Cosmological Radiative Transfer and the Epoch of Reionization

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Bibliografia:
Haardt & Madau, 2012, ApJ, 746, 125

Trasporto Radiativo Cosmologico ed epoca della Reionizzazione

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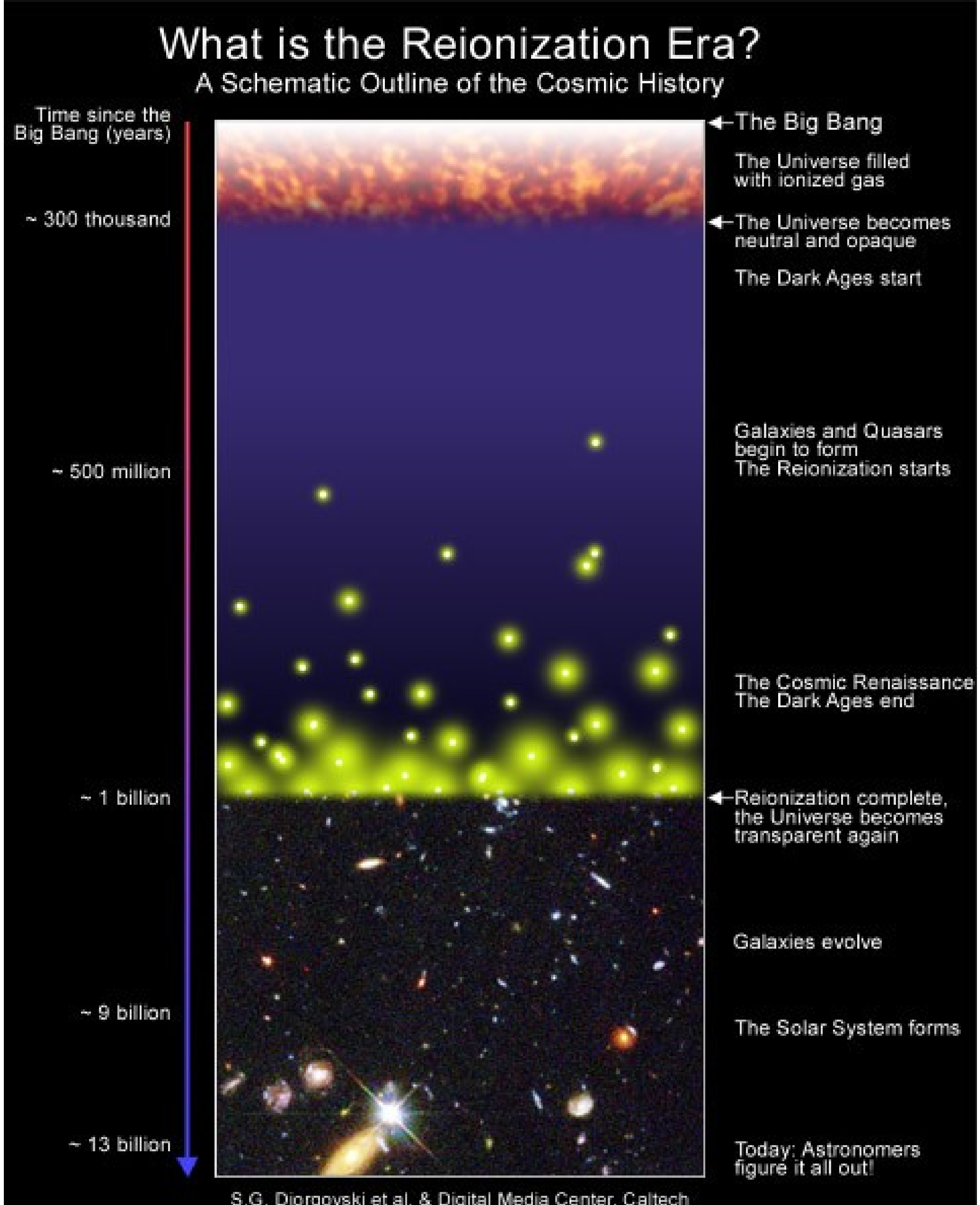
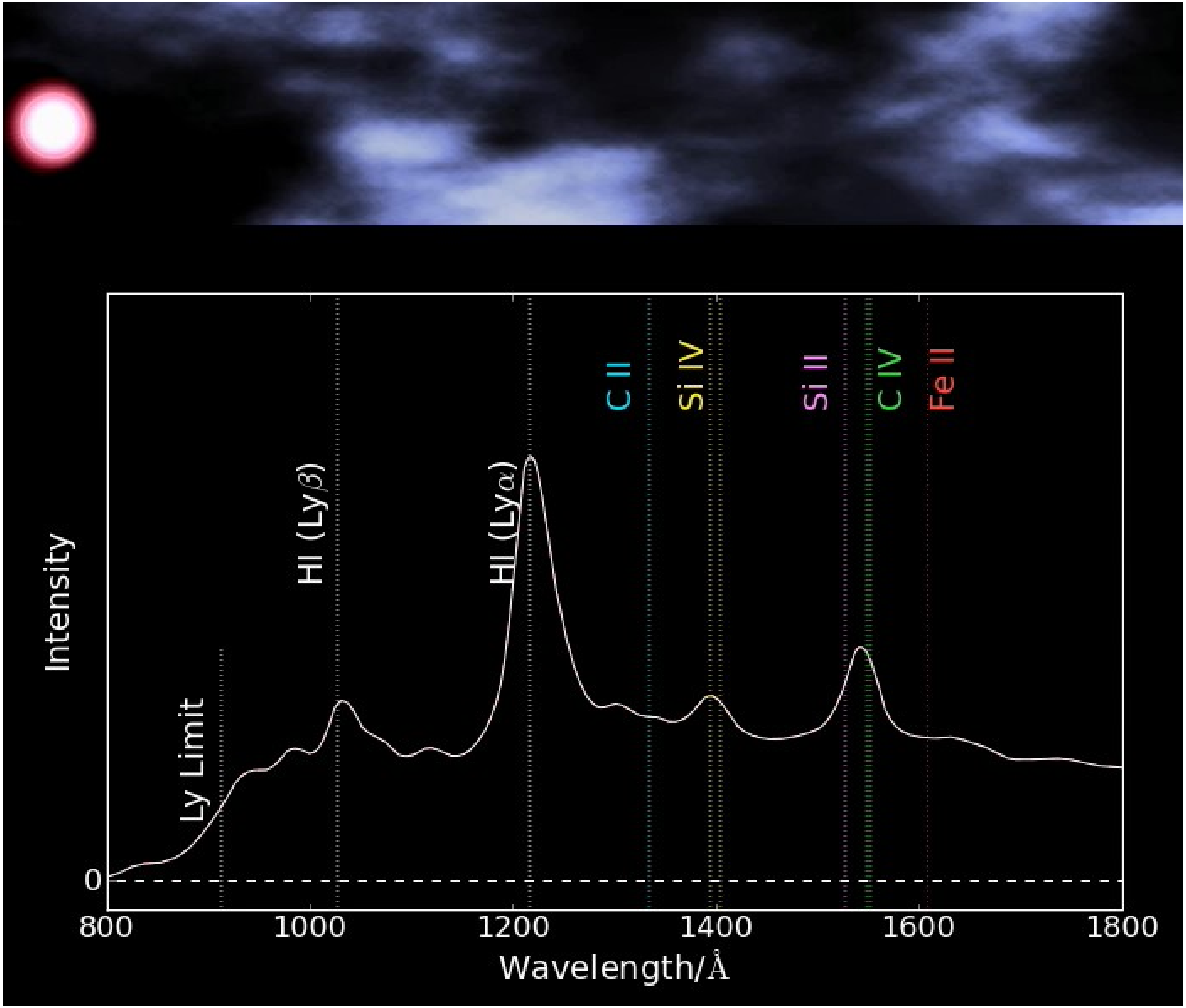
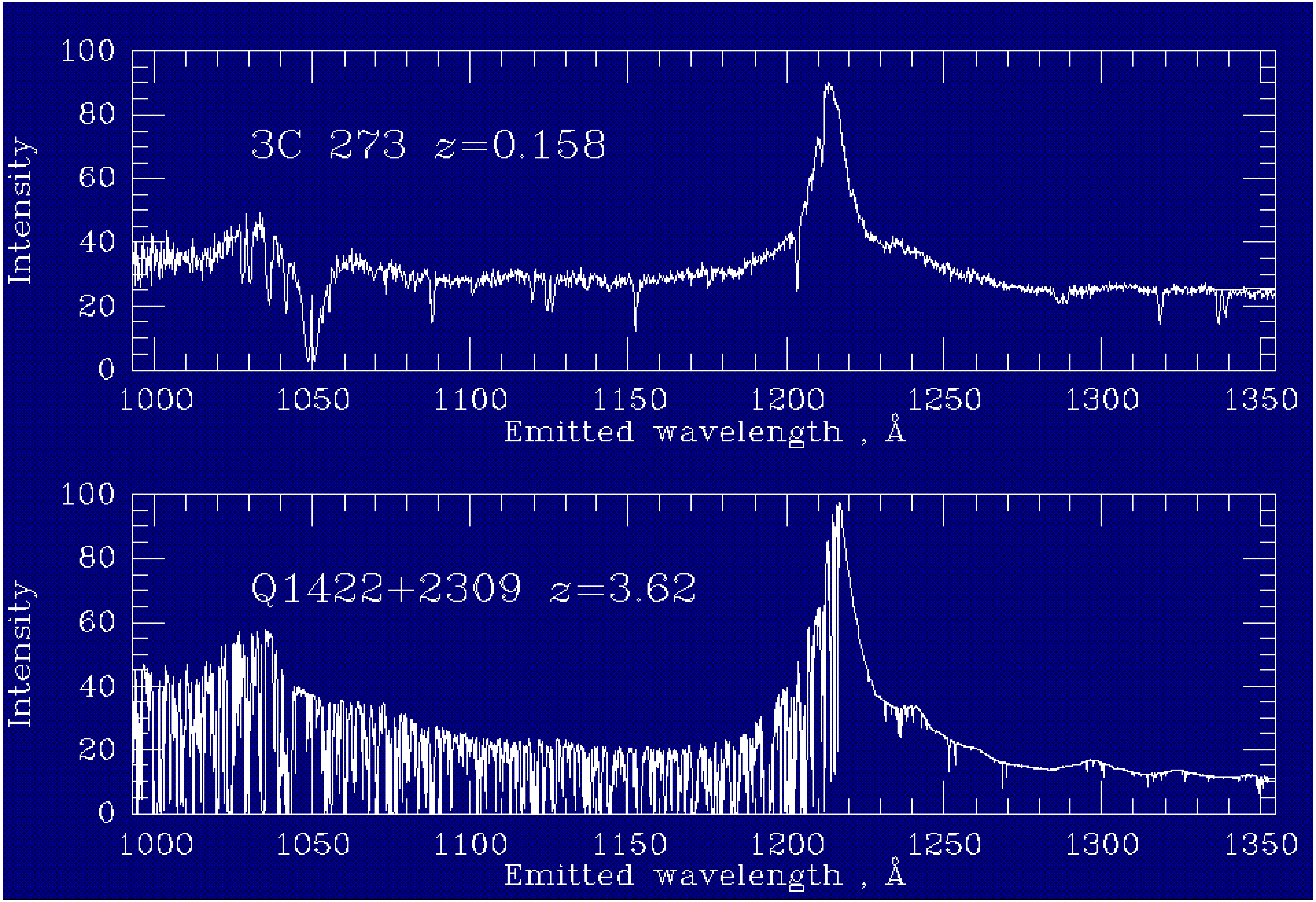
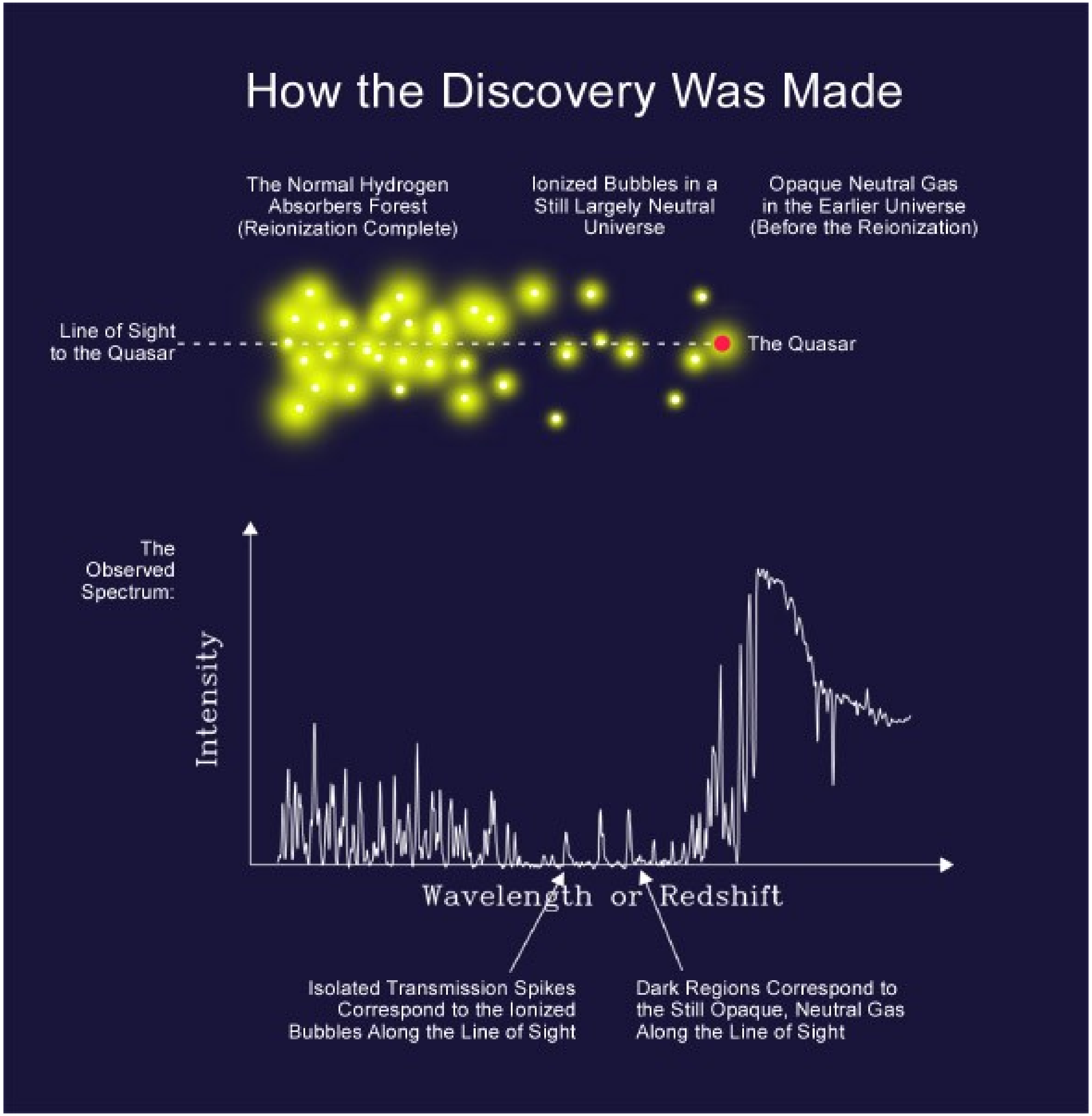

What is the Reionization Era?
A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

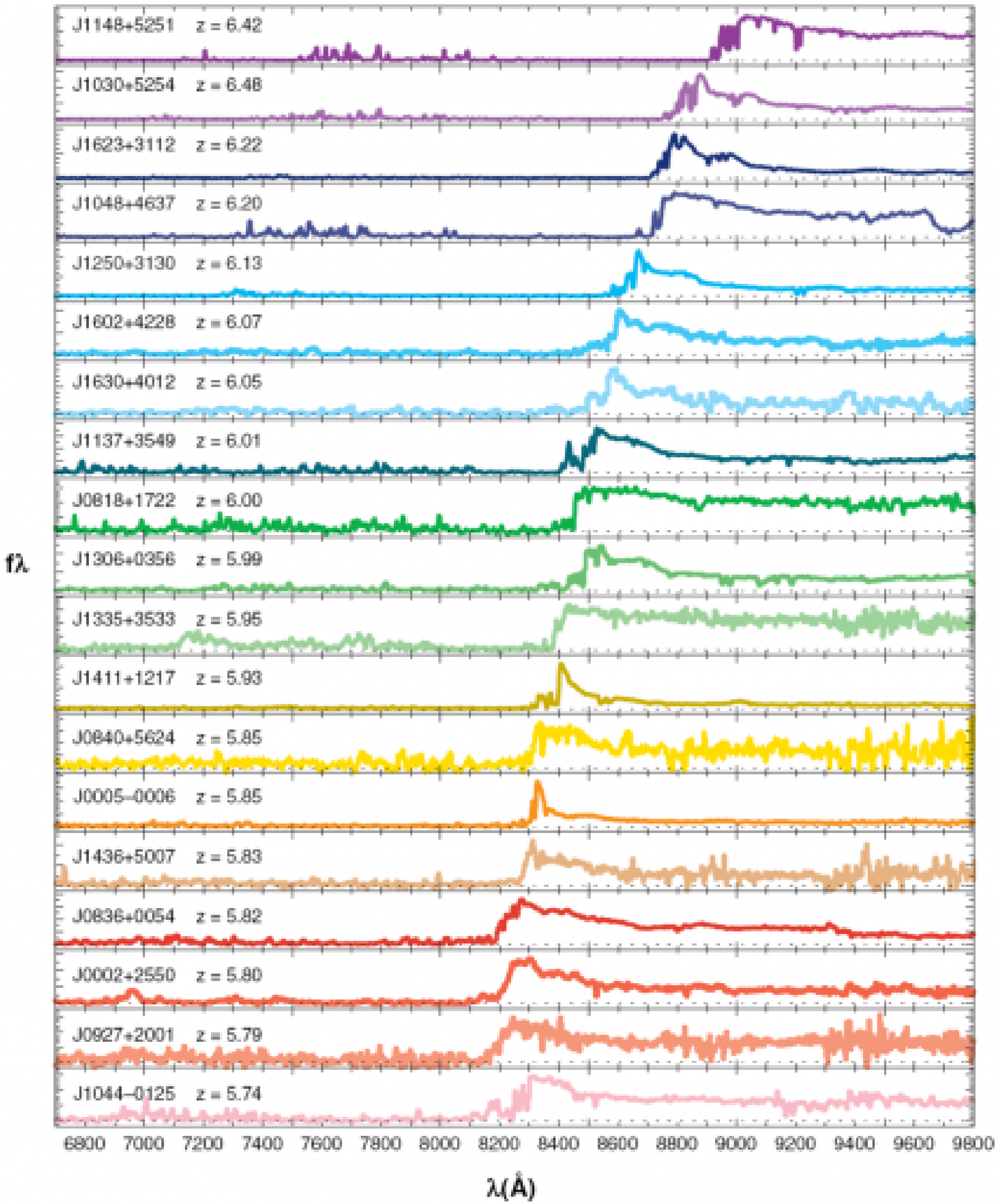

Intensity
0
800
1000
1200
1400
1600
1800
Wavelength/Å
Ly Limit
HI (Lyβ)
HI (Lyα)
C II
Si IV
Si II
C IV
Fe II

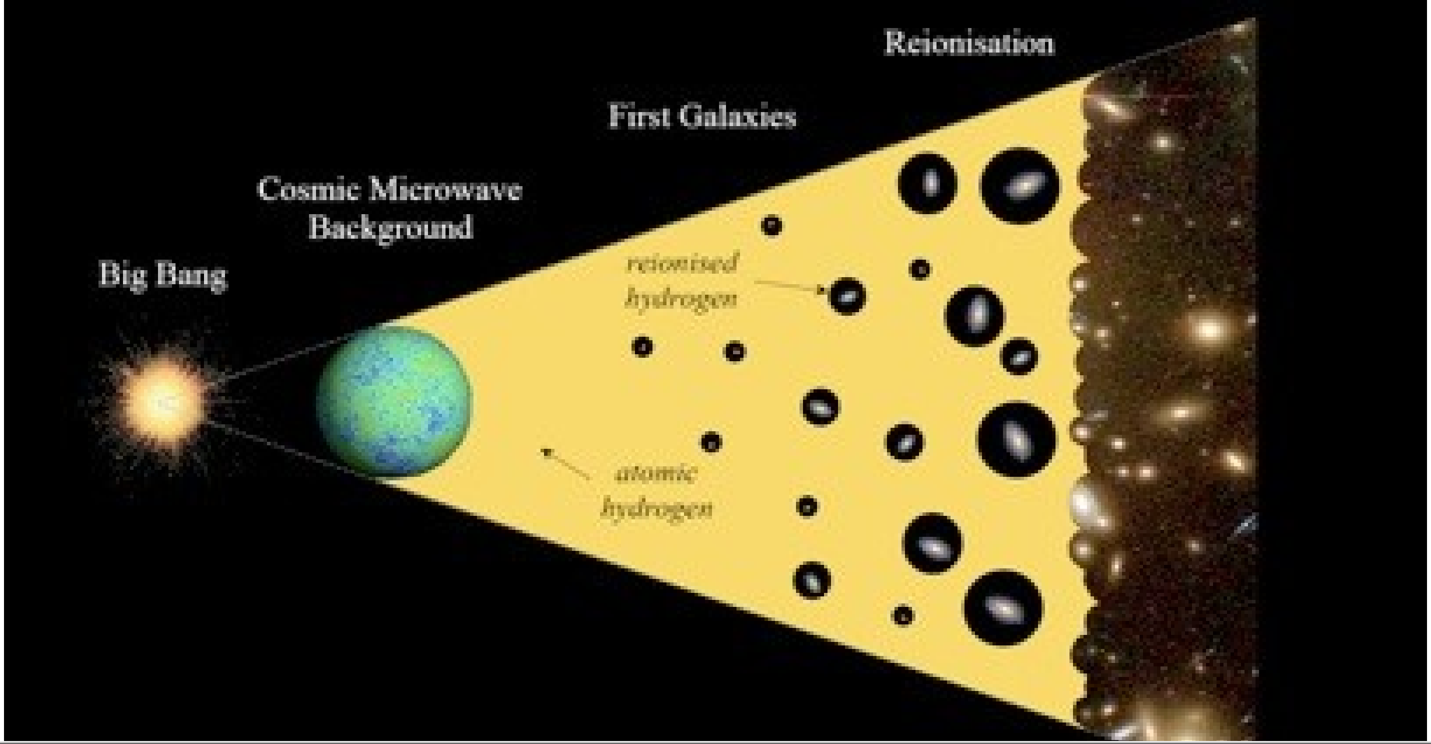


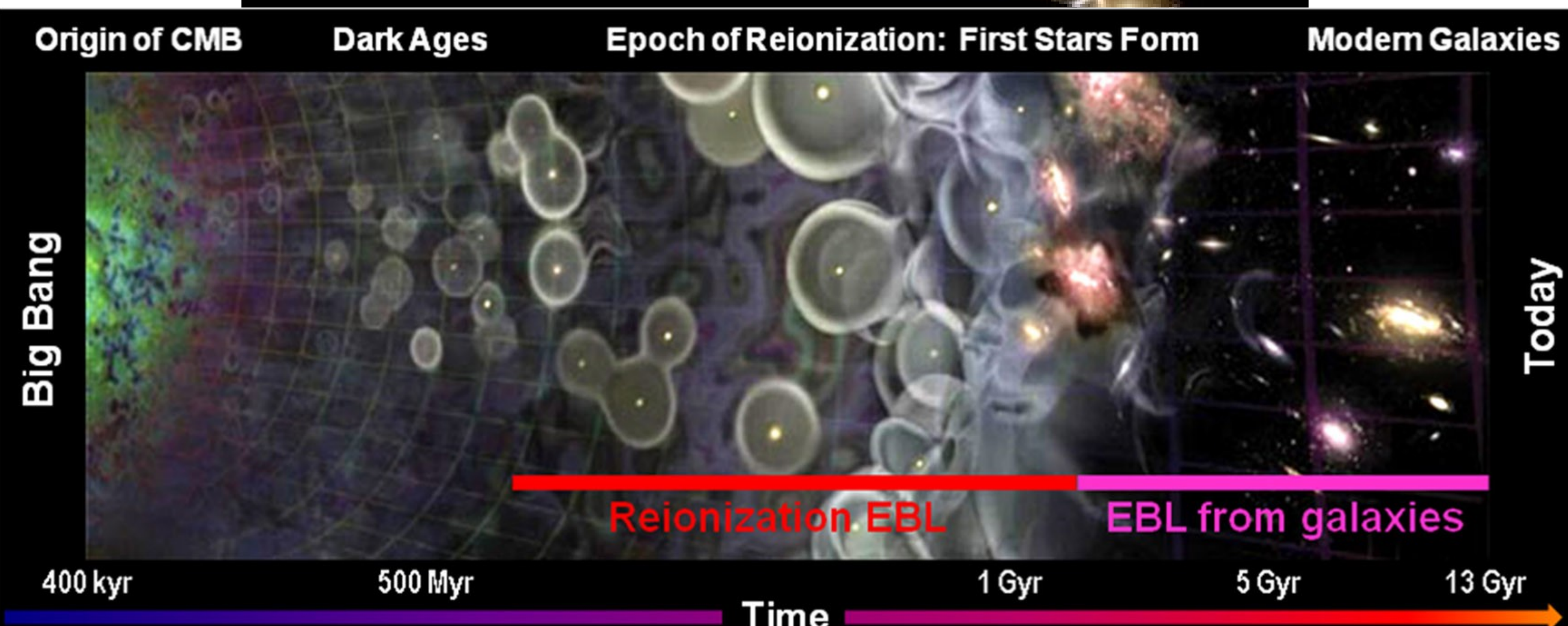
3C 273 z=0.158
Intensity
100
80
60
40
20
0
1000
1050
1100
1150
1200
1250
1300
1350
Emitted wavelength , Å
Q1422+2309 z=3.62
Intensity
100
80
60
40
20
0
1000
1050
1100
1150
1200
1250
1300
1350
Emitted wavelength , Å

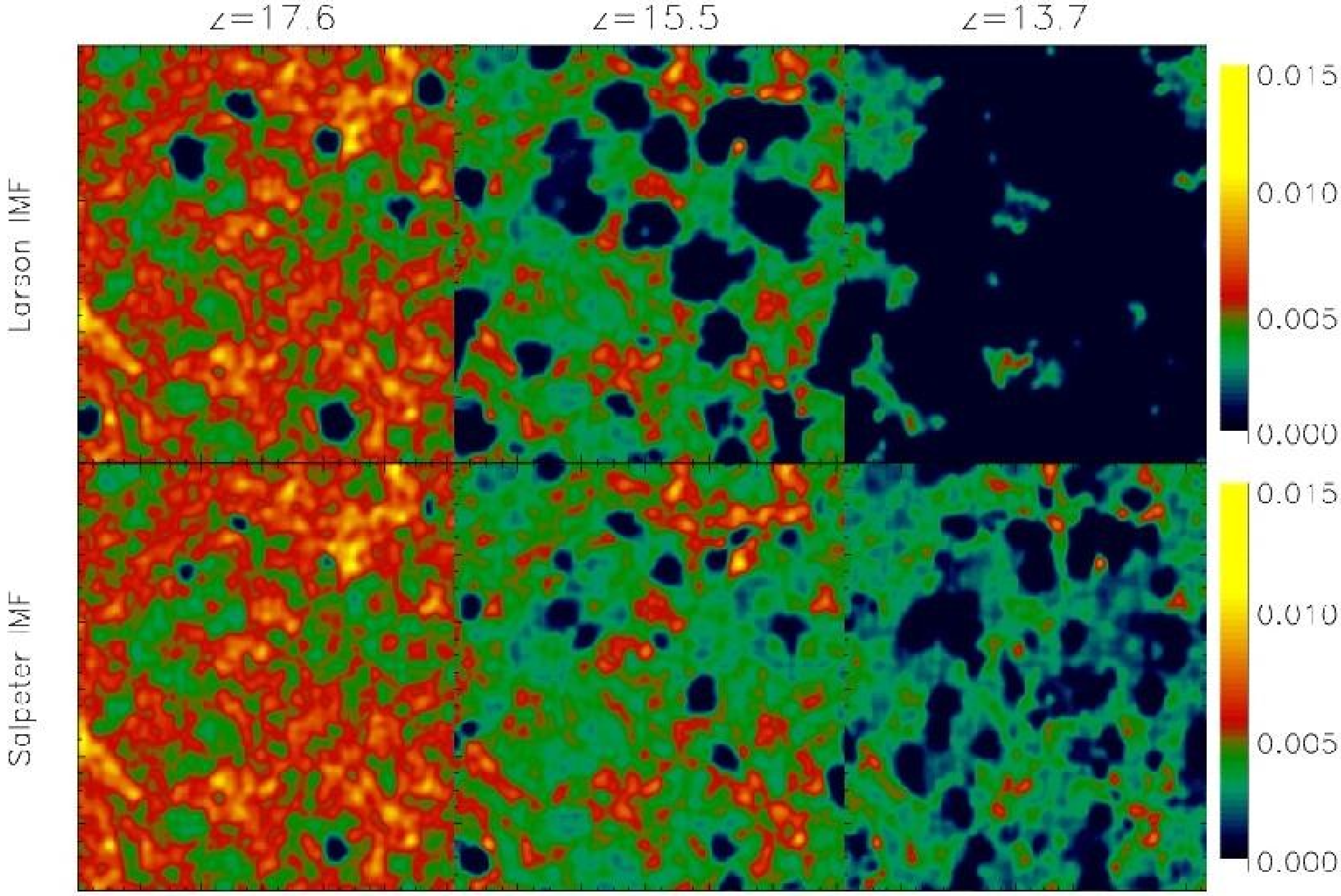
Gunn & Peterson Effect




J1148+5251 z = 6.42
J1030+5254 z = 6.48
J1623+3112 z = 6.22
J1048+4637 z = 6.20
J1250+3130 z = 6.13
J1602+4228 z = 6.07
J1630+4012 z = 6.05
J1137+3549 z = 6.01
J0818+1722 z = 6.00
J1306+0356 z = 5.99
J1335+3533 z = 5.95
J1411+1217 z = 5.93
J0840+5624 z = 5.85
J0005–0006 z = 5.85
J1436+5007 z = 5.83
J0836+0054 z = 5.82
J0002+2550 z = 5.80
J0927+2001 z = 5.79
J1044–0125 z = 5.74
fλ
6800 7000 7200 7400 7600 7800 8000 8200 8400 8600 8800 9000 9200 9400 9600 9800
λ(Å)


Reionisation
First Galaxies
Cosmic Microwave
Background
Big Bang
reionised
hydrogen
atomic
hydrogen


Origin of CMB
Dark Ages
Epoch of Reionization: First Stars Form
Modern Galaxies
Big Bang
Today
Reionization EBL
EBL from galaxies
400 kyr
500 Myr
1 Gyr
5 Gyr
13 Gyr
Time


z=17.6
z=15.5
z=13.7
Larson IMF
Salpeter IMF
0.015
0.010
0.005
0.000
0.015
0.010
0.005
0.000

HII volume filling factor

$$\frac{dQ_{\rm H\,II}}{dt} = \frac{\dot{n}_{\rm ion}}{\bar{n}_{\rm H}} - \frac{Q_{\rm H\,II}}{\bar{t}_{\rm rec}}$$

Filling Factor of reionized H

Mean comoving density of H atoms

Recombination Rate

$$\bar{t}_{\rm rec}\ ({\rm Gyr}) \simeq 0.93\,\frac{3}{C(z)}\left(\frac{T(a)}{2\times 10^4\ {\rm K}}\right)^{0.7}\left(\frac{1+z}{7}\right)^{-3}$$

HII volume filling factor

Rate of ionizing photons per unit comoving volume

$$\dot{N}_{\rm ion}(z) = \int_{\nu_{\rm H}}^{\nu_{\rm up}} \frac{\rho_\nu}{h_p \nu} {\rm d}\nu$$

Comoving Volume Emissivity

[s^{-1} Mpc^{-3}]

Photoionization rate

$$\Gamma(z) = 4\pi \int_{\nu_{\rm H}}^{\nu_{\rm up}} \frac{J(\nu, z)}{h_p \nu} \sigma_{\rm H\,I}(\nu)\,{\rm d}\nu$$

Background intensity

Absorbing cross-section for HI

[s^{-1}]

νH = LL (912 Å) frequency

Nup = 4 x νH

Cosmological Radiative Transfer

Equation of cosmological radiative transfer:
time evolution of the time- and space-averaged monochromatic intensity J_ν

$$\left(\frac{\partial}{\partial t} - \nu H \frac{\partial}{\partial \nu}\right) J_\nu + 3 H J_\nu = -c\kappa_\nu J_\nu + \frac{c}{4\pi}\epsilon_\nu$$

Hubble function (H)

Absorption coefficient (κ_ν)

Proper Volume Emissivity (ϵ_ν)

Solution (e.g. Peebles 1993):

$$J_{\nu_o}(z_o) = \frac{c}{4\pi}\int_{z_o}^{\infty} |dt/dz| dz \frac{(1+z_o)^3}{(1+z)^3}\epsilon_\nu(z) e^{-\bar{\tau}}$$

Cosmological Radiative Transfer

$$J_{\nu_o}(z_o) = \frac{c}{4\pi}\int_{z_o}^{\infty} |dt/dz|\, dz\, \frac{(1+z_o)^3}{(1+z)^3}\,\epsilon_\nu(z)\, e^{-\bar{\tau}}$$

Frequency Redshift of the observer

Line element

$$|dt/dz| = H^{-1}(1+z)^{-1}$$

Frequency at emission

$$\nu = \nu_o(1+z)/(1+z_o)$$

Cosmological Radiative Transfer

$$J_{\nu_o}(z_o) = \frac{c}{4\pi} \int_{z_o}^{\infty} |dt/dz| dz \frac{(1+z_o)^3}{(1+z)^3} \epsilon_\nu(z) e^{-\bar{\tau}}$$

Effective absorption optical depth

$$\bar{\tau}_c(\nu_o, z_o, z) = \int_{z_o}^{z} dz' \int_0^{\infty} dN_{\rm H\,I}\, f(N_{\rm H\,I}, z')(1 - e^{-\tau_c})$$

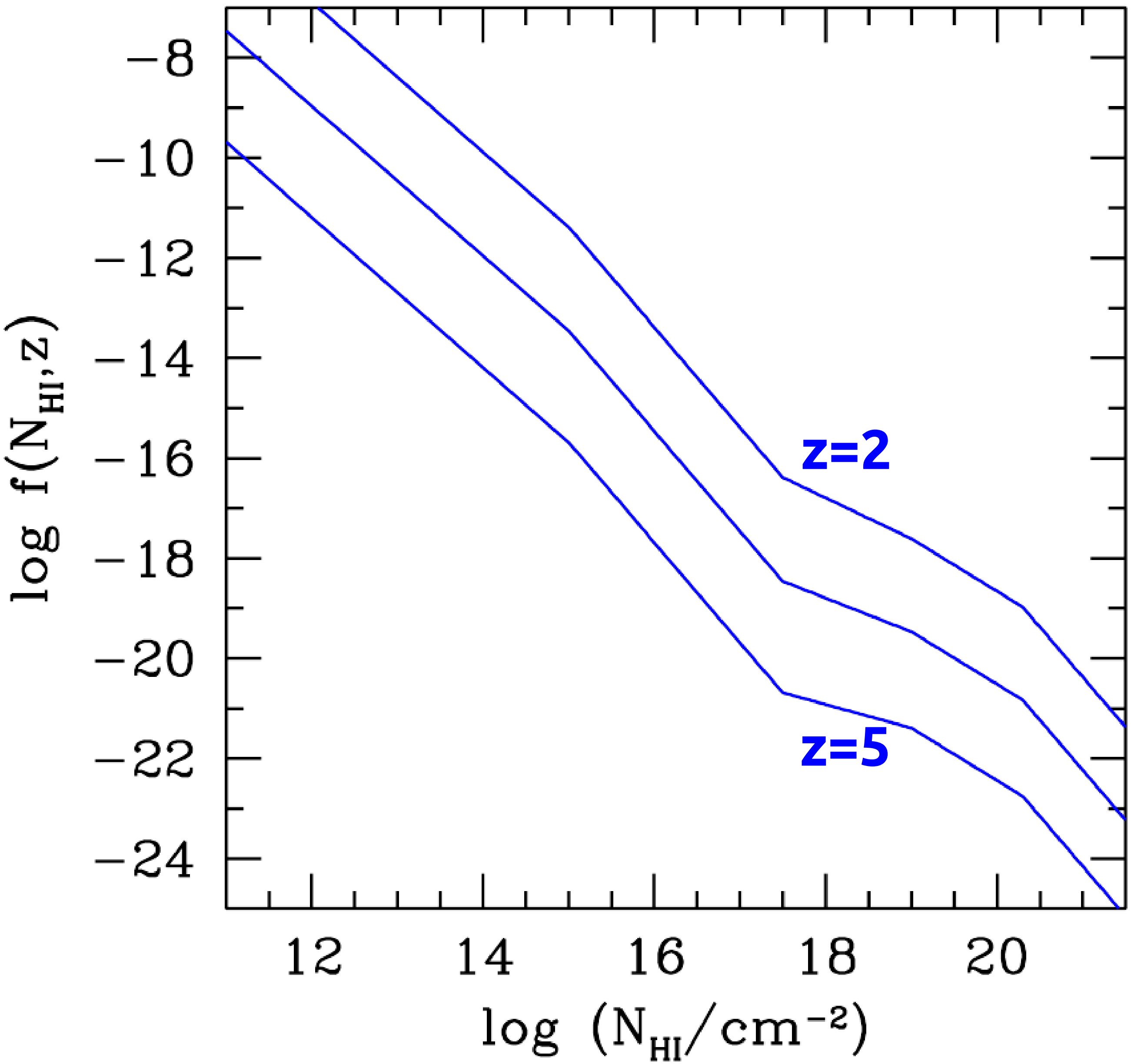
Optical depth through an individual absorber at frequency $\nu' = \nu_o(1+z')/(1+z_o)$
(pure H and He gas)

$$\tau_c(\nu') = N_{\rm H\,I}\sigma_{\rm H\,I}(\nu') + N_{\rm He\,I}\sigma_{\rm He\,I}(\nu') + N_{\rm He\,II}\sigma_{\rm He\,II}(\nu')$$

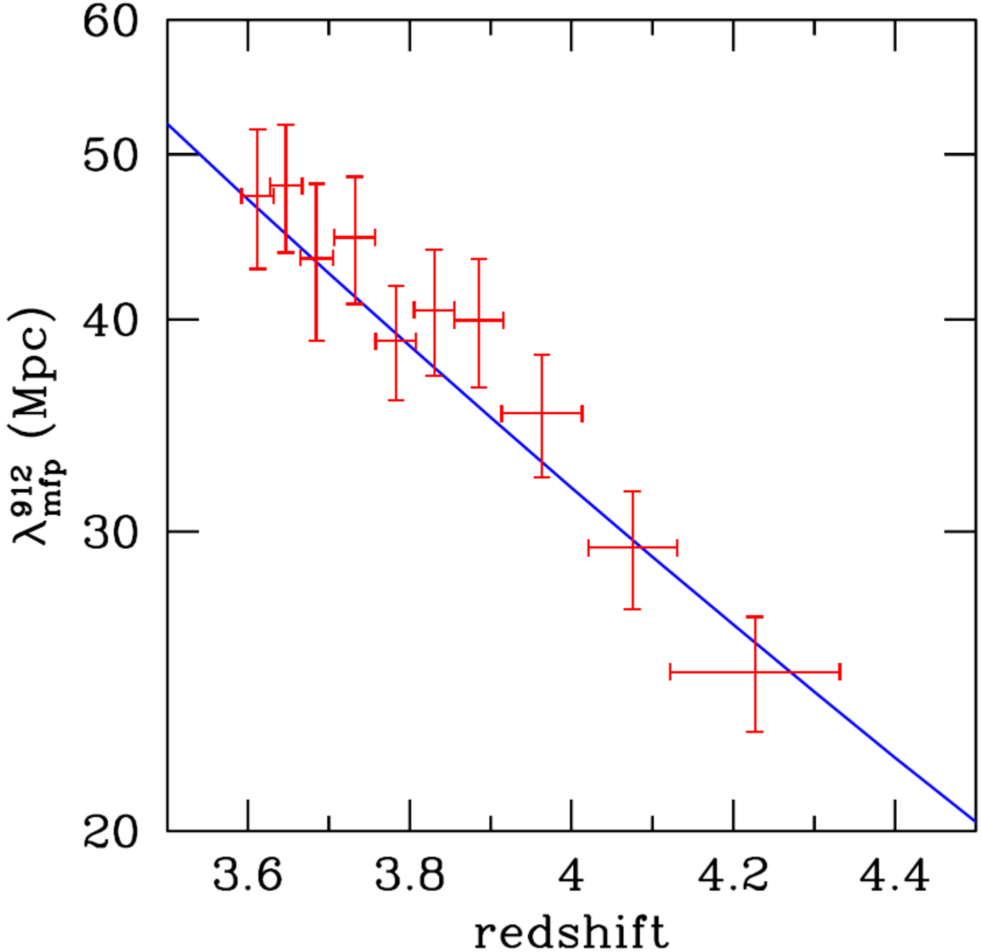
Bivariate distribution of absorbers in redshift and column density

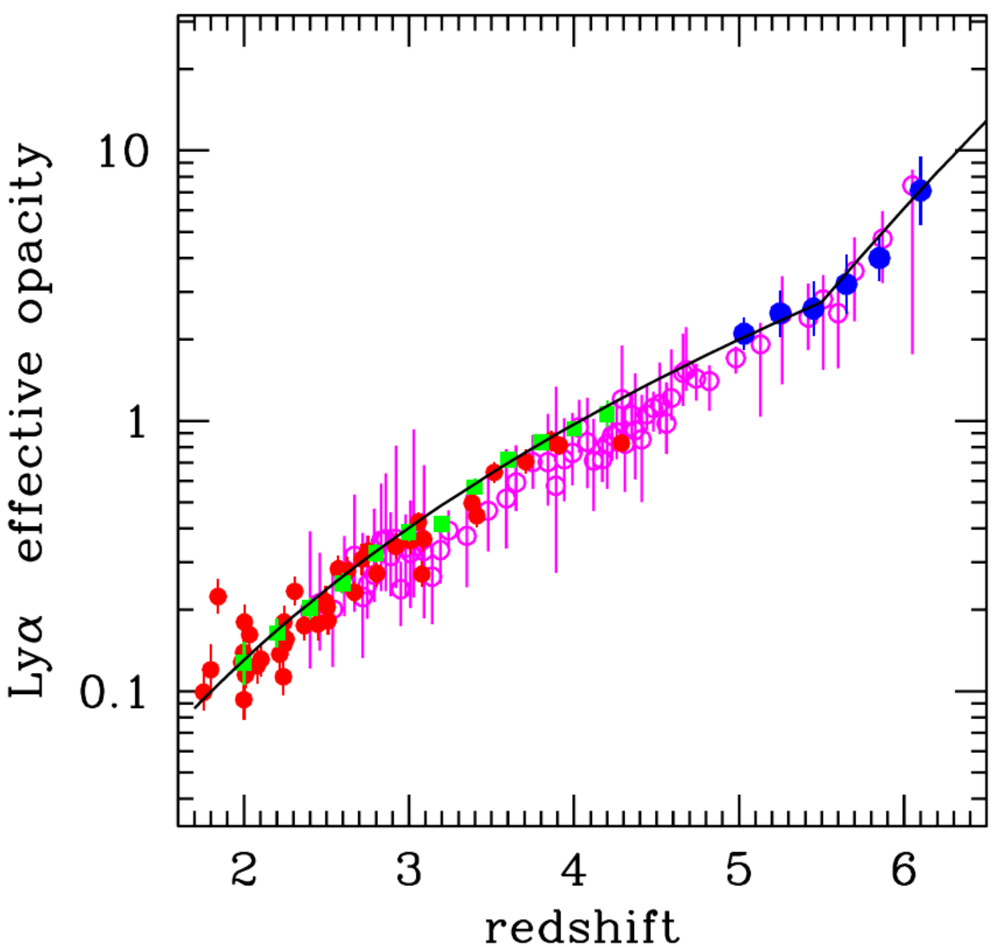
$$f(N_{\rm H\,I}, z) = A\, N_{\rm H\,I}^{-\beta}(1+z)^{\gamma}$$

$$f(N_{\rm H\,I}, z) = A\, N_{\rm H\,I}^{-\beta}(1+z)^{\gamma}$$

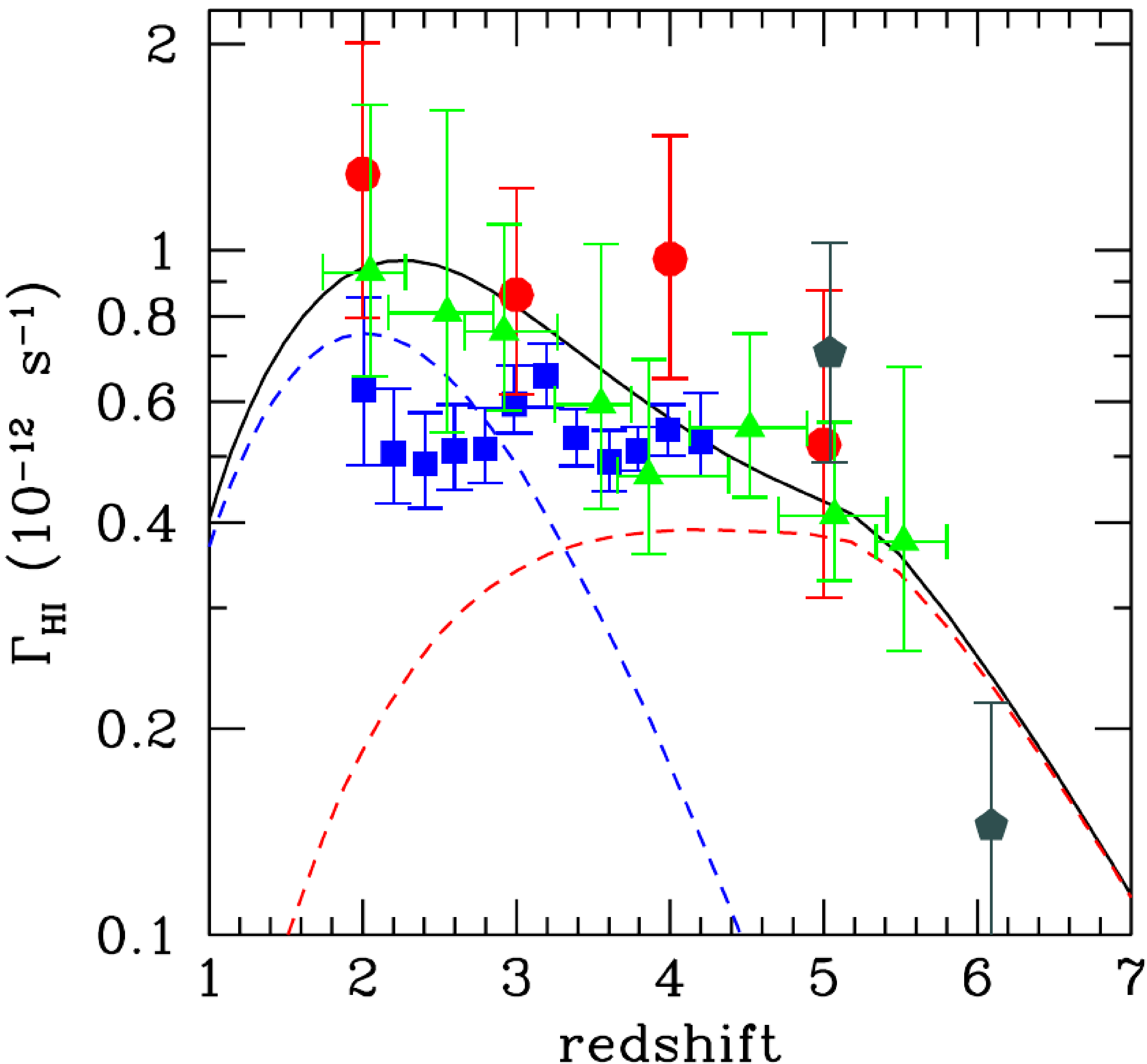


Cosmological Radiative Transfer





$$\lambda_{\rm mfp}^{912} = c|dt/dz| \times \frac{dz}{d\bar{\tau}_c}\bigg|_{\nu=\nu_{912}}$$



2
1
0.8
0.6
0.4
0.2
0.1
Γ_{HI} (10^{-12} s^{-1})
1
2
3
4
5
6
7
redshift

Sources of ionizing photons

Sources of ionizing photons

- Galaxies & Stars
- Active Galactix Nuclei & QSOs
- Exotic objects
  - Miniquasars
  - Pop III stars
  - DM decay

Source Contribution

$$J_{\nu_o}(z_o) = \frac{c}{4\pi} \int_{z_o}^{\infty} |dt/dz| dz \frac{(1+z_o)^3}{(1+z)^3} \epsilon_\nu(z) e^{-\bar{\tau}}$$

Comoving Volume Emissivity

$$\dot{N}_{\rm ion}(z) = \int_{\nu_{\rm H}}^{\nu_{\rm up}} \frac{\rho_\nu}{h_p \nu} \mathrm{d}\nu$$

Source Contribution

$$\rho_\nu = \int_{L_{\min}}^{\infty} f_{\mathrm{esc}}(L, z)\, \Phi(L, z)\, L_\nu(L)\, \mathrm{d}L$$

Minimum Luminosity

Escape Fraction

Luminosity Function

Spectral Shape

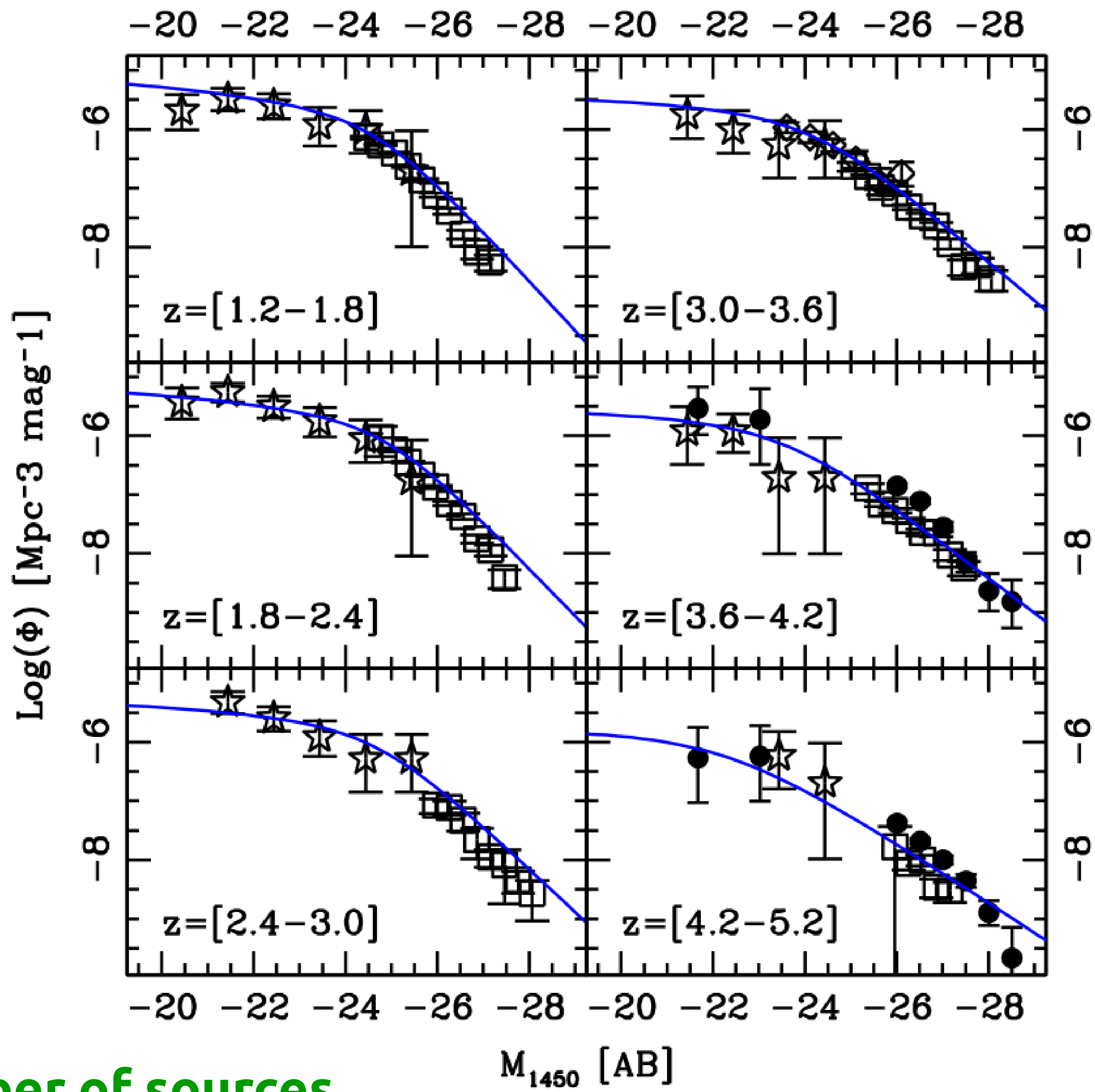
Active Galactic Nuclei (AGNs)

$$\Phi(L_{145}, z) = \frac{\Phi^\star(L^\star)}{(L_{145}/L^\star)^{-\alpha} + (L_{145}/L^\star)^{-\beta}}$$

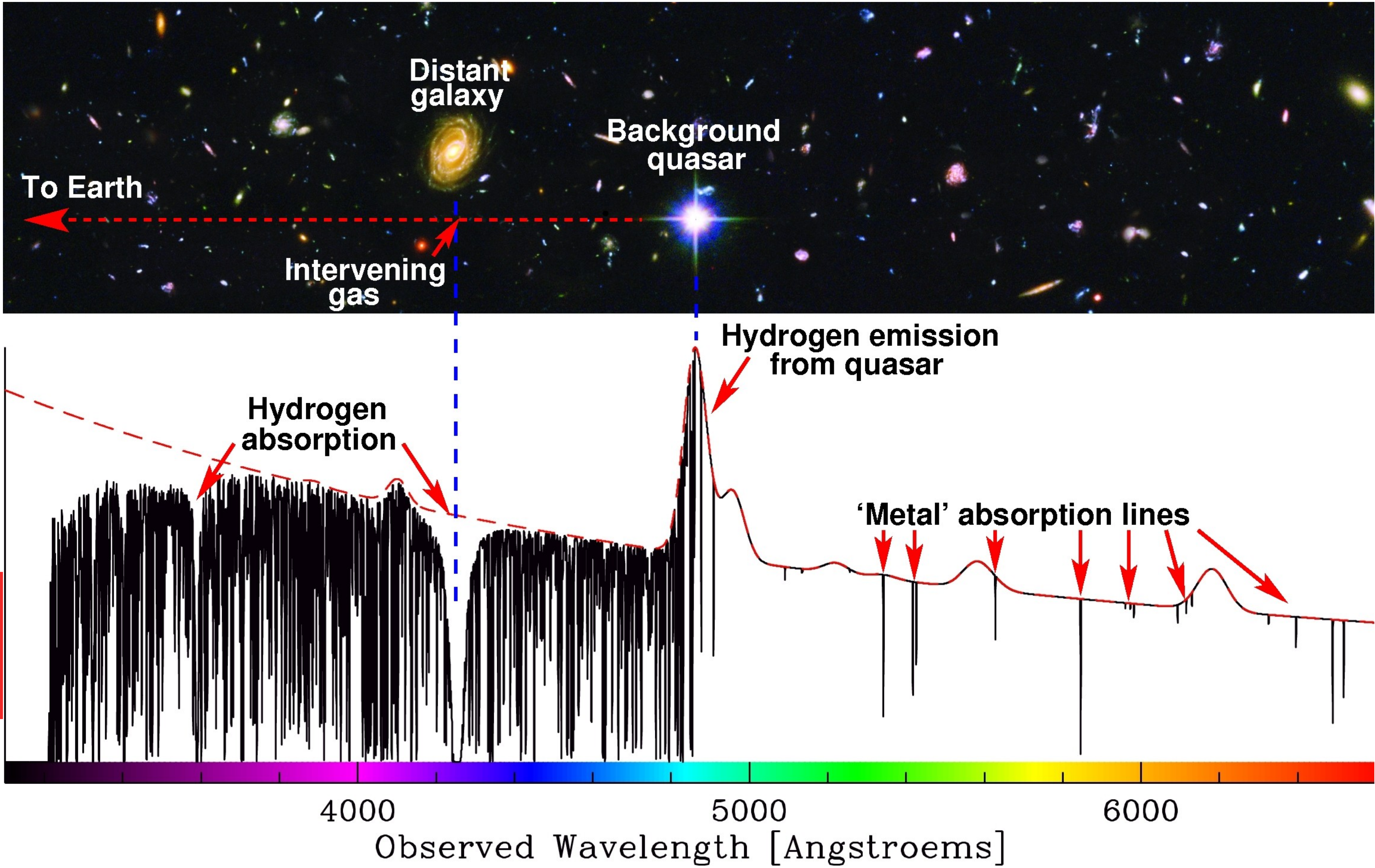
or, expressed in magnitudes:

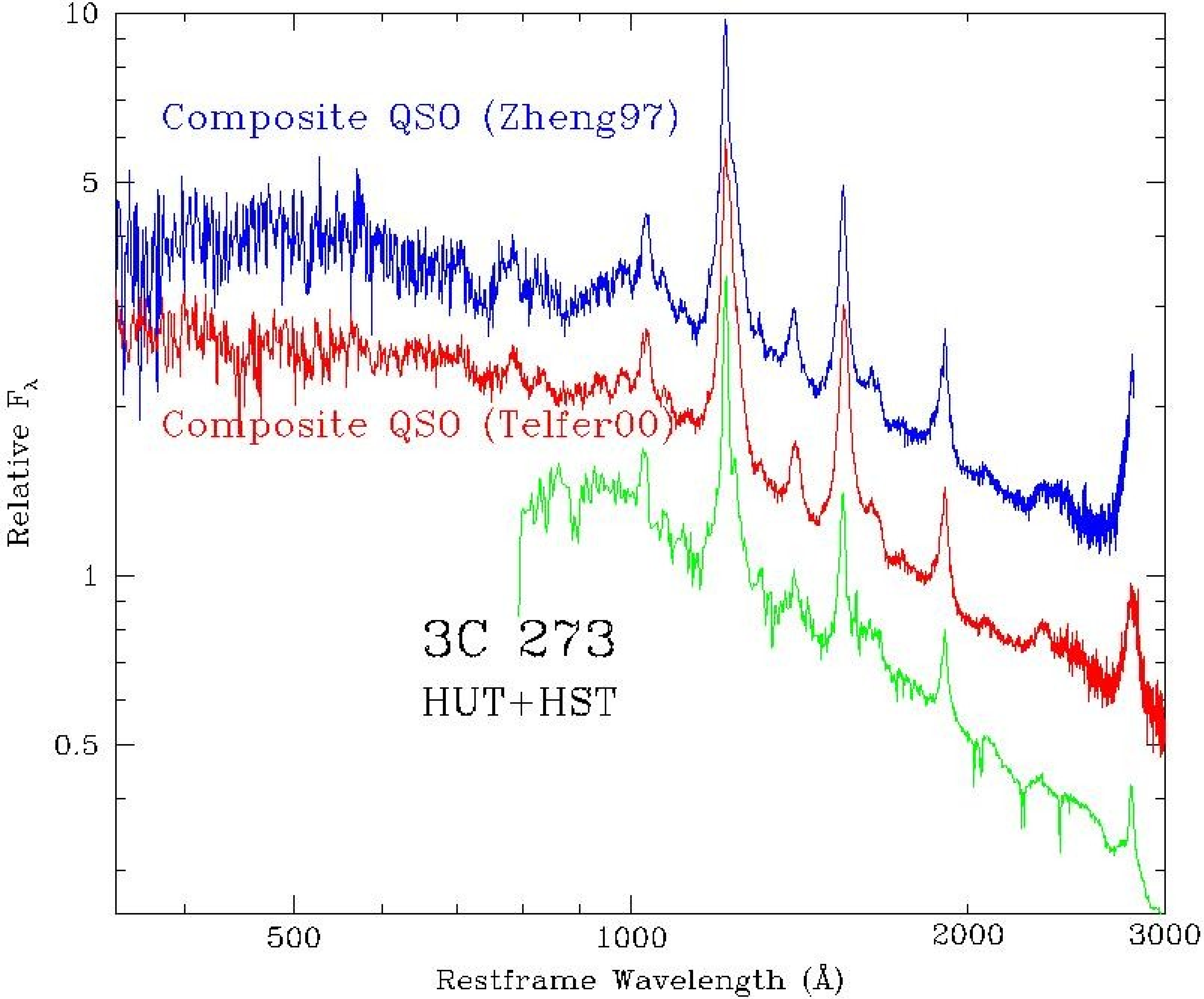
$$\Phi(M_{145}, z) = \frac{\Phi^\star(M^\star)}{10^{0.4(\alpha+1)(M_{145}-M^\star)} + 10^{0.4(\beta+1)(M_{145}-M^\star)}}.$$

Active Galactic Nuclei (AGNs)



Small number of sources


Distant galaxy
Background quasar
To Earth
Intervening gas
Hydrogen emission from quasar
Hydrogen absorption
'Metal' absorption lines
4000
5000
6000
Observed Wavelength [Angstroems]



Steep spectra → Large number of ionizing photons per source

Lyman Break Galaxies (LBGs)

The *Luminosity Function* (LF) $\Phi(L)$ gives the number dN of galaxies present in a volume dV with luminosities between $[L, L + dL]$:

$$dN = \Phi(L) dV dL \tag{1.1}$$

This function can be computed from a galaxy catalogue once the adopted objective selection criteria are specified and the distance of each object is known. In general the shape of the optical LF is well represented by the so called *Schechter Function*:

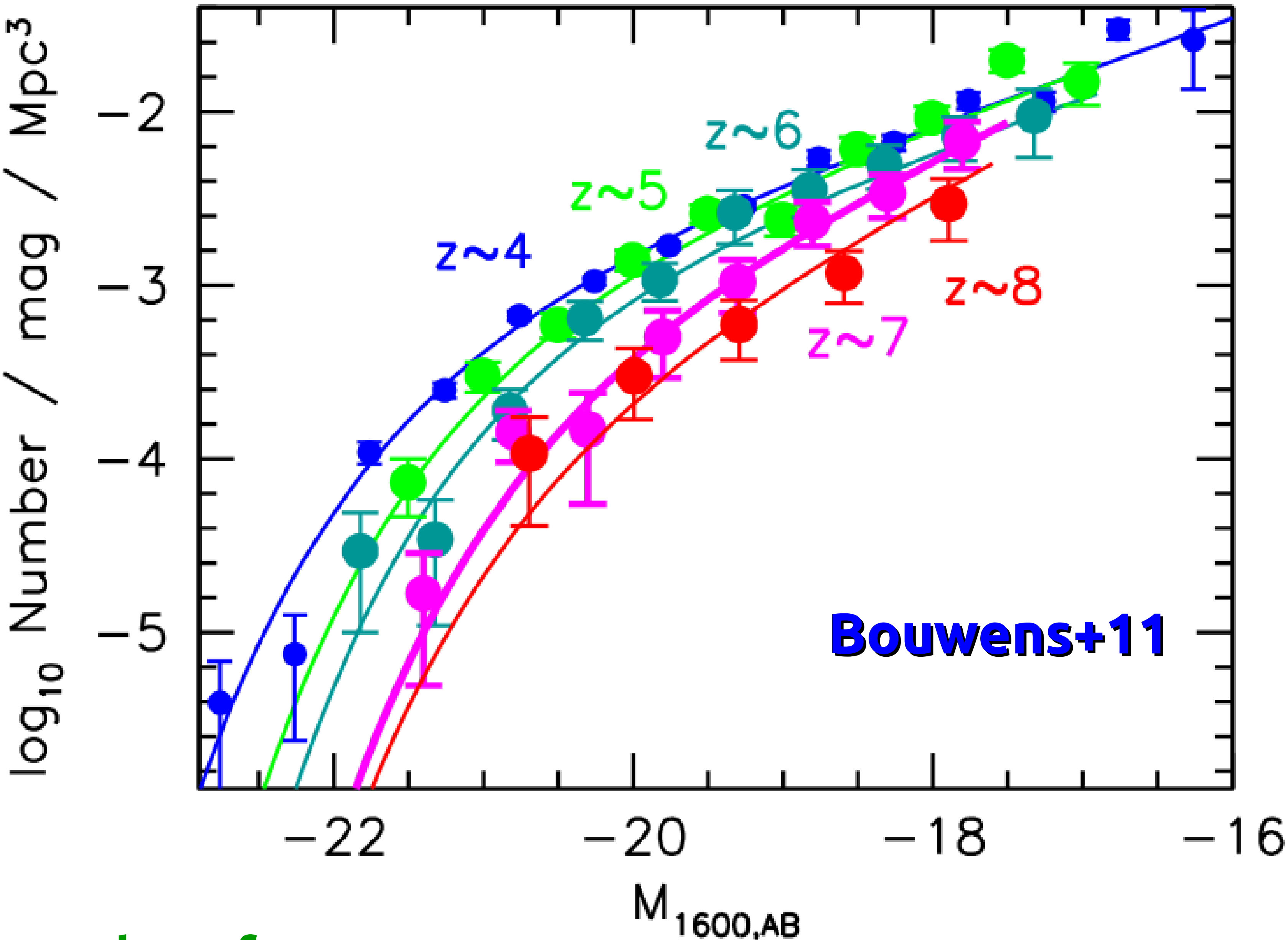
$$\Phi(L)dL = \Phi^\star (L/L^\star)^\alpha e^{-L/L^\star} d(L/L^\star) \tag{1.2}$$

The parameter $\Phi^\star$ is related to the number of galaxies in the catalogue with typical luminosity $L^\star$:

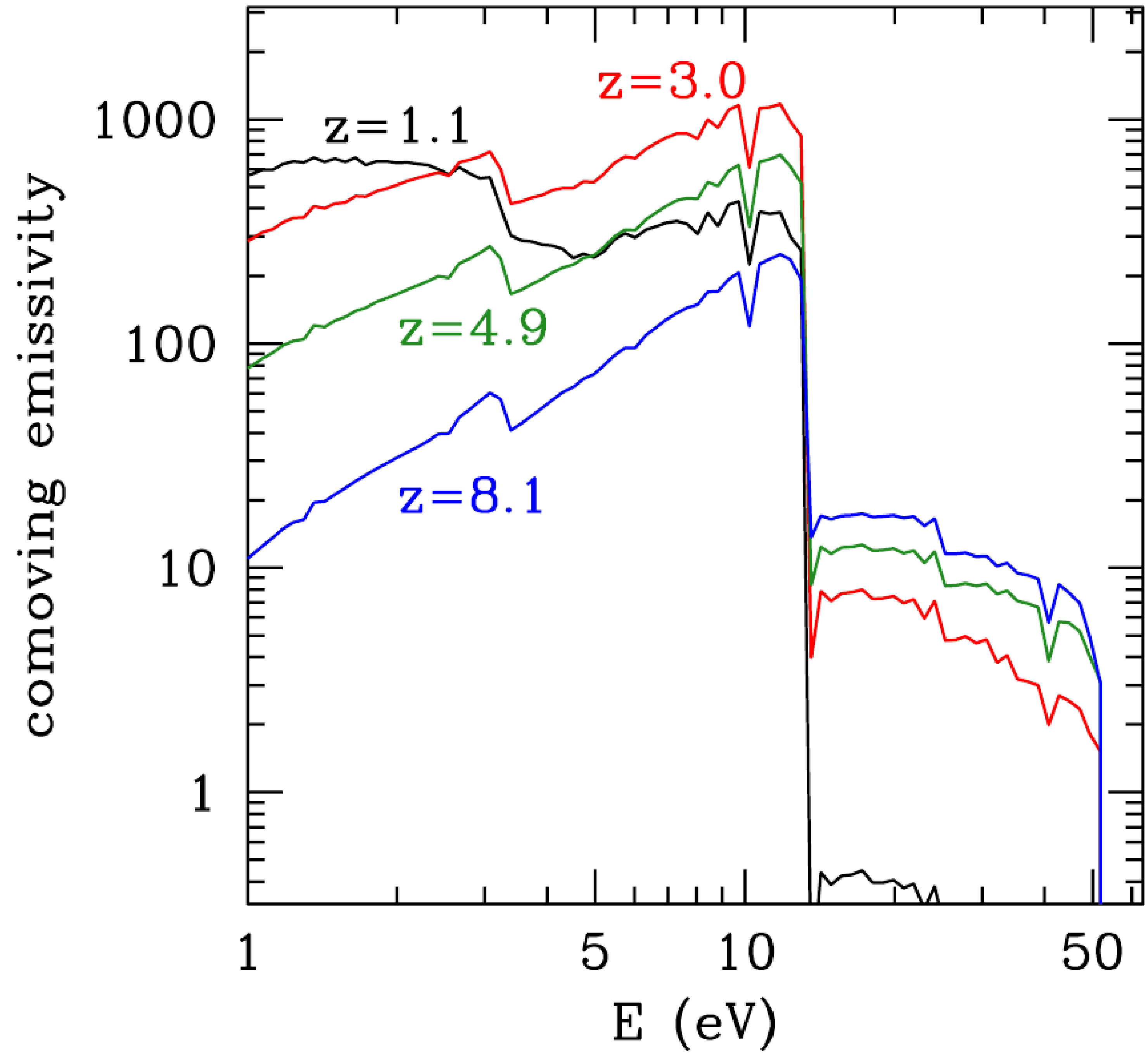
$$\Phi(L^\star) = (\Phi^\star/L^\star)e^{-1}$$

The Schechter function is specified by the two parameters $L^\star$ and α. For luminosities fainter than $L^\star$ it reduces to a power-law with slope α; at brighter luminosities it gets an exponential shape. The parameter $L^\star$ is the knee of

Lyman Break Galaxies (LBGs)

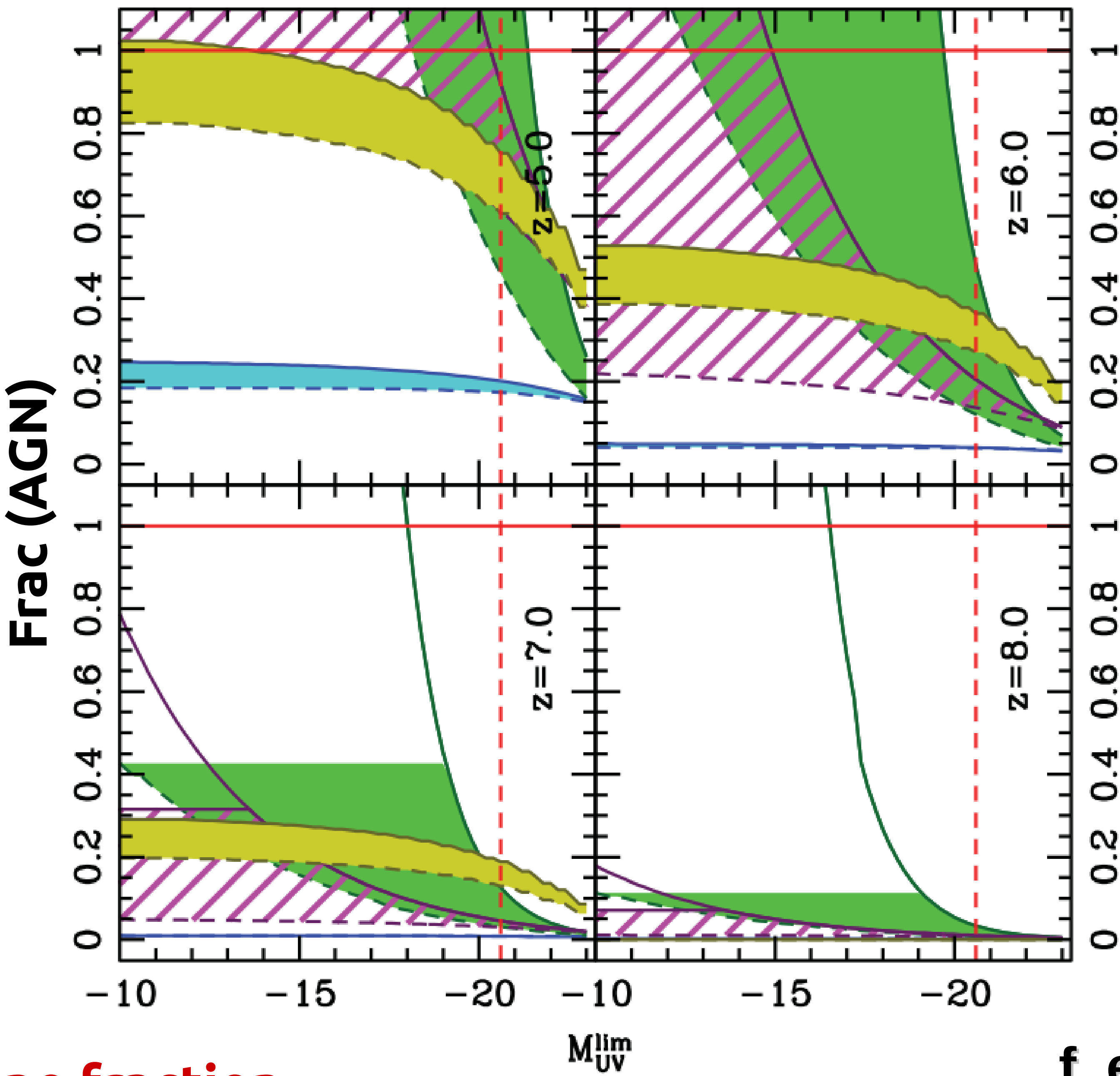


Large number of sources



Shallow spectra → Small number of ionizing photons per source

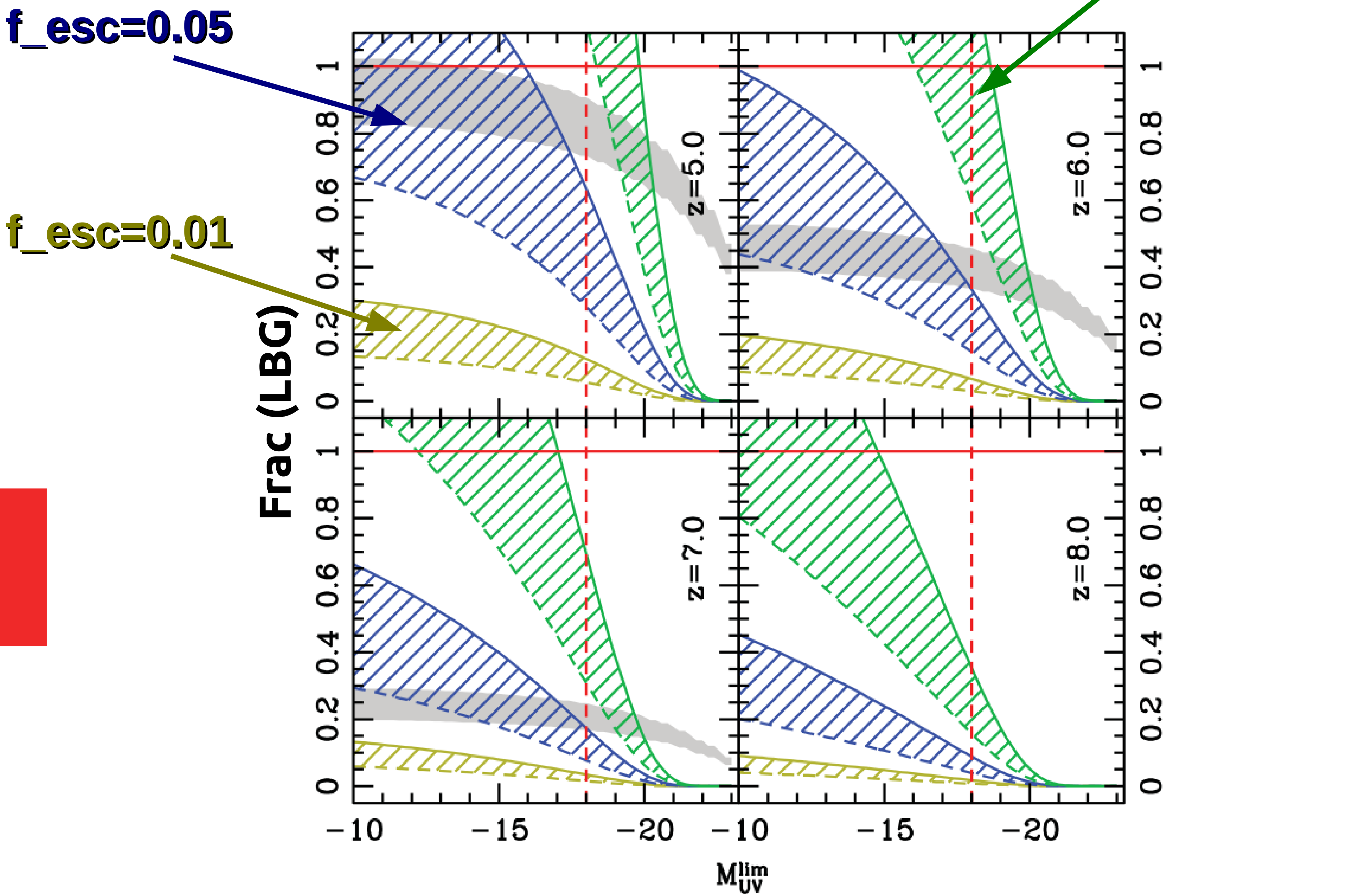
AGN Contribution



High escape fraction

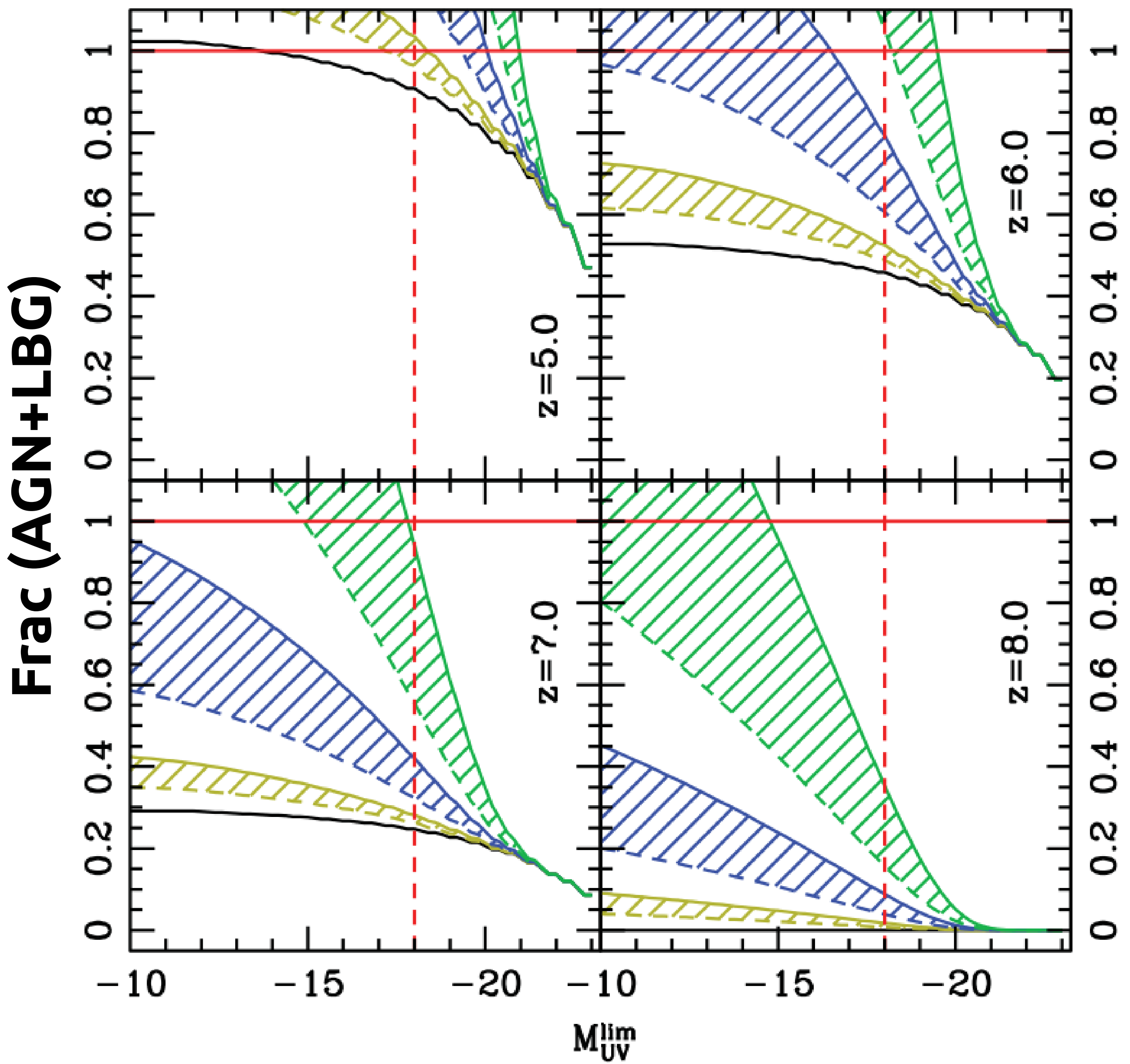
f_esc = 1 – 0.75

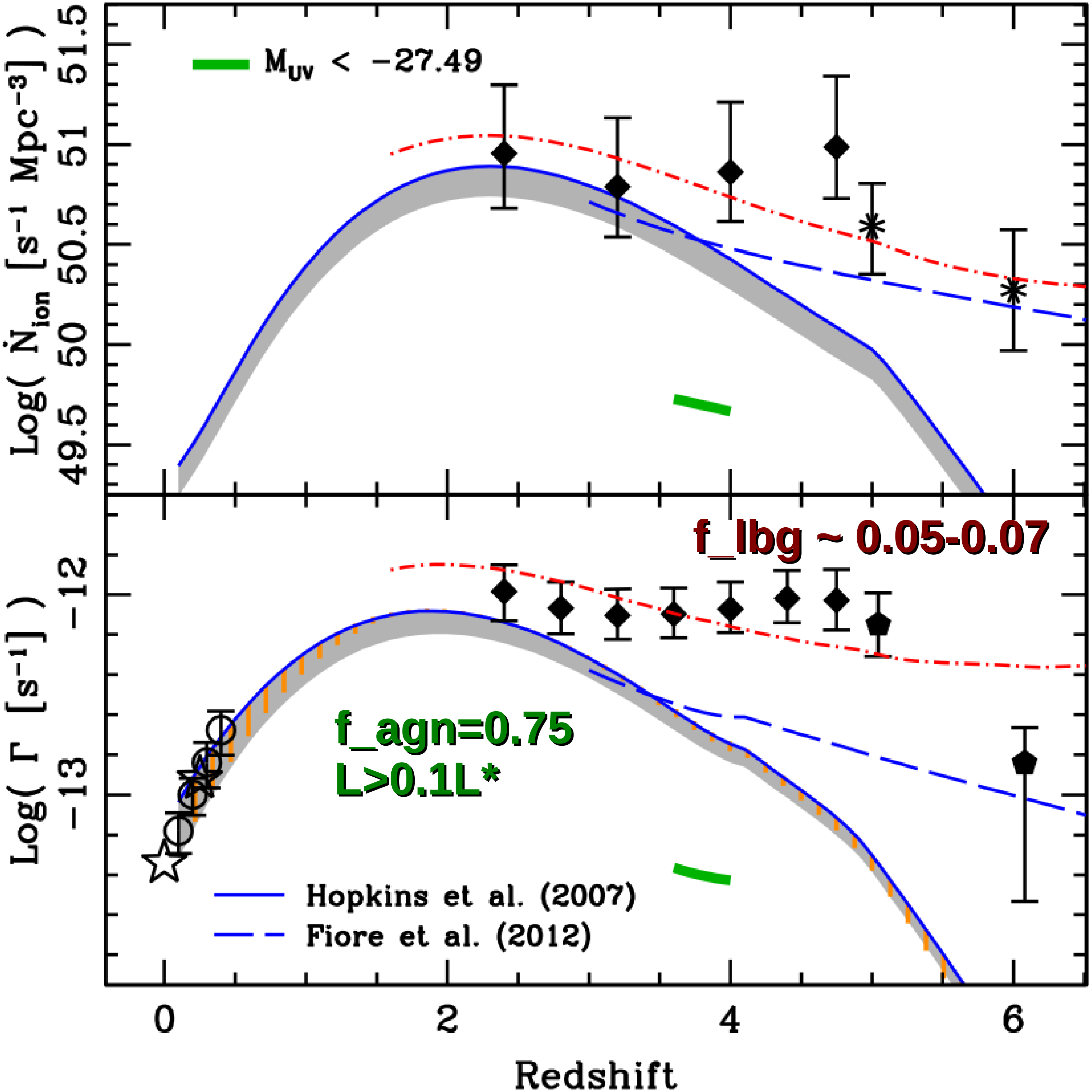
LBG Contribution



Low escape fraction

Combined Contribution





$M_{UV} < -27.49$
Log($\dot{N}_{ion}$ [s^{-1} Mpc^{-3}])
f_lbg ~ 0.05-0.07
Log(Γ [s^{-1}])
f_agn=0.75
L>0.1L*
Hopkins et al. (2007)
Fiore et al. (2012)
Redshift

- AGN provide a relevant (but sub-dominant) contribution to reionization
- Sources fainter than the current limits should provide a relevant contribution to reionization

Conclusions