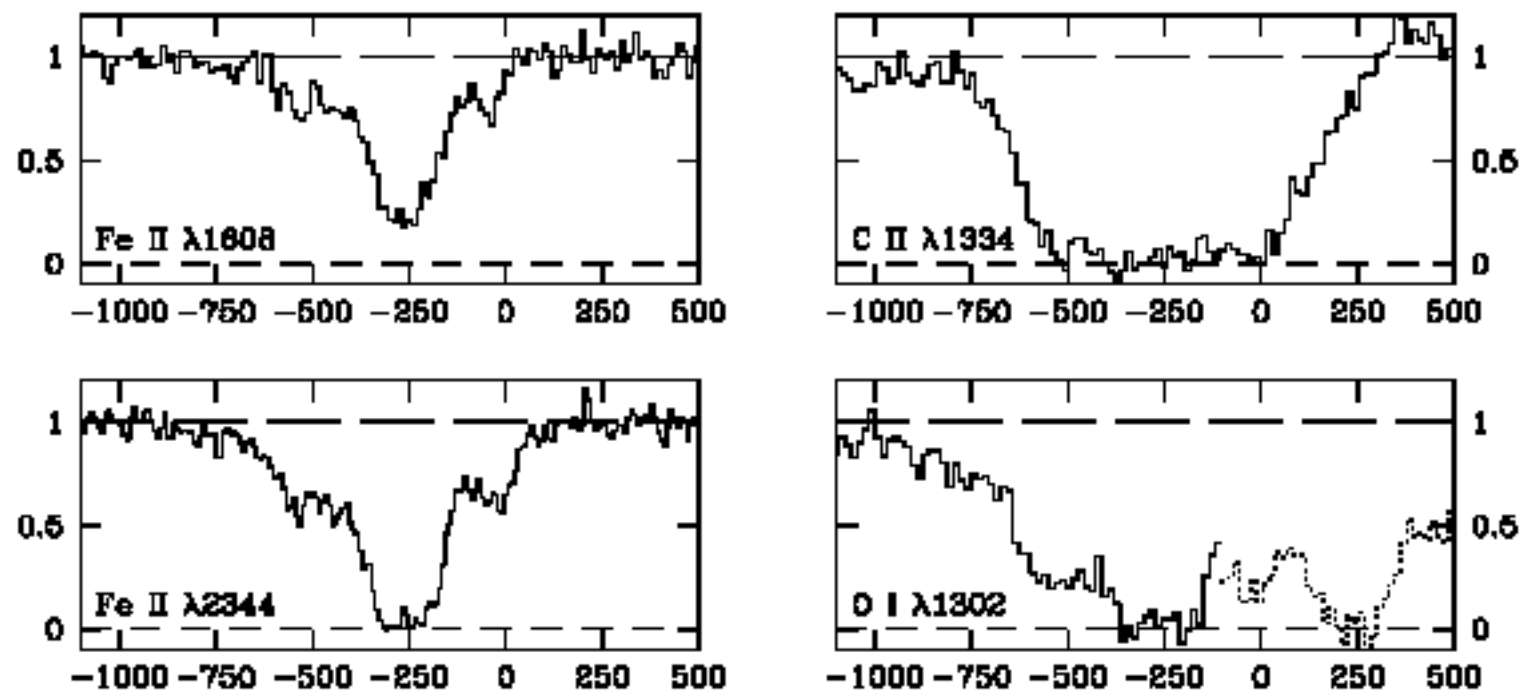
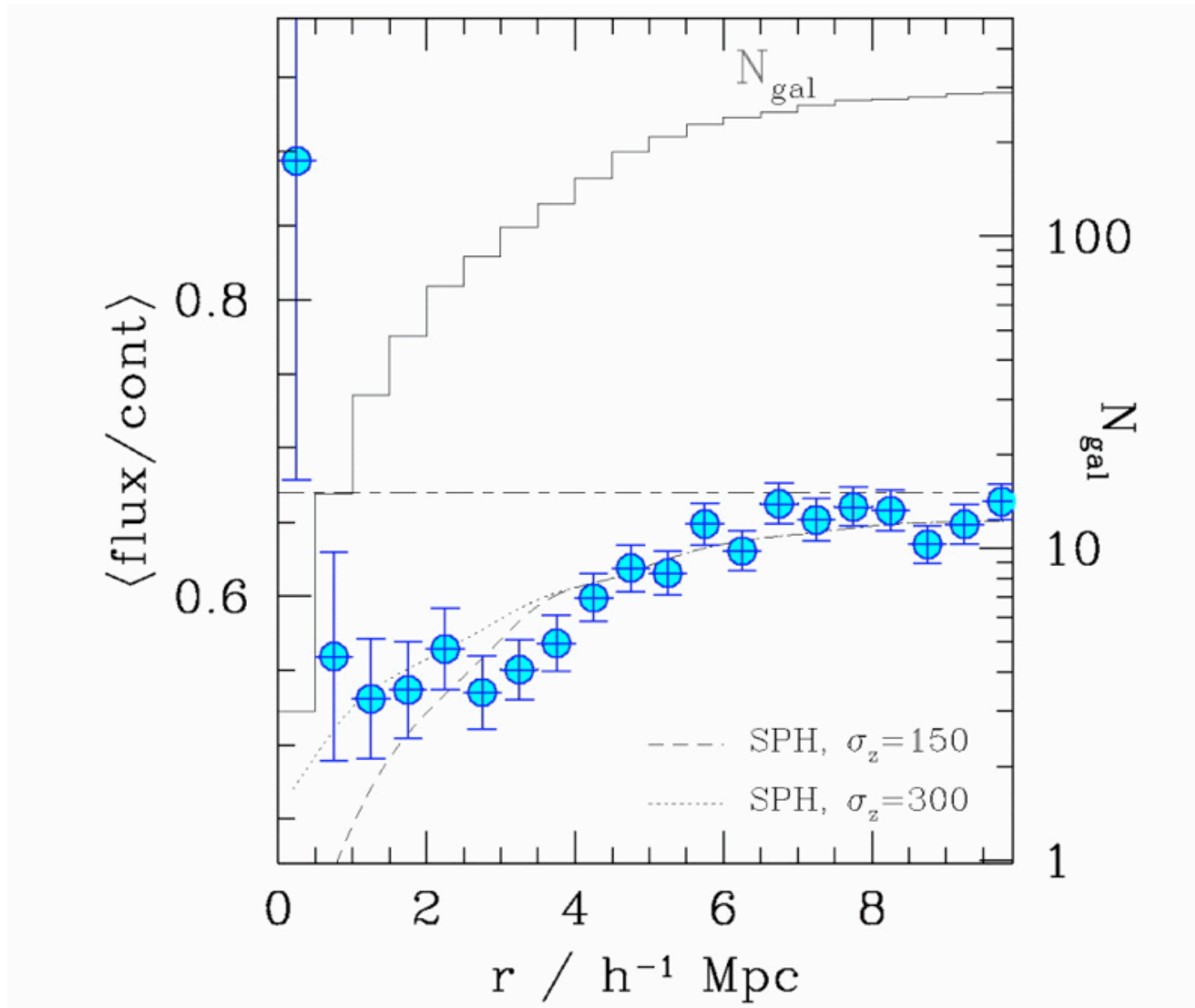


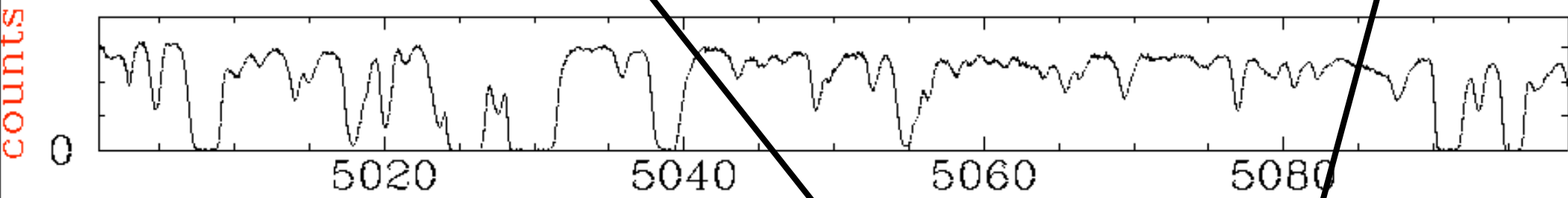
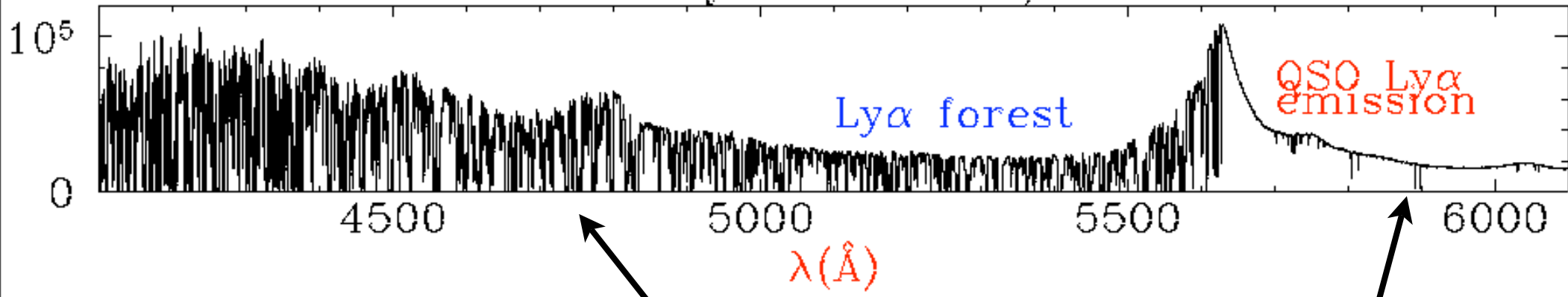
FIG. 1.—Normalized profiles of interstellar absorption lines in cB58. Here we have collected examples of absorption lines from species that are the dominant ion stages in H I regions (except for C I), illustrating a range of line strengths. The y -axis is residual intensity, while the x -axis is velocity (in km s^{-1}) relative to the stellar systemic redshift $z_{\text{stars}} = 2.7276$ (see § 3.1). Each bin corresponds to a wavelength interval $\delta\lambda = 0.067 \text{ \AA}$, equivalent to a velocity interval $\delta v = 8.5\text{--}17.5 \text{ km s}^{-1}$ for the transitions shown here. Dotted lines are used to indicate blends with absorption features that are *not* those labeled in each panel. [See the electronic edition of the *Journal* for a color version of this figure.]

Pettini et al

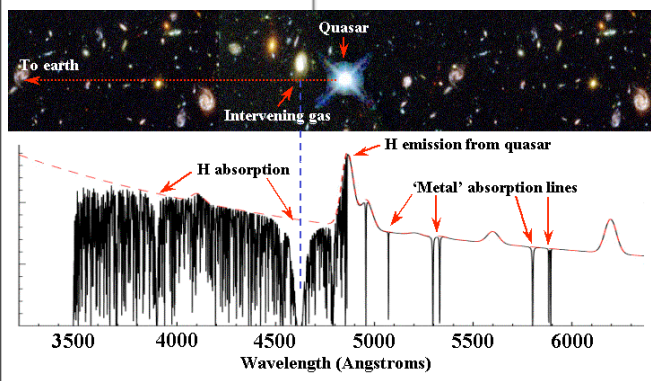
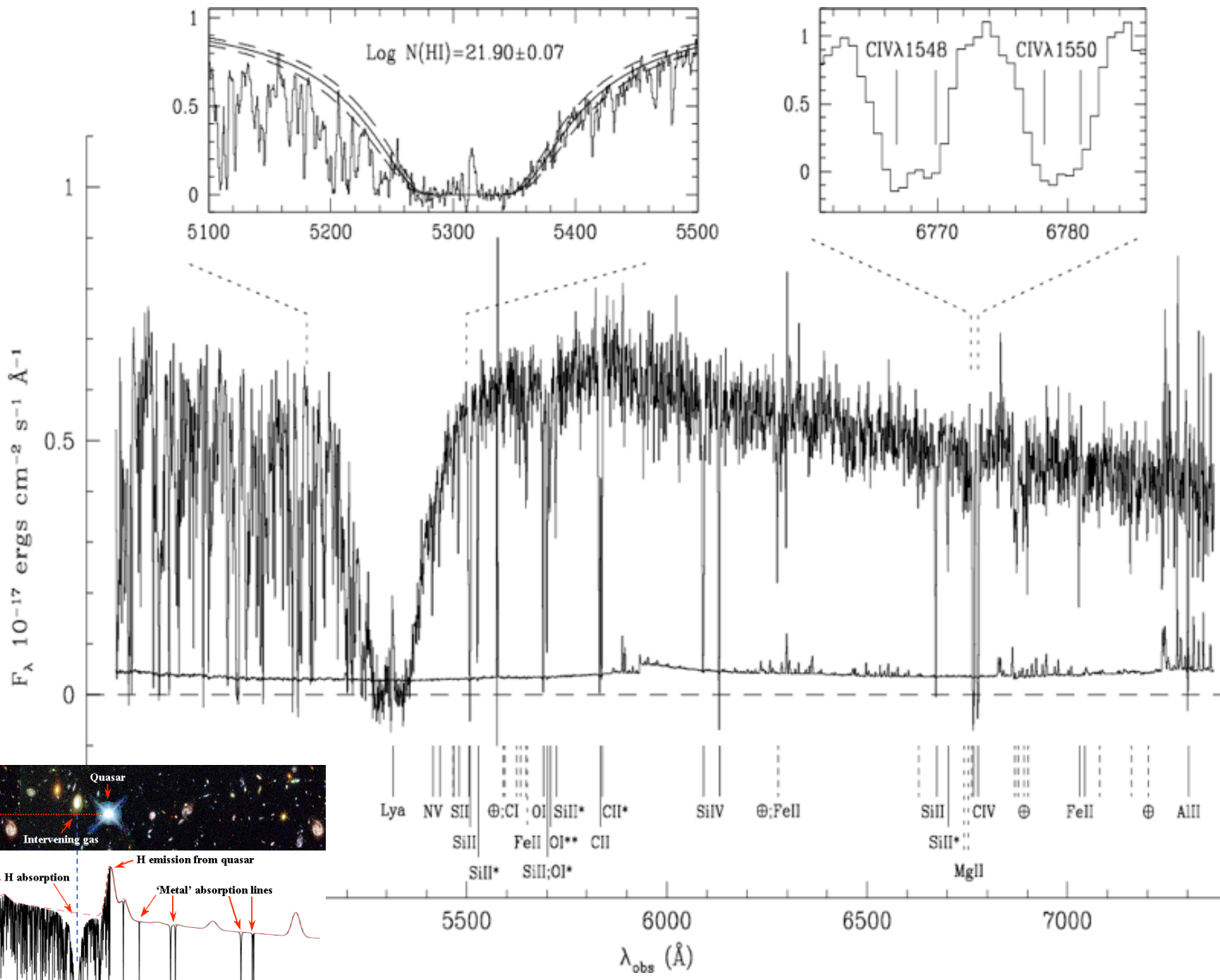
Adelberger et al 03



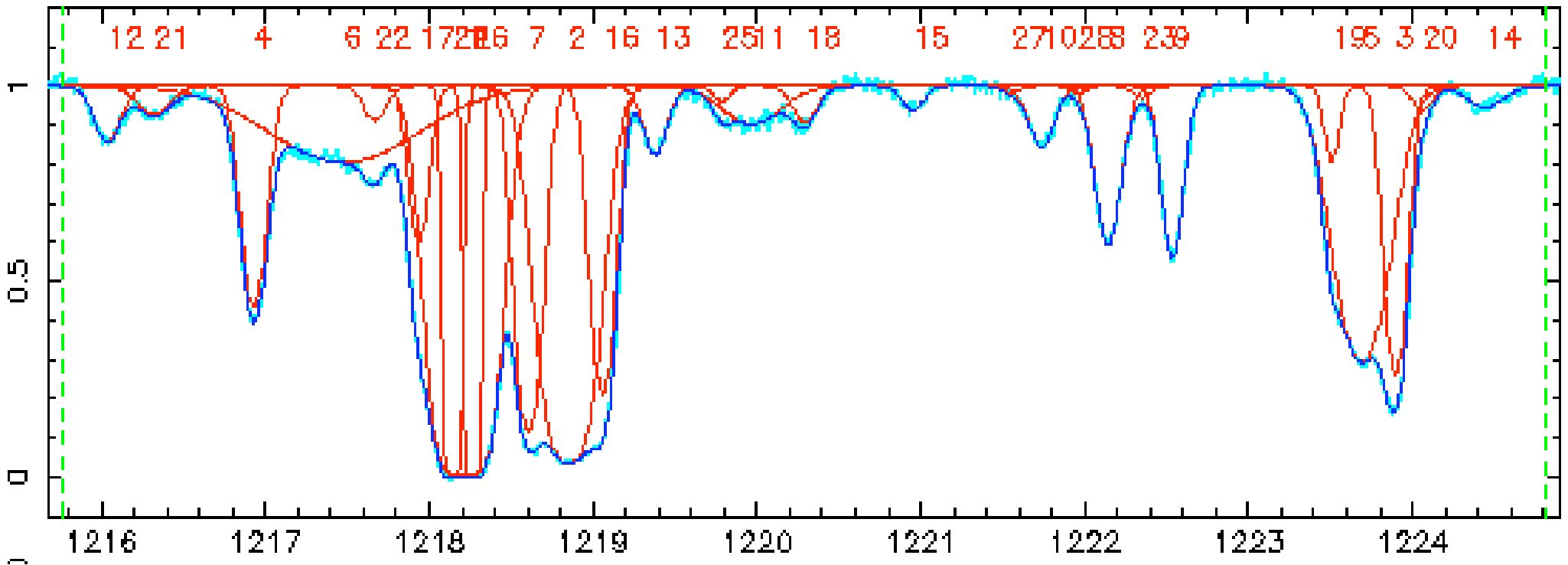
QSO 1422+231, 18 hours with KeckI



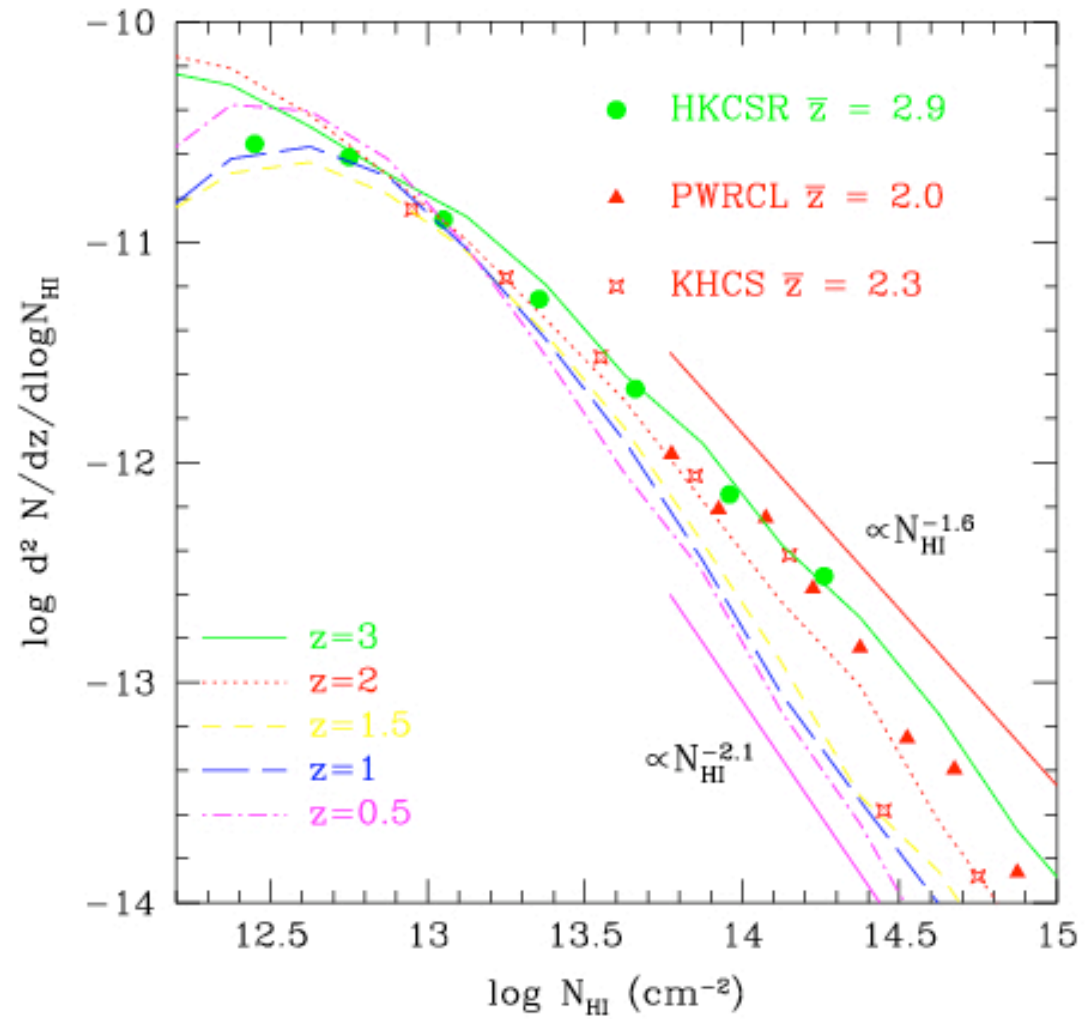
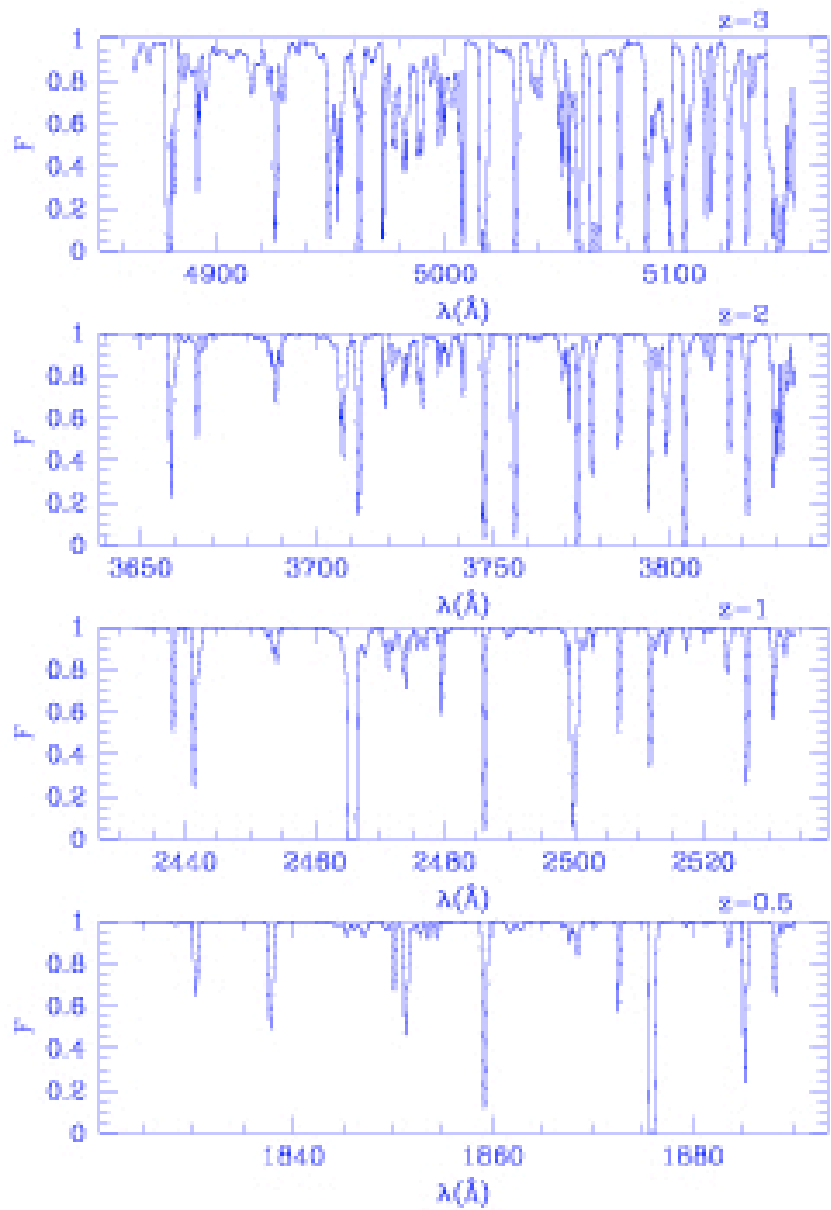
Metals: C iv, Si iv, O vi

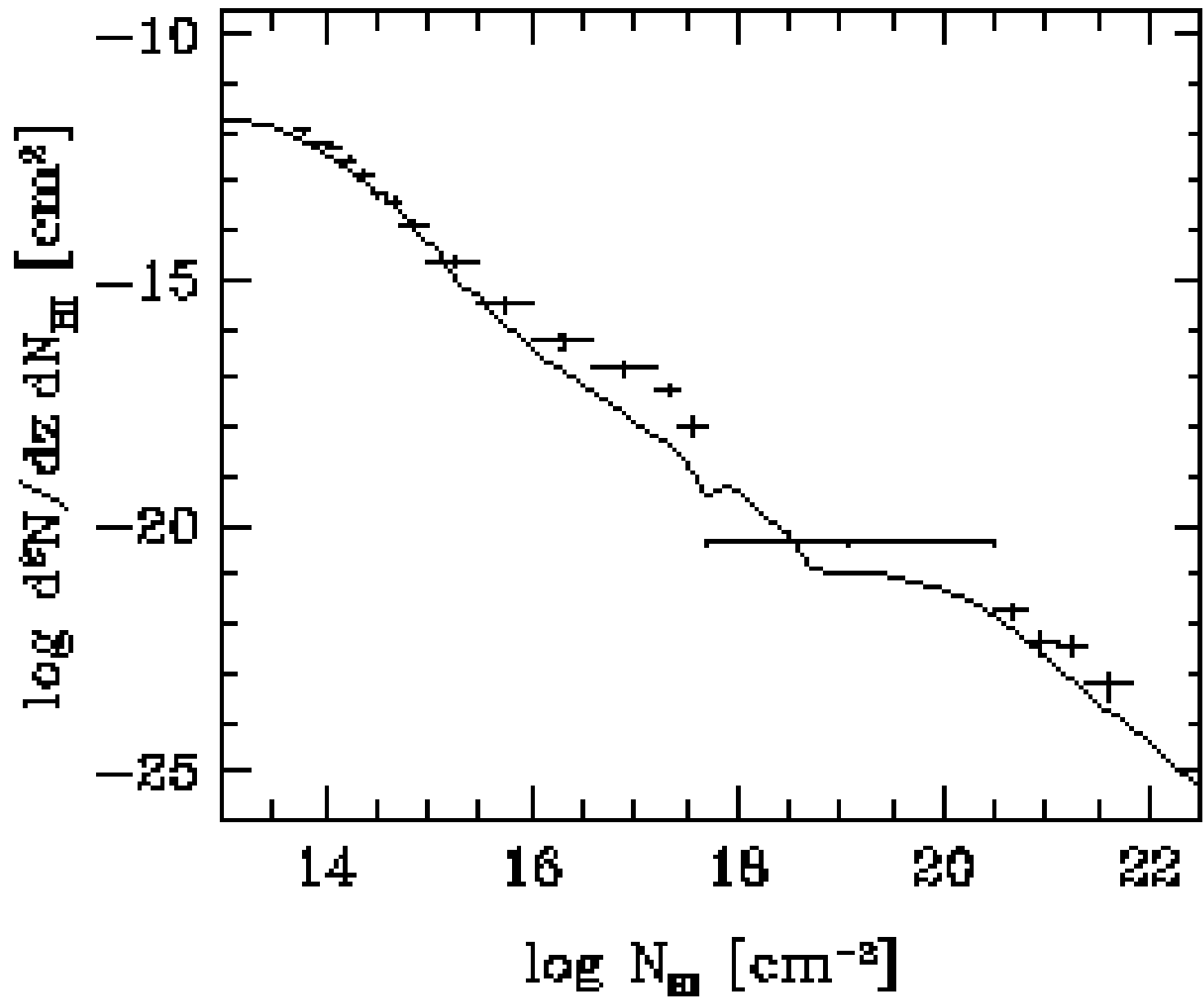


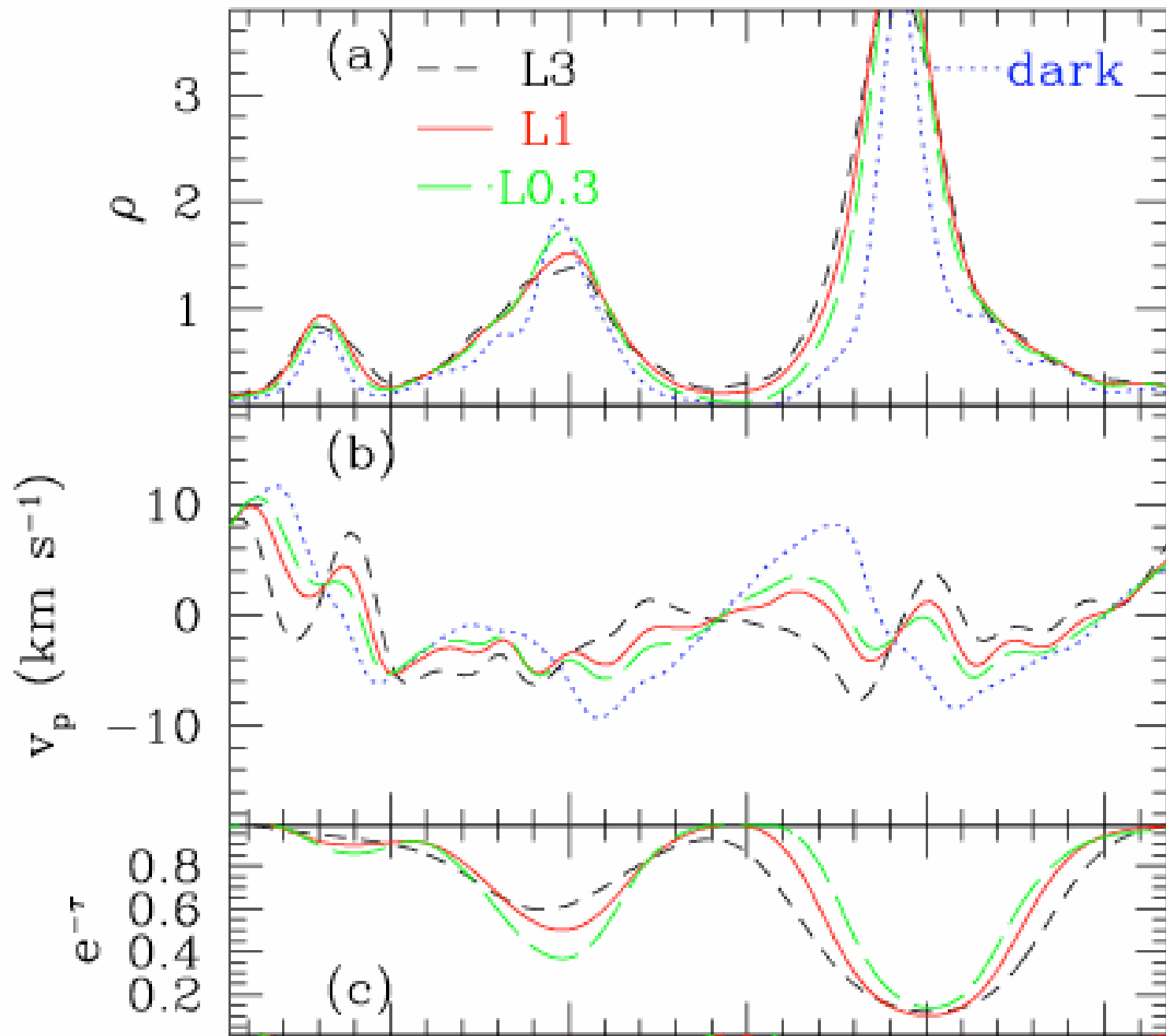
Tom Theuns



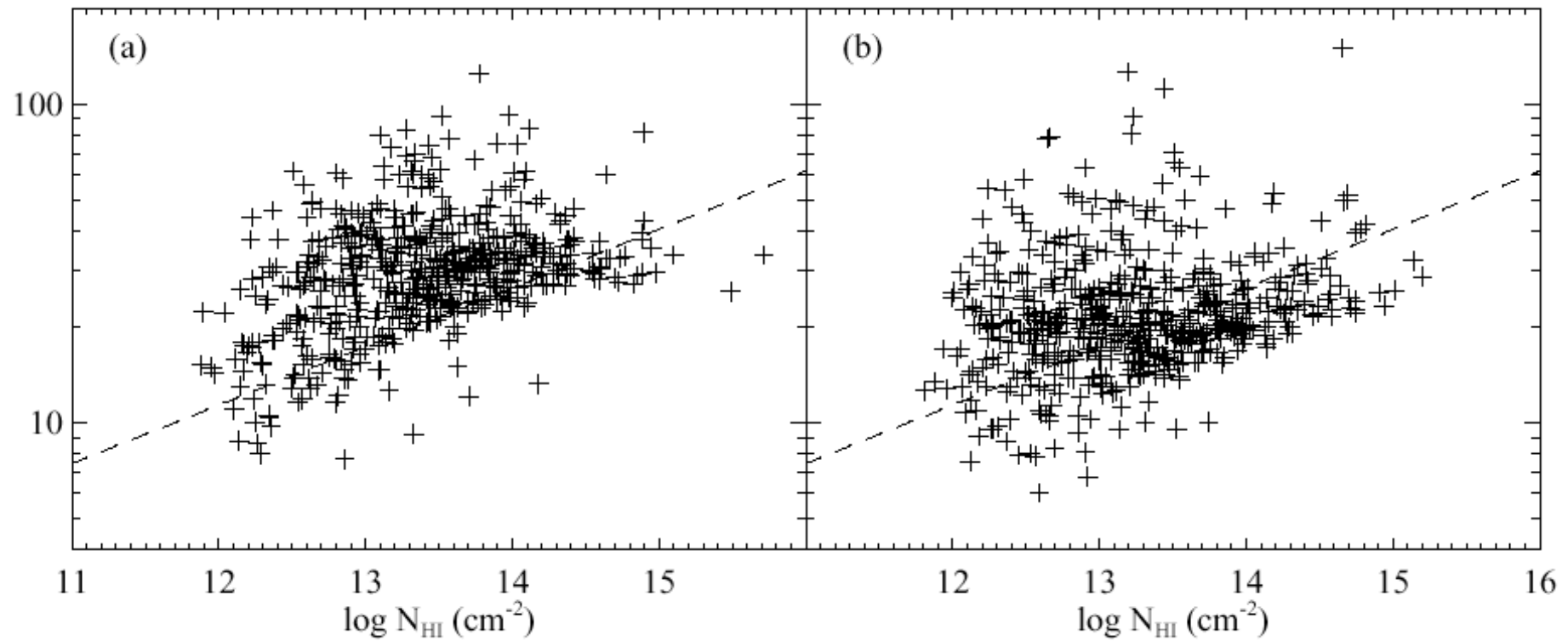
Line-fitting with vpf

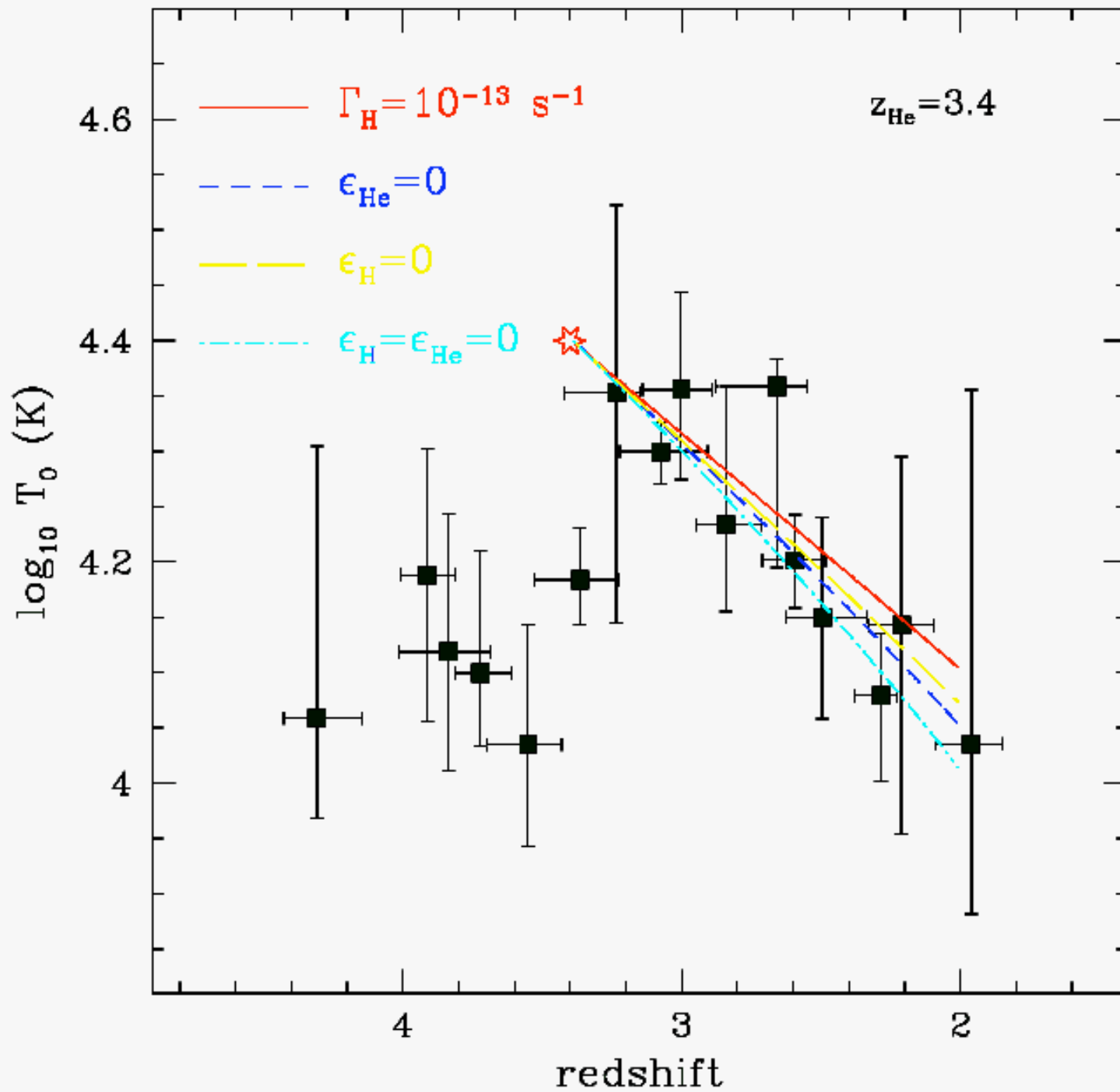


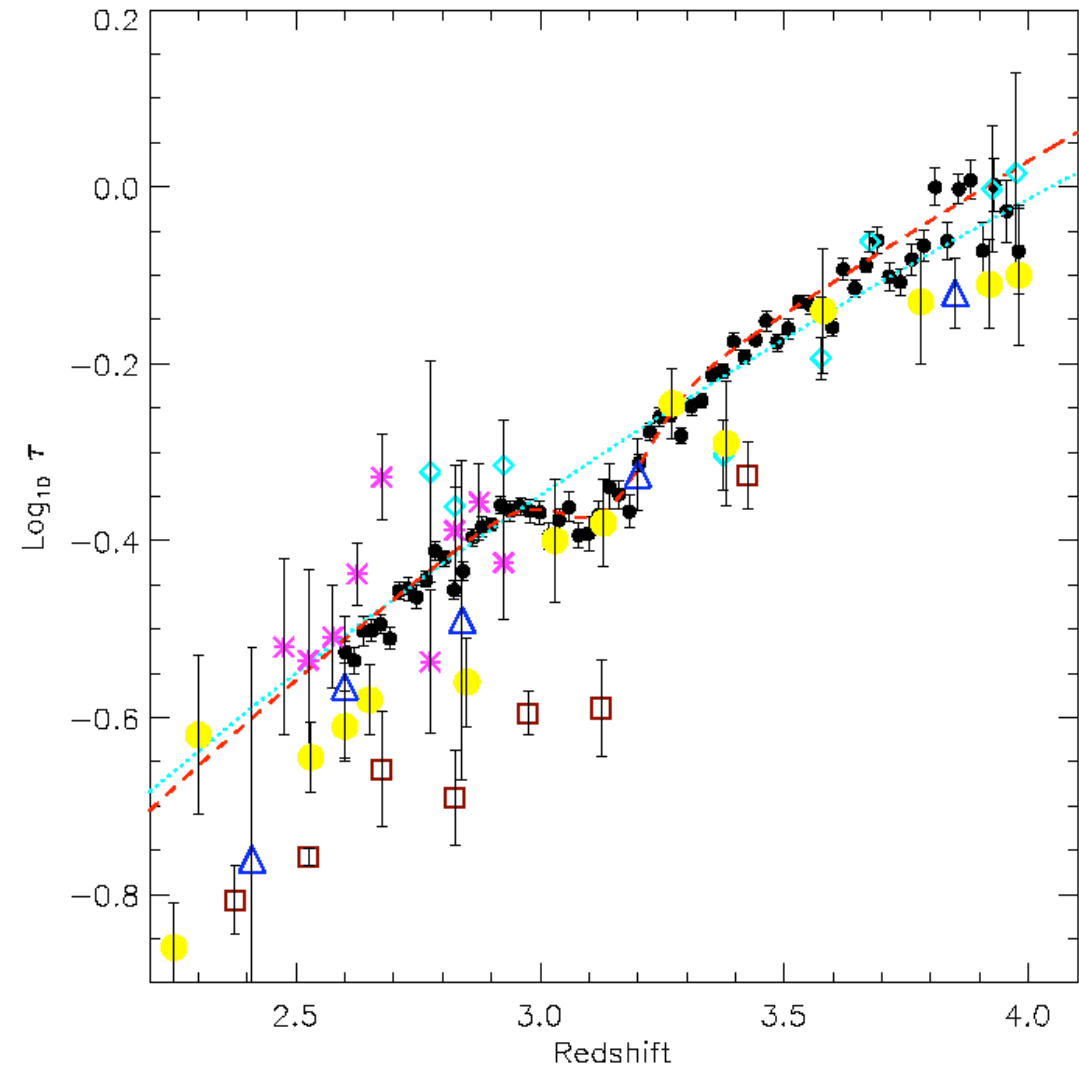
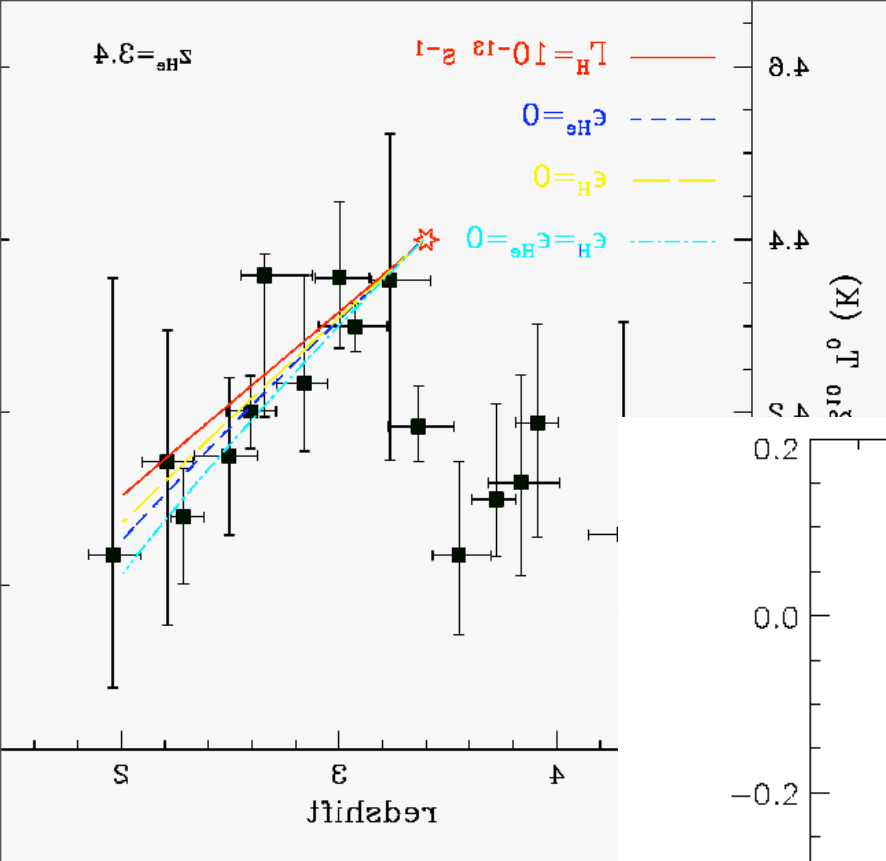




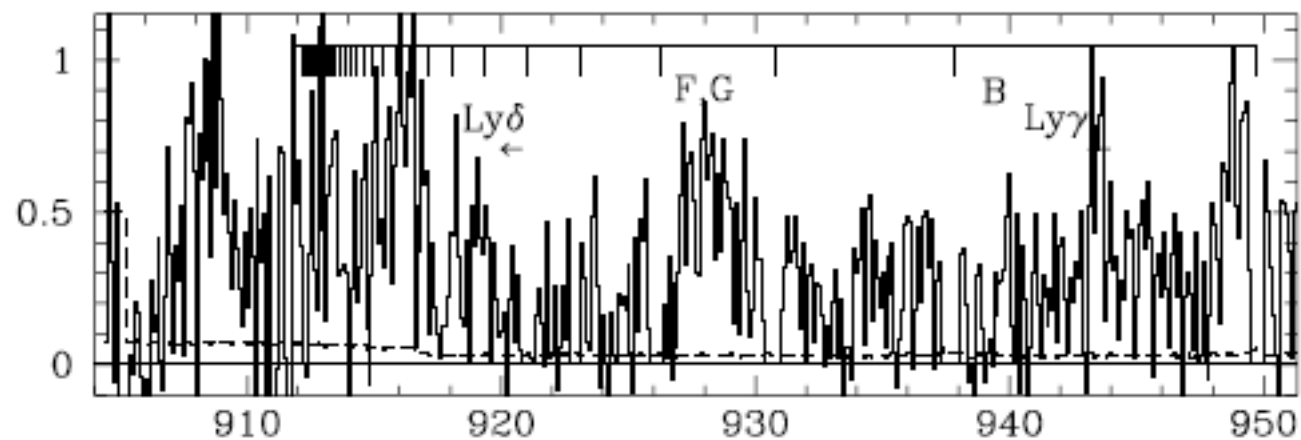
Effect of temperature on cut-off in the b-N relation



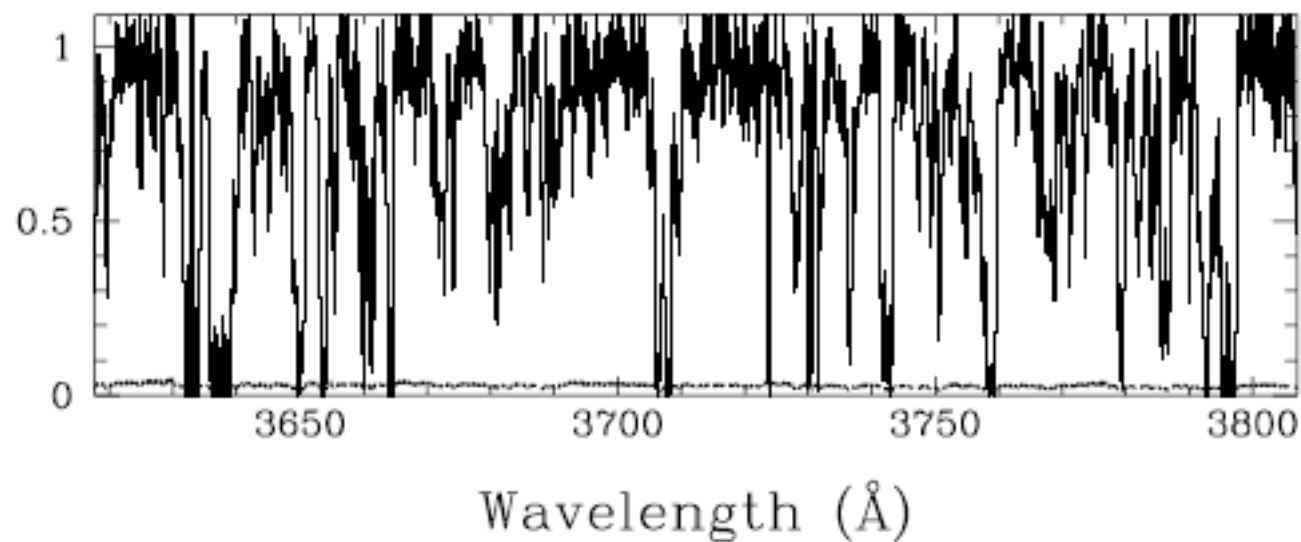


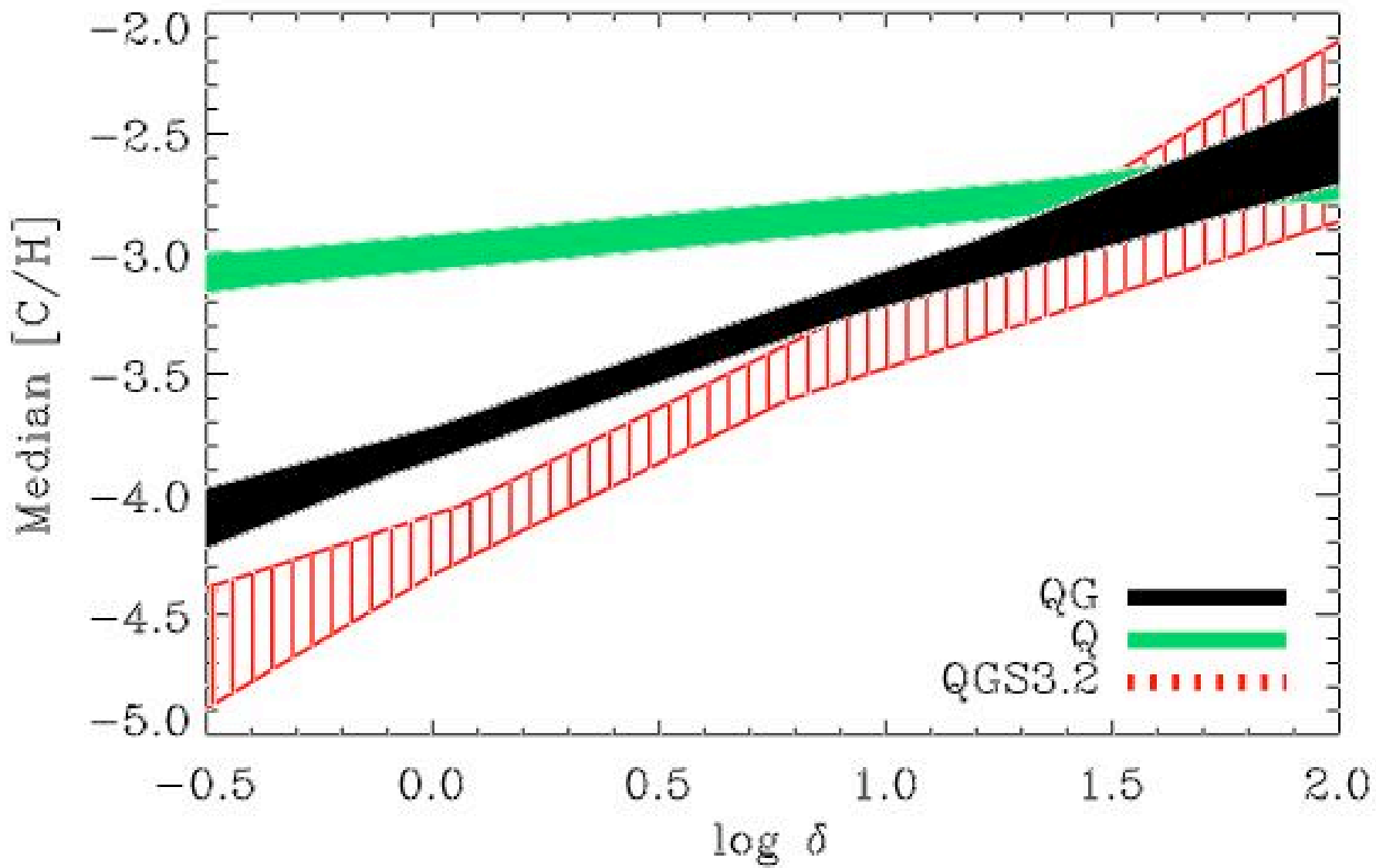


HeII

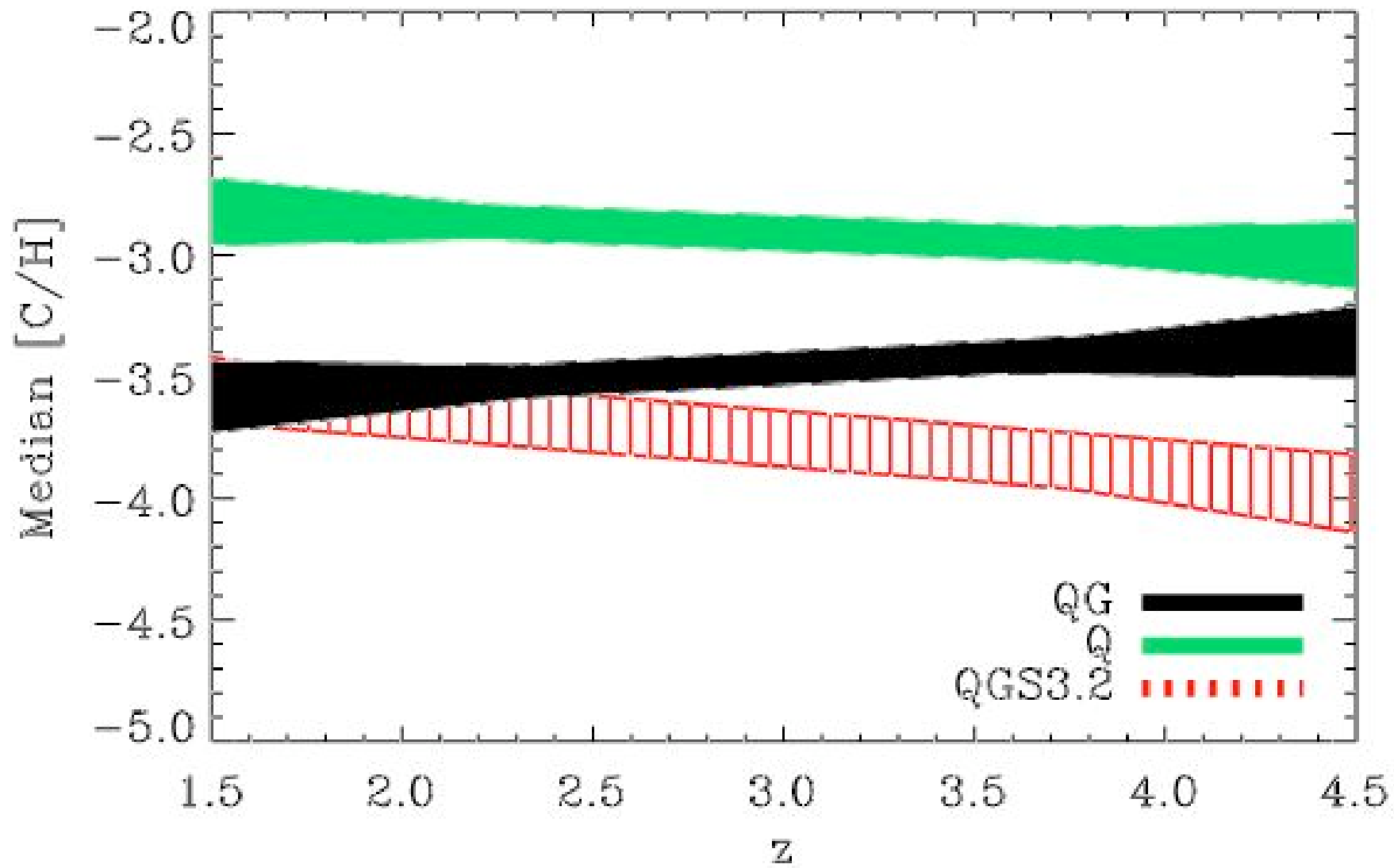


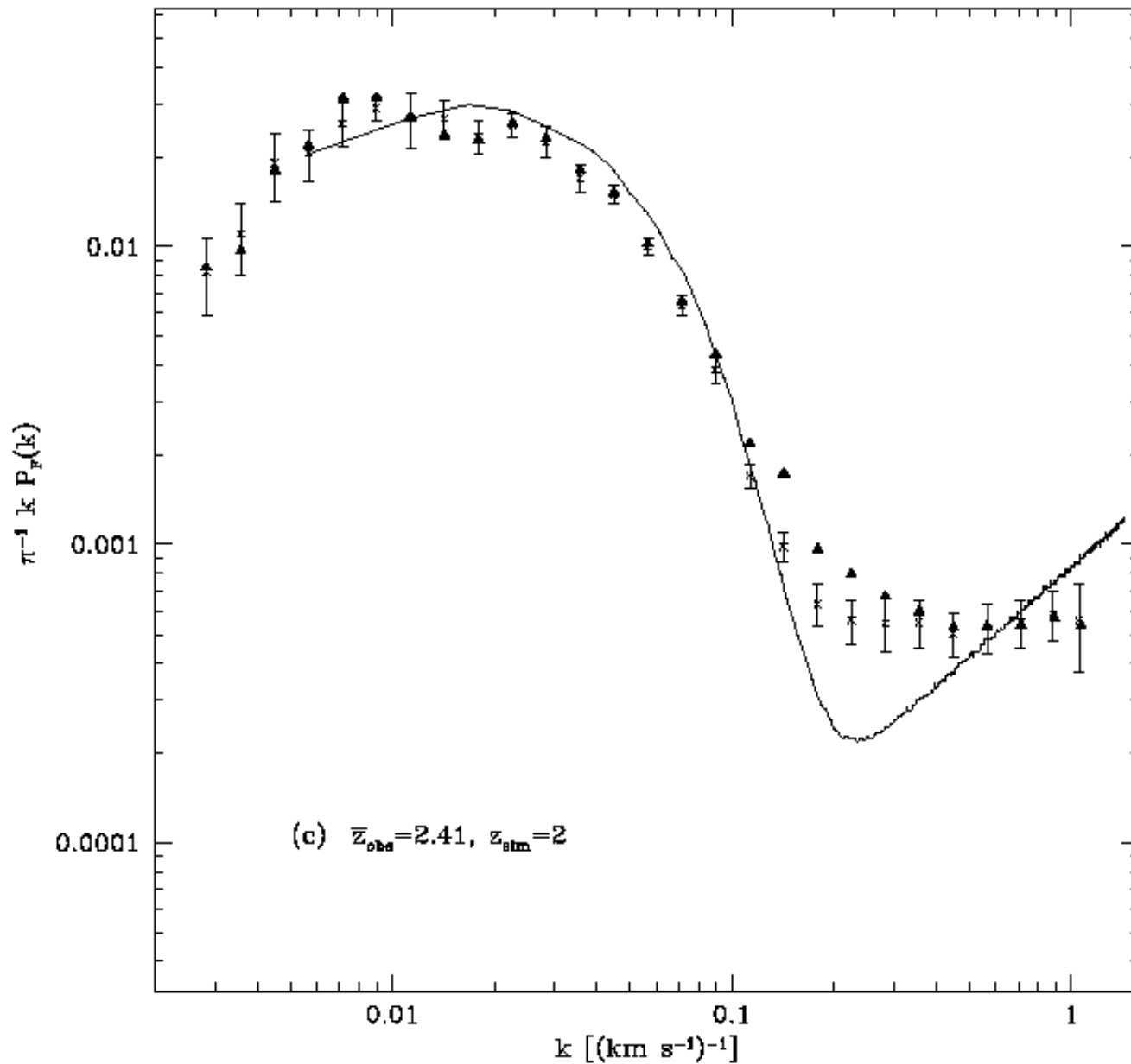
HI





Schaye et al





Lyman-alpha flux power spectrum