The Probes and Sources of Cosmic Reionization

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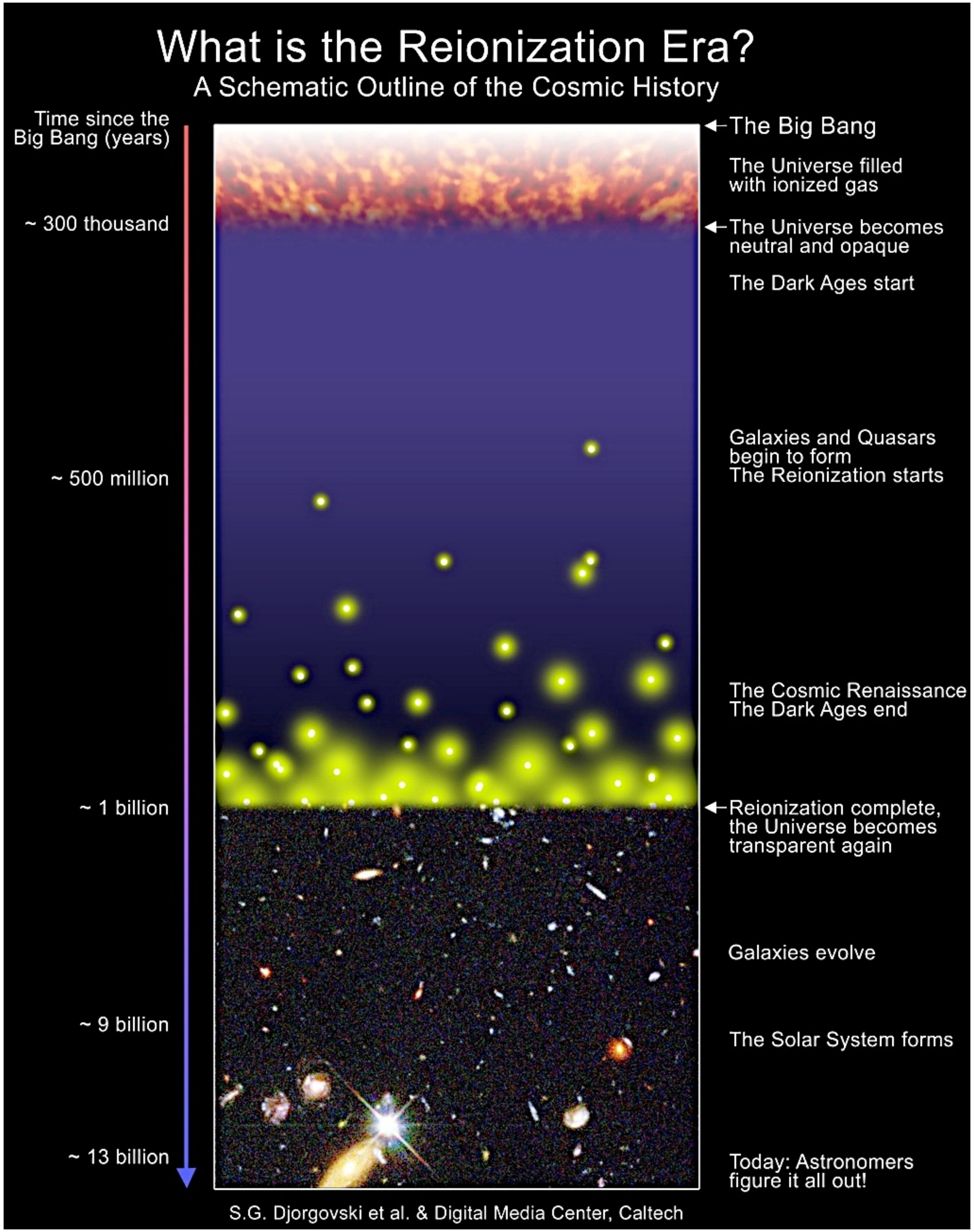
TALK OUTLINE

1. Dark Ages and Reionization
2. Observations: QSO Absorption Lines and CMB
3. Helium Reionization
4. UV Background Models
5. Open Problems

The epoch of reionization (EoR) is the last global phase transition of the Universe. It has an astrophysical origin.

The cosmic ionizing background originates from the integrated emission of all ionizing sources in the Universe. It determines the thermal and ionization state of the IGM, the repository of most of the baryons in the Universe at high redshift.

It is a crucial yet most uncertain input parameter for cosmological simulations of LSS and galaxy formation, for interpreting QSO absorption-line data and derive information on the distribution of primordial gas and of the nucleosynthetic products of star formation - CIII, CIV, SiIII, SiIV, OVI, etc.



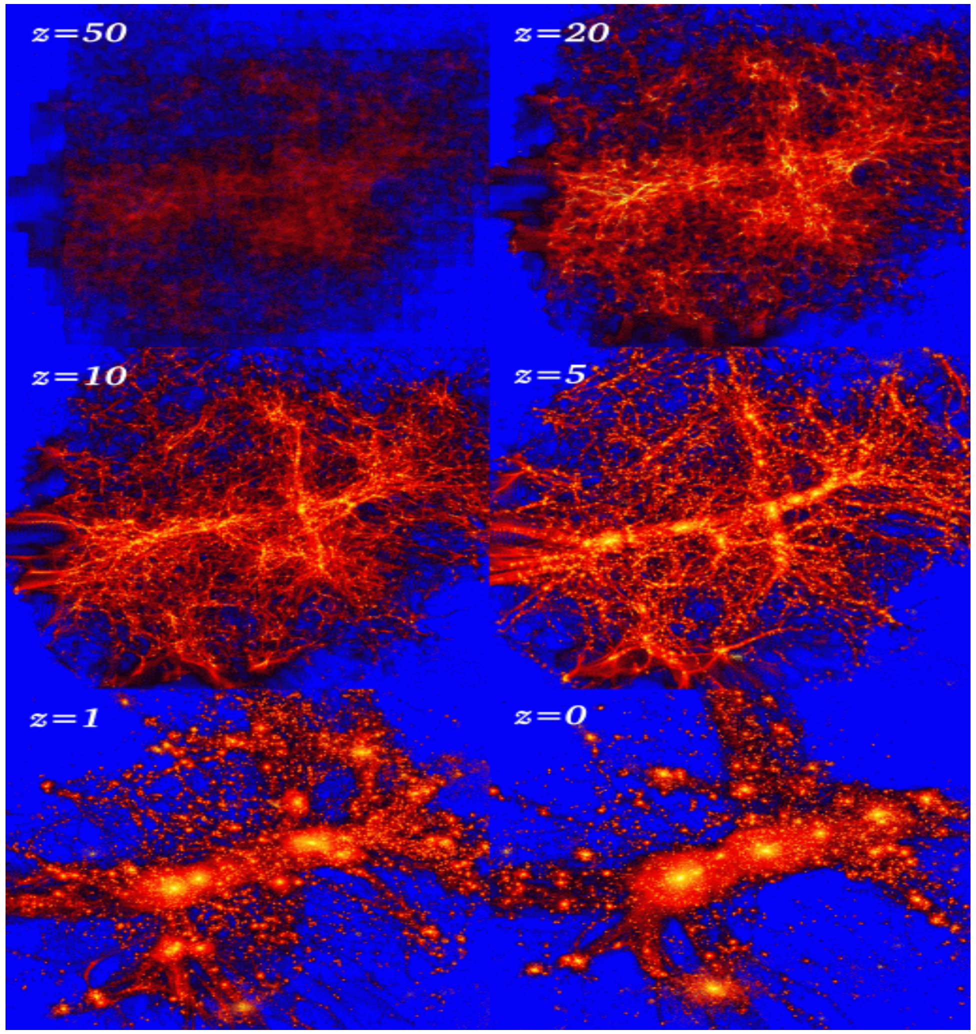
S.G. Djorgovski et al. & Digital Media Center, Caltech

The "Dark Ages"

The fate of DM:

CDM: Small scales collapse first
BOTTOM-UP HIERARCHY

DM-HALOS COLLAPSE AS:
$M = 10^{15}/(1+z)^{6}\, M_{\odot}$



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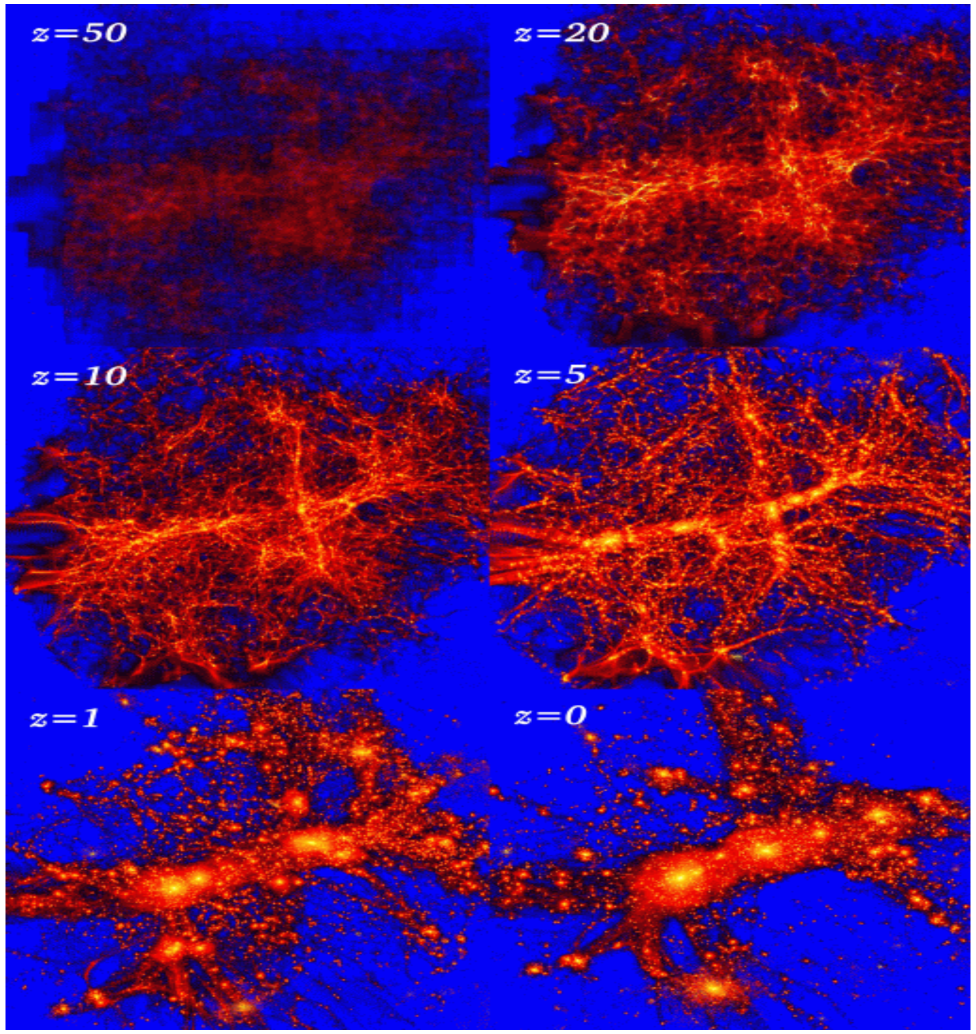


The fate of baryons:

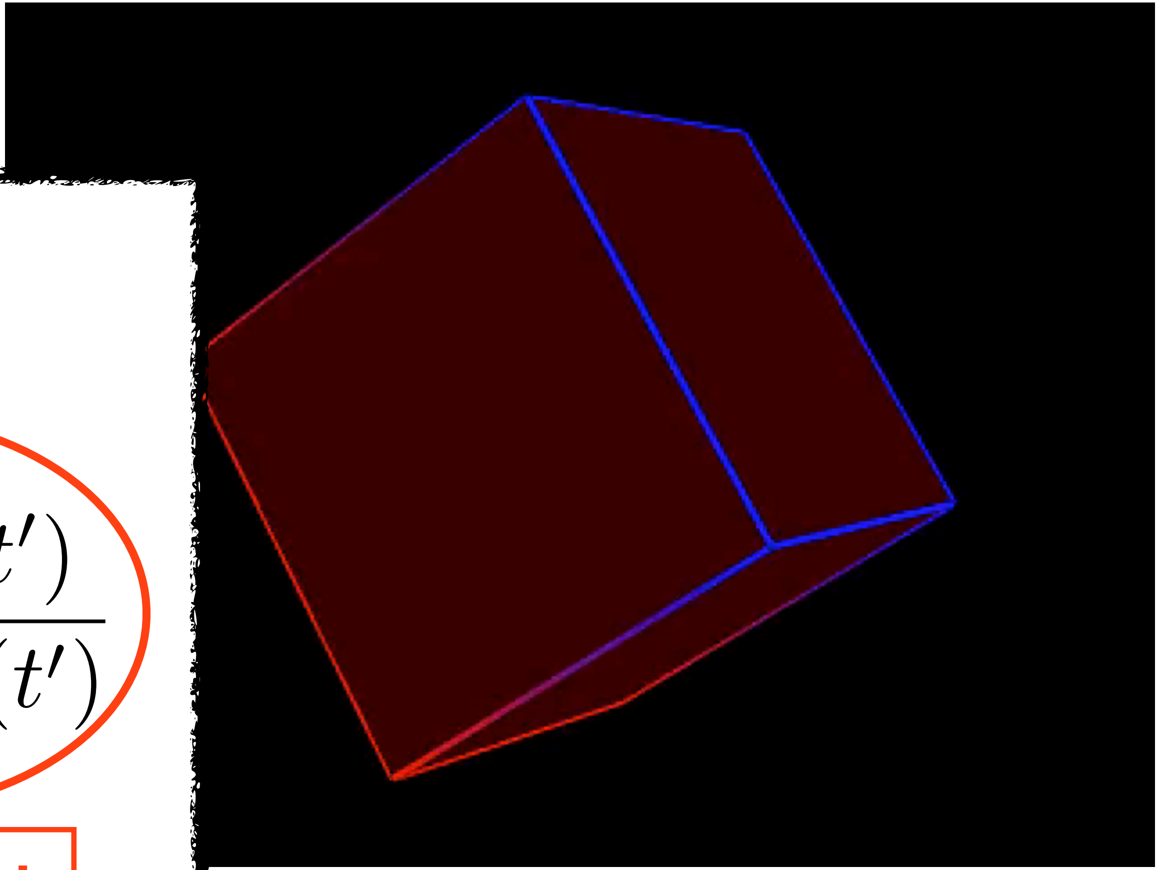
At z≈130 (not at z_{dec}!) baryons are free to fall into DM halos (collapsing since z=3600)

COOLING TIME >> HUBBLE TIME ➜ ADIABATIC COLLAPSE
Baryons virialize as DM particles

COOLING TIME << HUBBLE TIME ➜ ISOTHERMAL COLLAPSE
Baryons fall into DM potential wells ➜ Self-gravitating baryonic objects (POPIII) ➜ END OF THE DARK AGES (z≈20-30)

Reionization in a Nutshell

@ milliFLOP speed (Madau, FH & Rees 1999)



Q is the Universe fraction of ionized hydrogen/helium by volume (known as the "porosity parameter"

$$Q(t) = \int_0^t dt' \frac{\dot{n}_\gamma(t')}{\langle n_H(t') \rangle} - \int_0^t dt' \frac{Q(t')}{t_{\rm rec}(t')}$$

source

sink

(No redshifting, photons absorbed locally)

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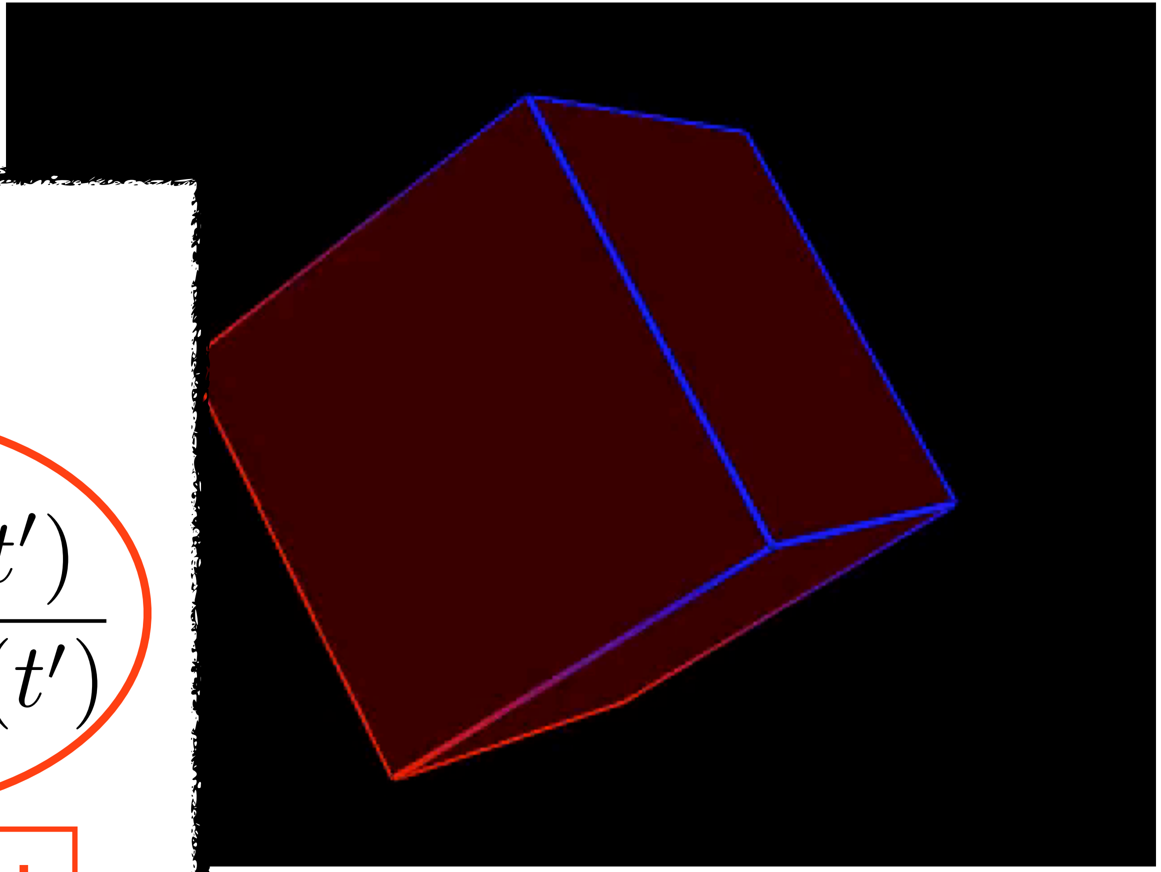

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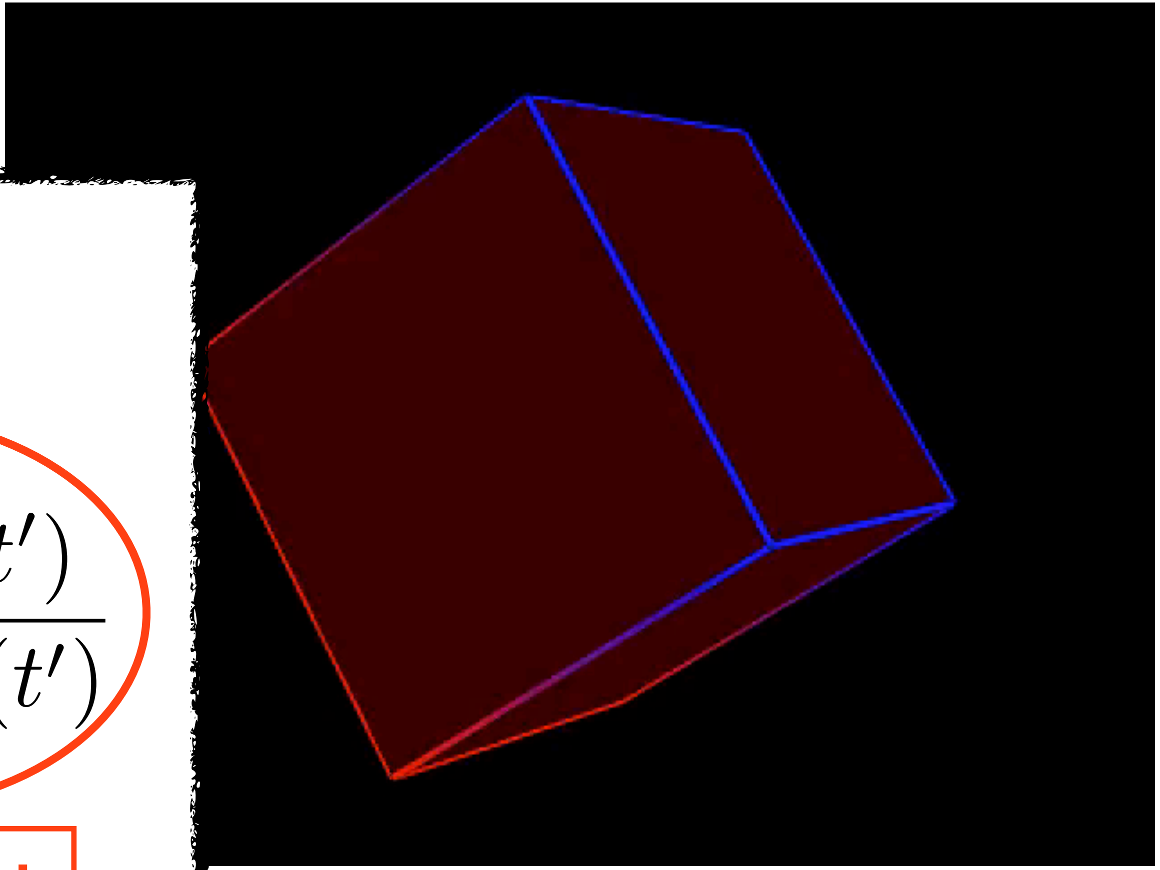

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source

sink

(No redshifting, photons absorbed locally)

$$\frac{dQ}{dt} = \frac{\dot{n}_\gamma}{\langle n_H\rangle} - \frac{Q}{t_{\rm rec}}$$

simple diff. eq. statistically describes transition from a neutral Universe to a fully ionized one!

Reionization in a Nutshell

$$t_{\rm rec} \ll t \longrightarrow Q \approx \frac{\dot{n}_\gamma}{\langle n_H \rangle} t_{\rm rec}$$

The Universe is completely reionized when Q=1, i.e., when

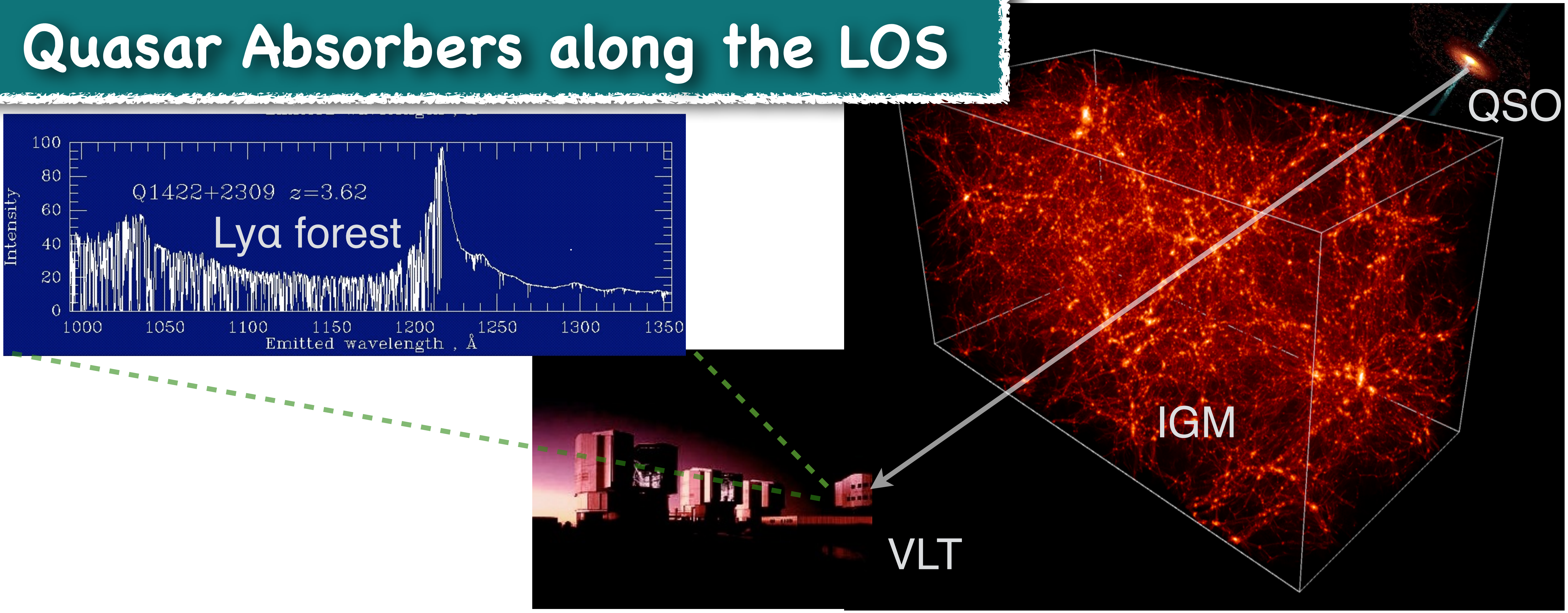
$$\dot{n}_\gamma t_{\rm rec} = \langle n_H \rangle$$

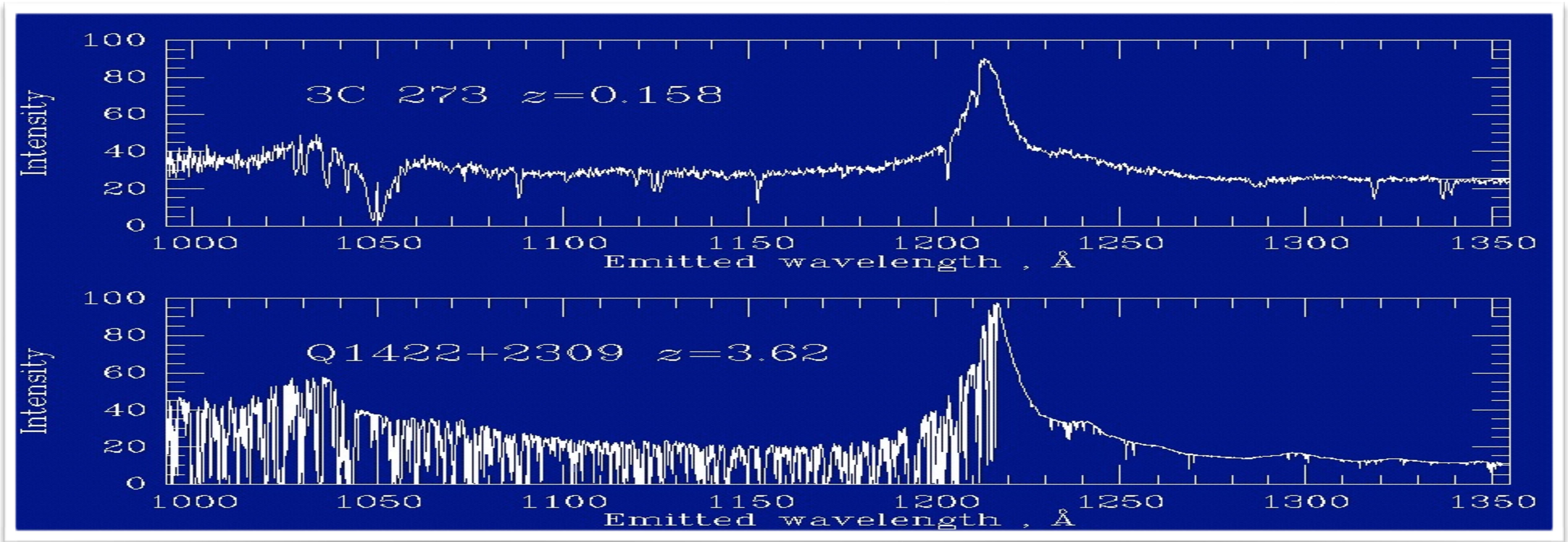
One ionizing photon per ion per recombination time.

Probes of Reionization

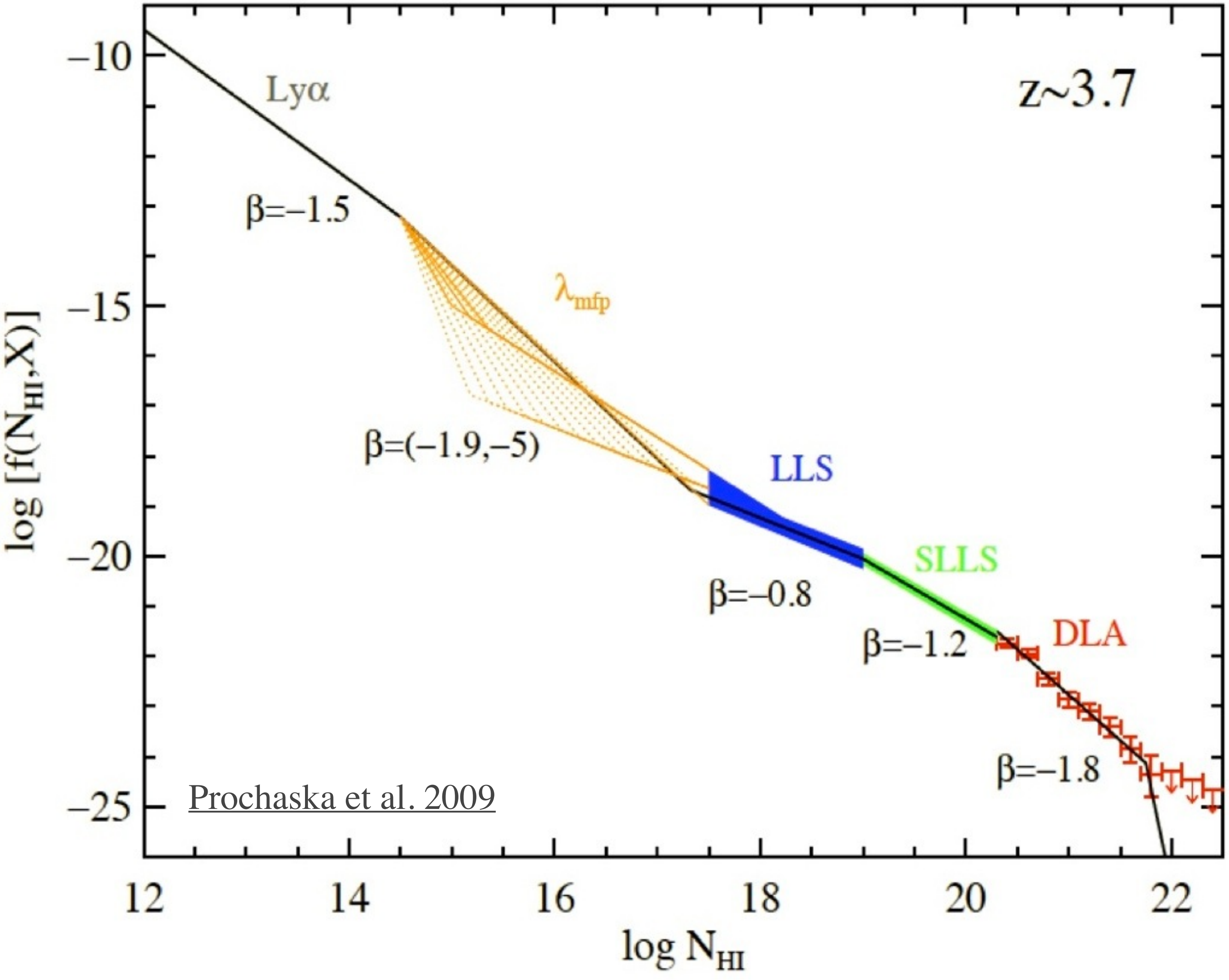
1) Gunn-Peterson depth statistics from QSOs
2) Electron-scattering optical depth from CMB
3) LAE redshift distribution
4) 21-cm line tomography (LOFAR, SKA)

Quasar Absorbers along the LOS





Quasar Absorbers along the LOS

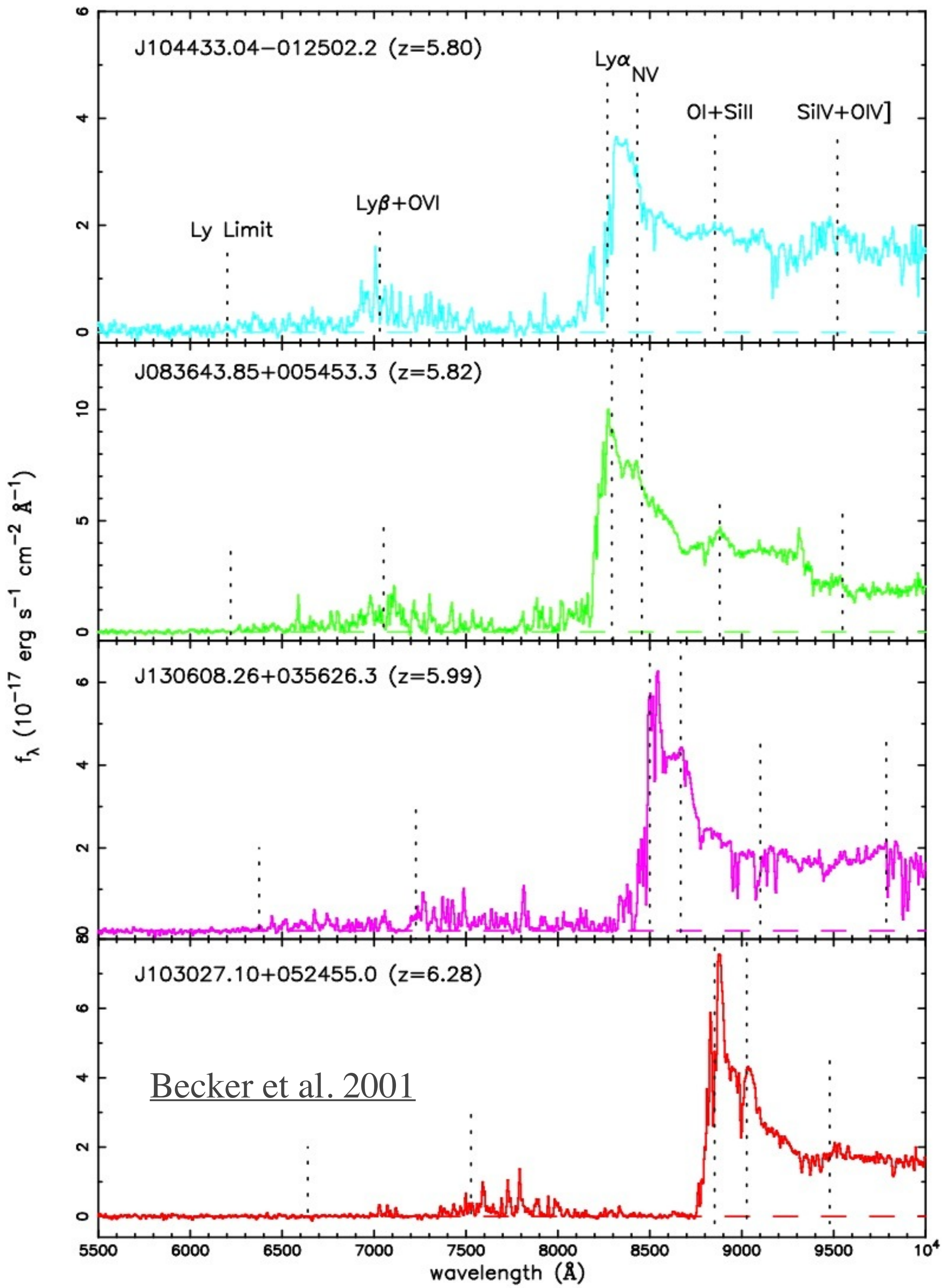


f(N_{HI},*z*) is defined by the probability *dP* that a los intersects an absorber with column N_{HI}, $N_{HI}+dN_{HI}$ at redshift z, $z+dz$,

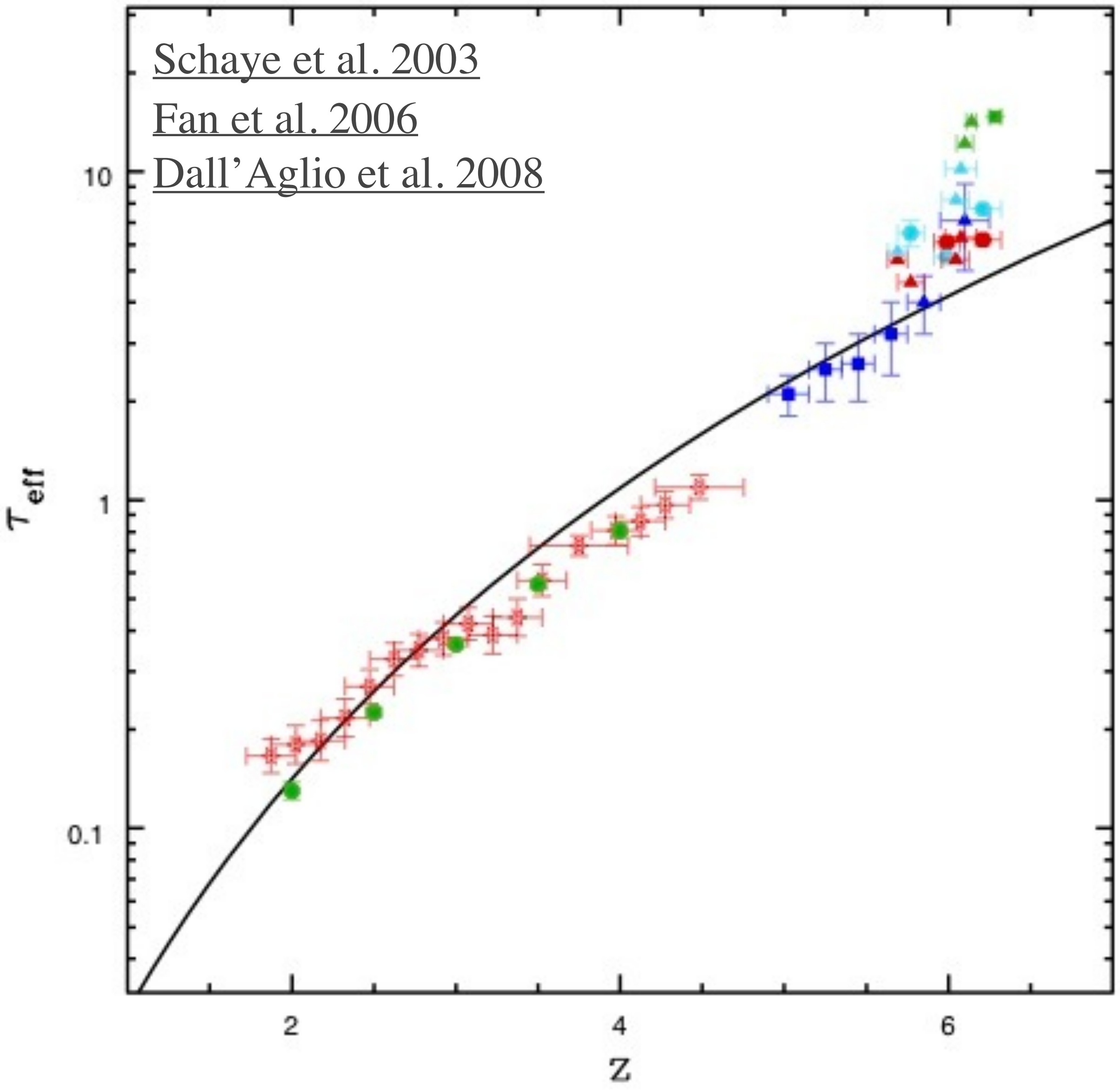
$$dP = f(N_{\rm HI}, z)dN_{\rm HI}dz$$

The number of absorbers increases with redshift.
The HI column distribution is not a single power-law.

Quasar Absorbers along the LOS



Becker et al. 2001



Schaye et al. 2003

Fan et al. 2006

Dall'Aglio et al. 2008

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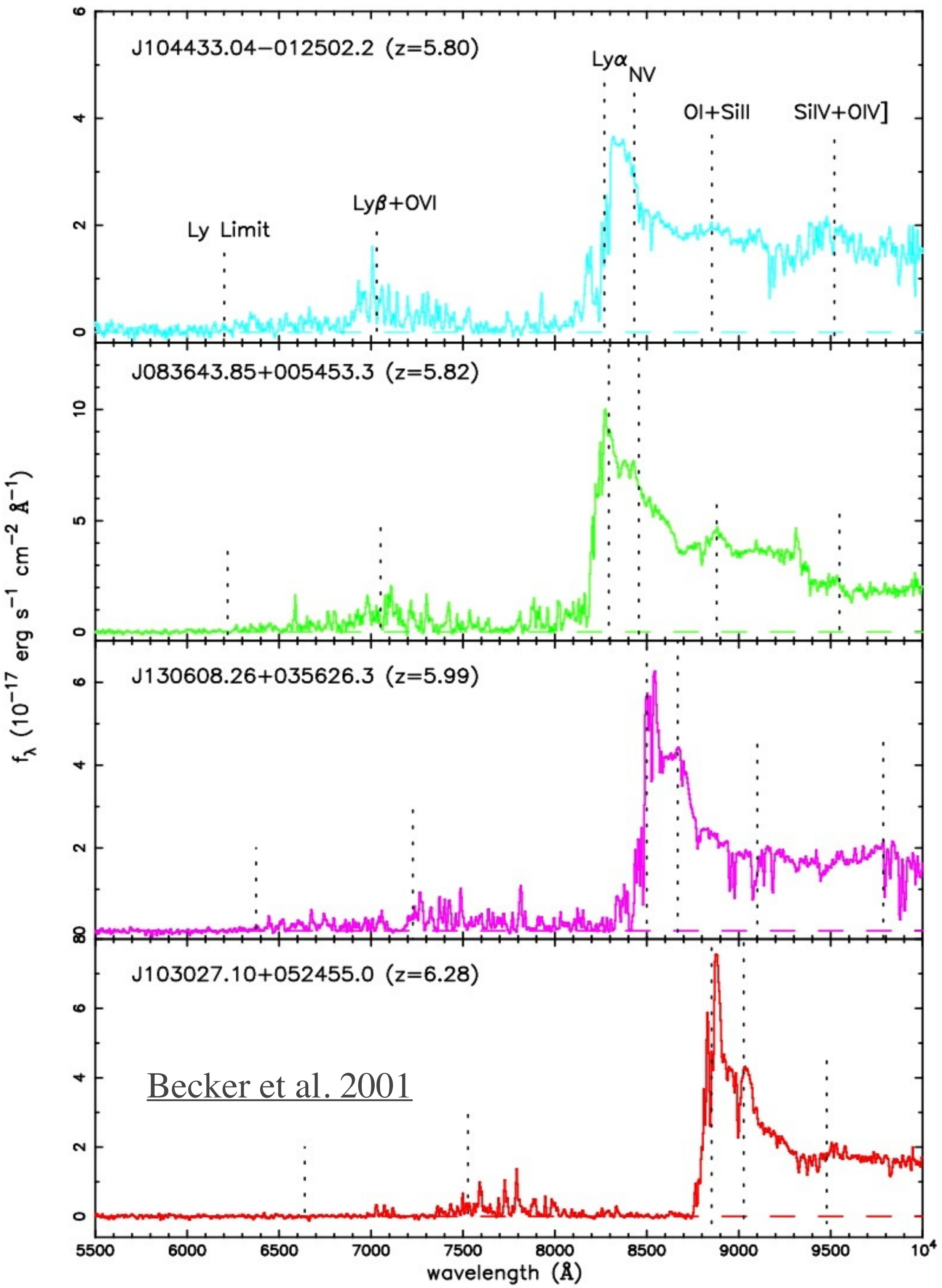

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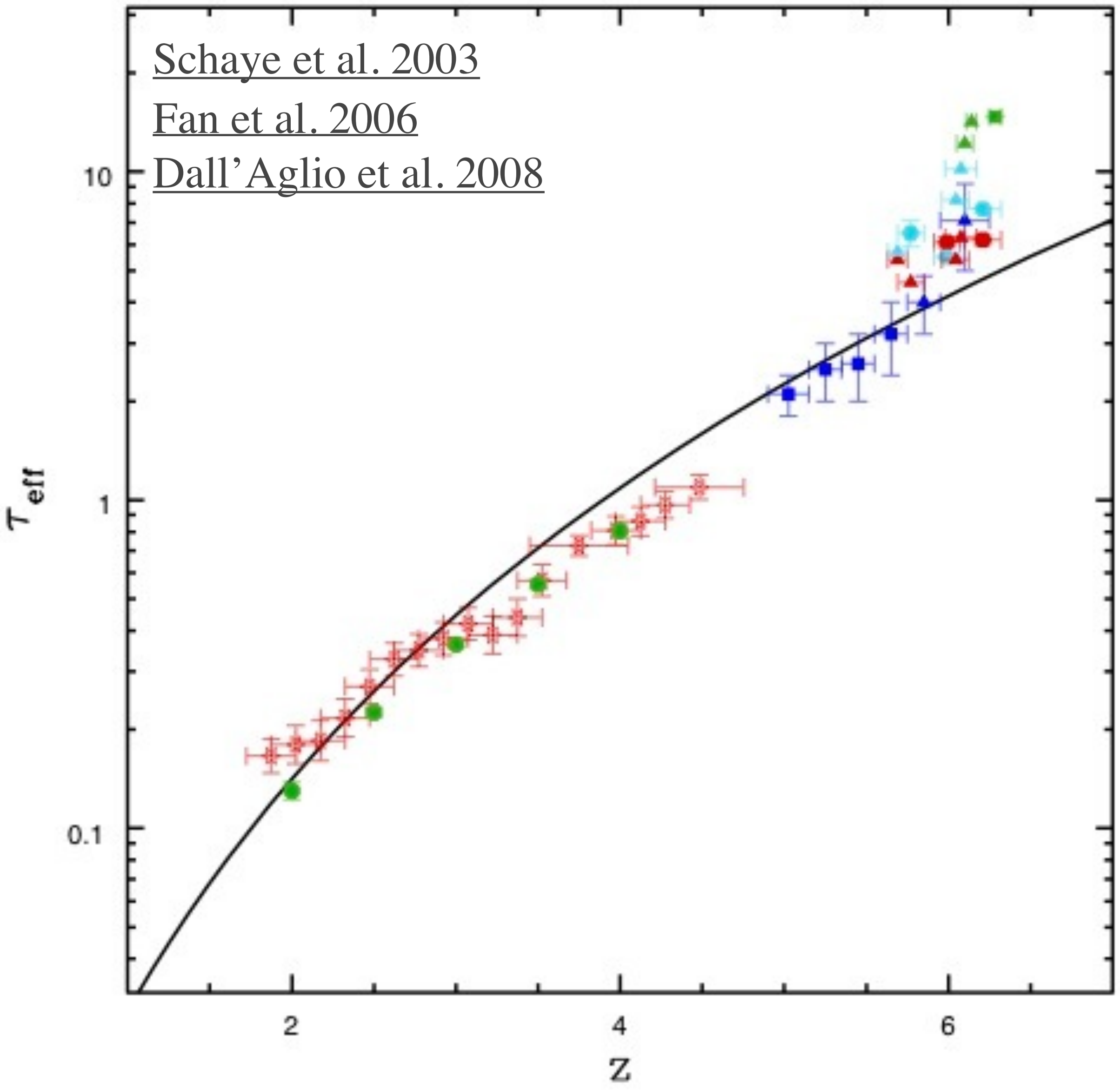

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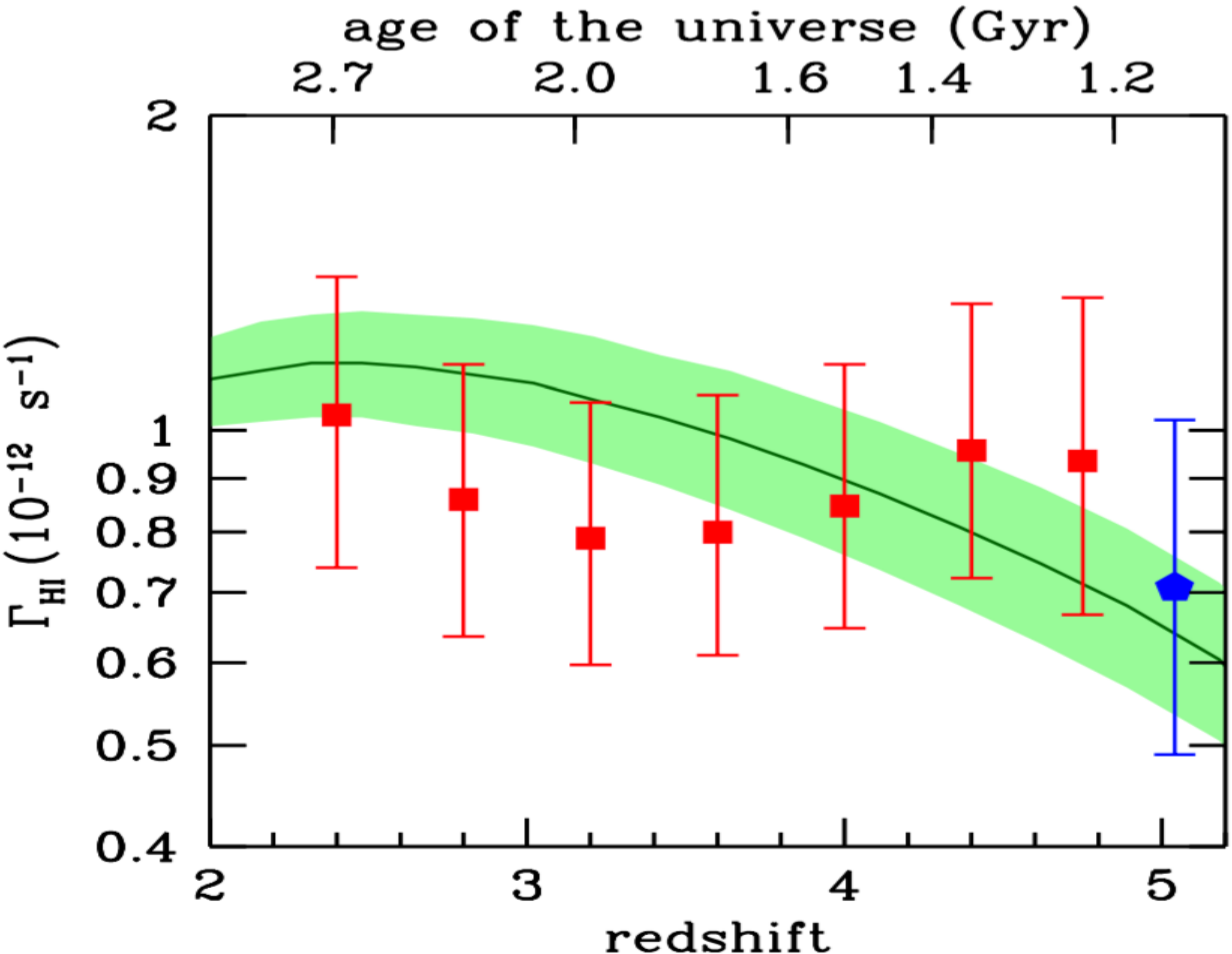
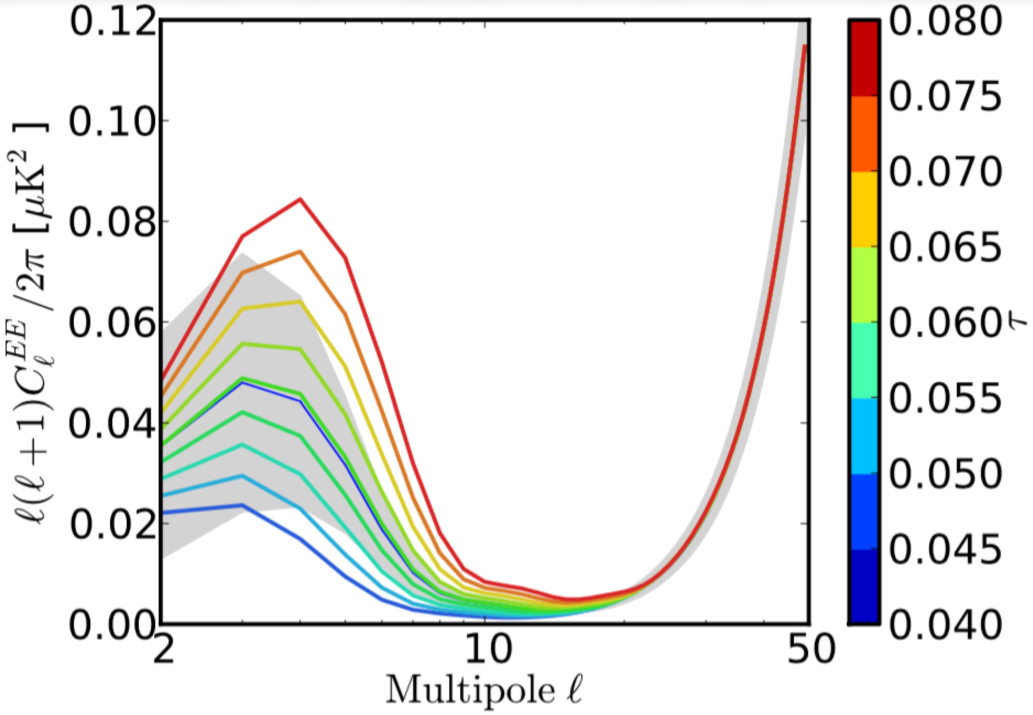
Hydrogen is highly ionized at z<5.7

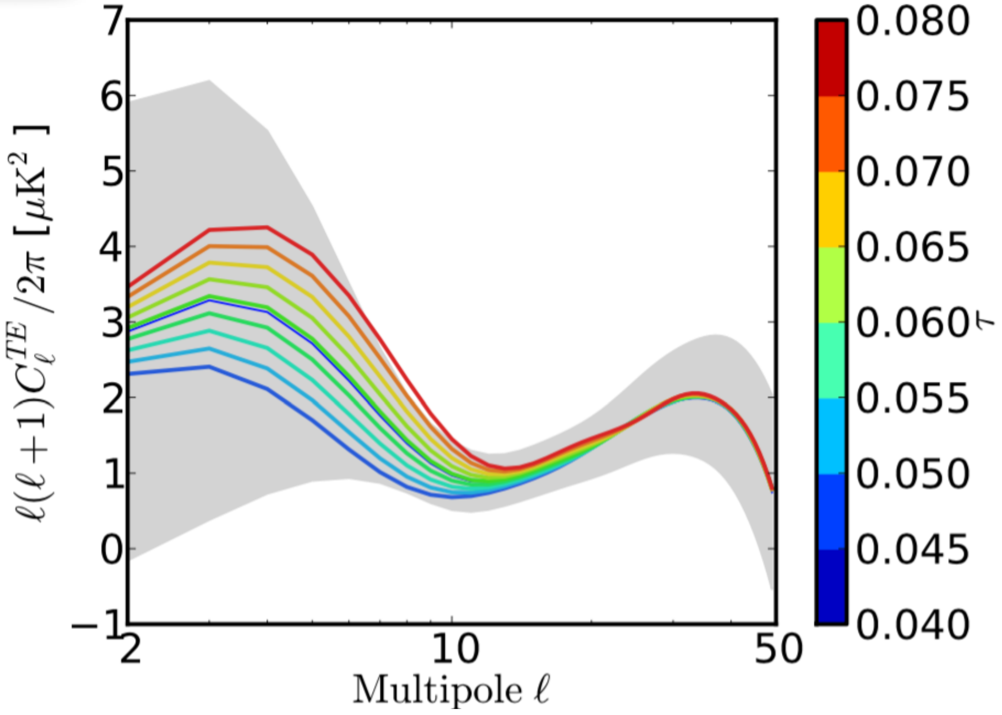


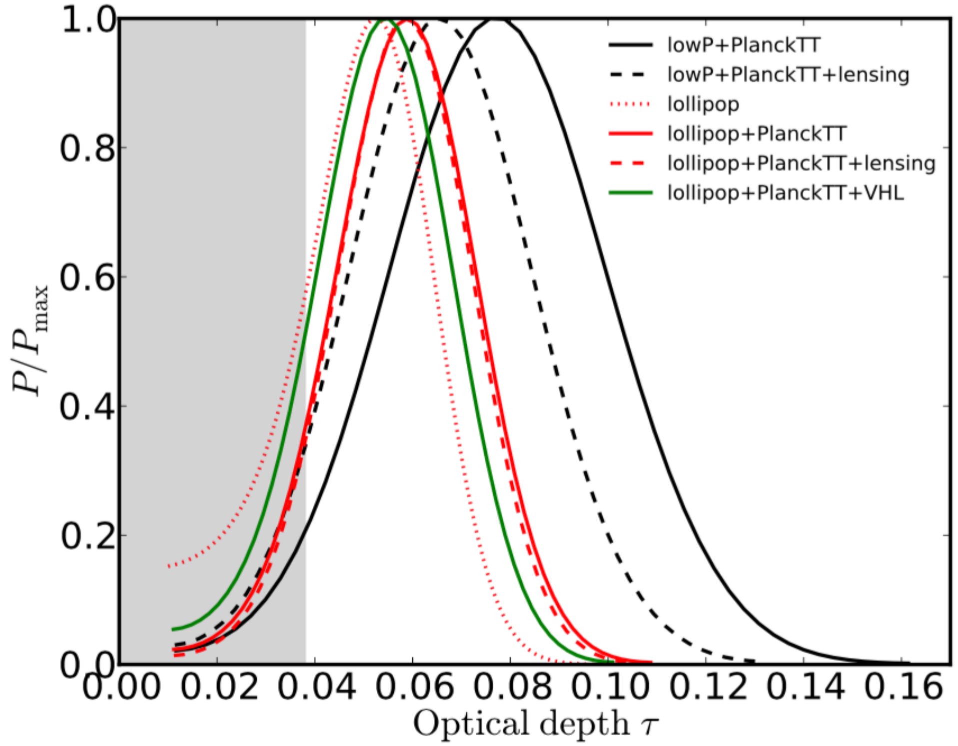
Becker and Bolton 2013

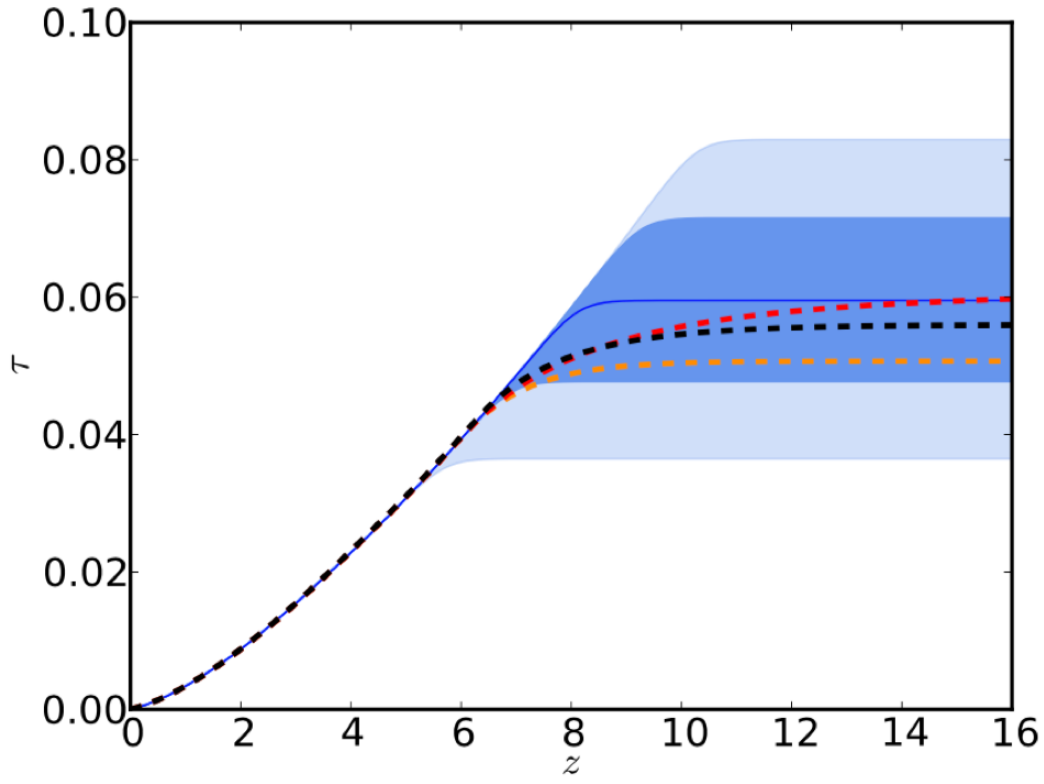
CMB Polarization

Planck Collaboration 2016





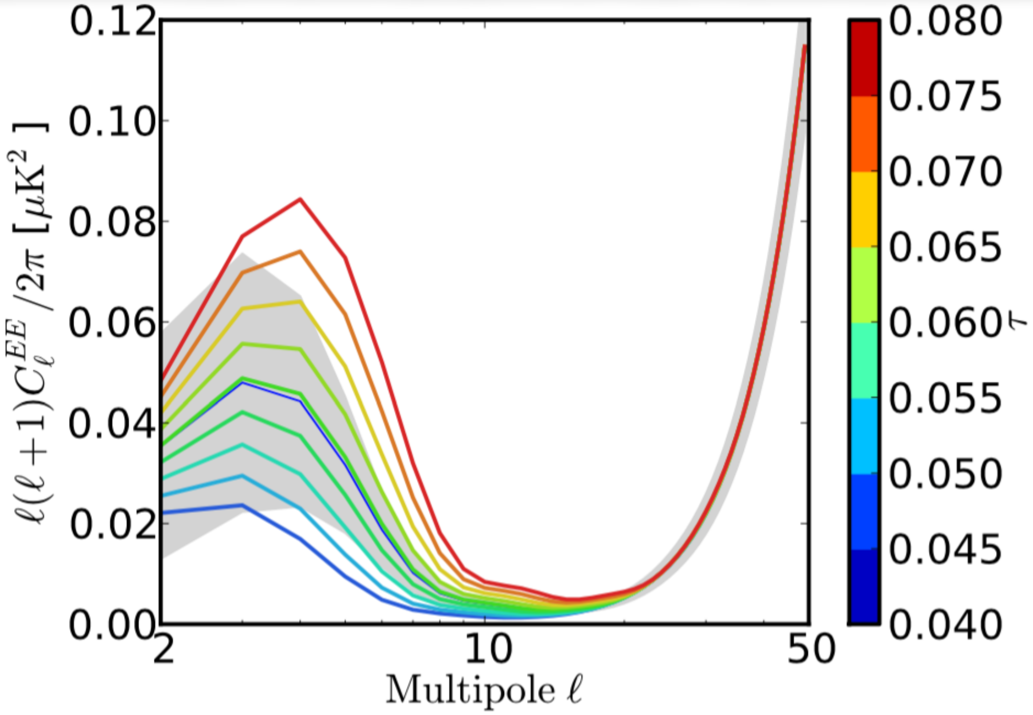


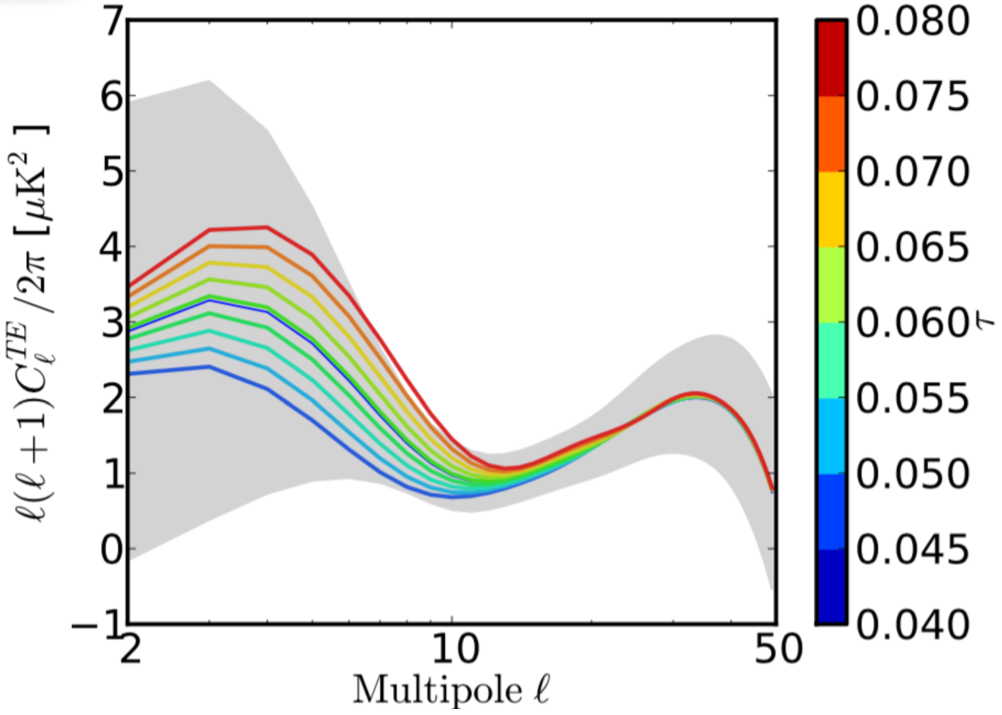


$$\tau_T = \int_0^z n_e(z)\sigma_T |cdt/dz| dz = \mathbf{0.058 \pm 0.012}$$

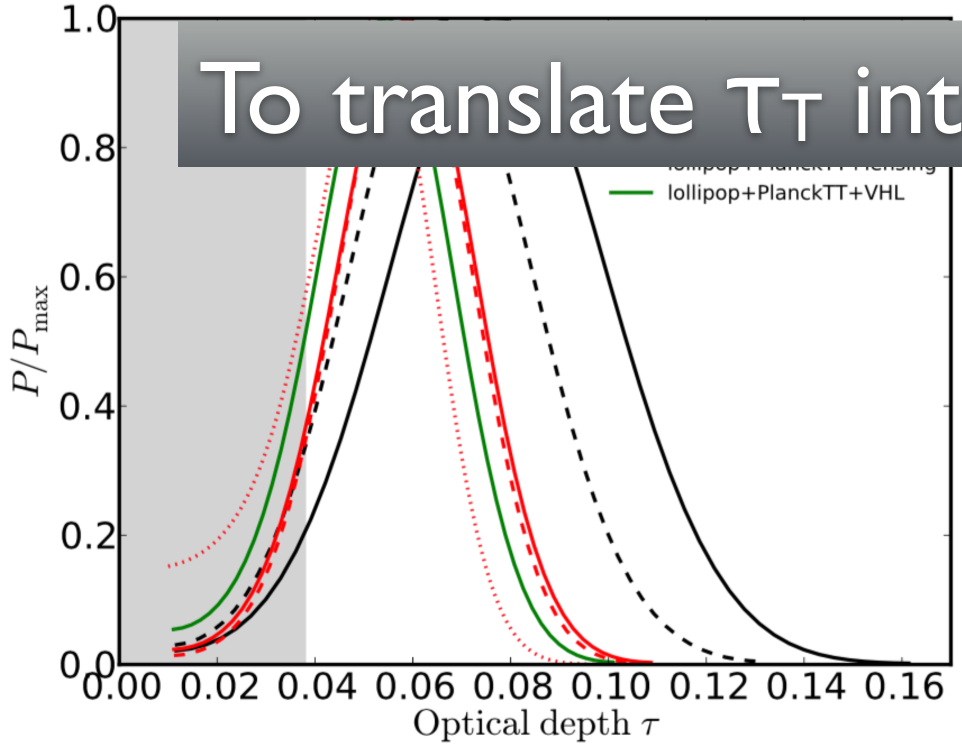
CMB Polarization

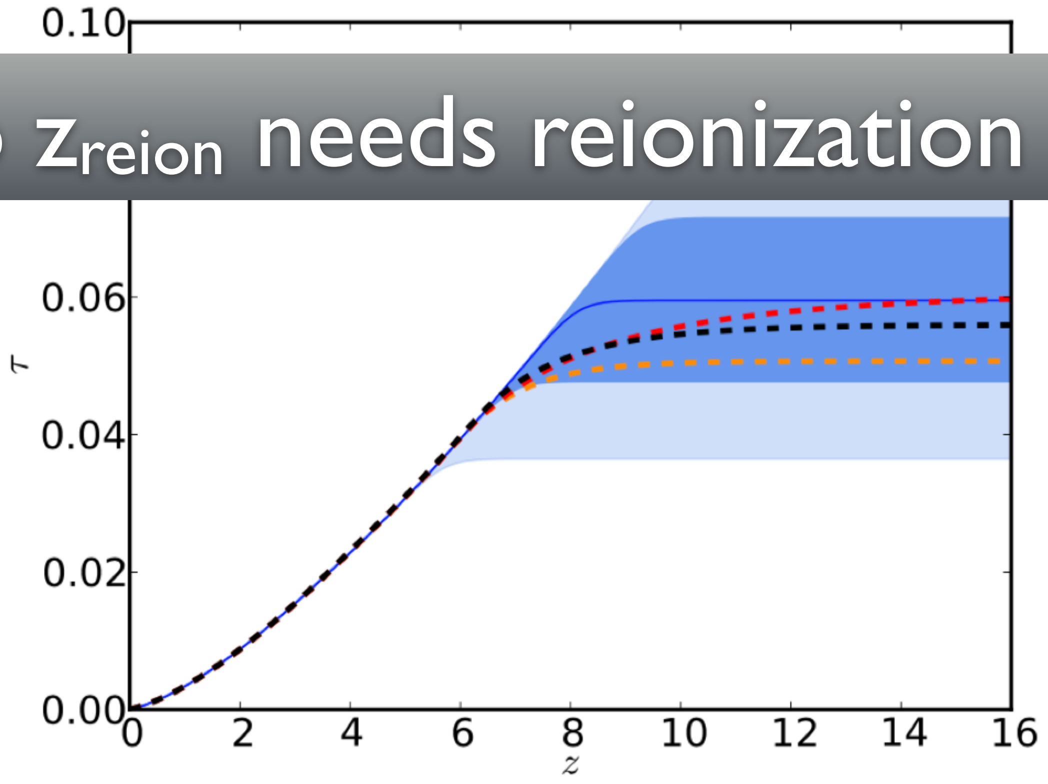
Planck Collaboration 2016





To translate τ_T into z_{reion} needs reionization models.





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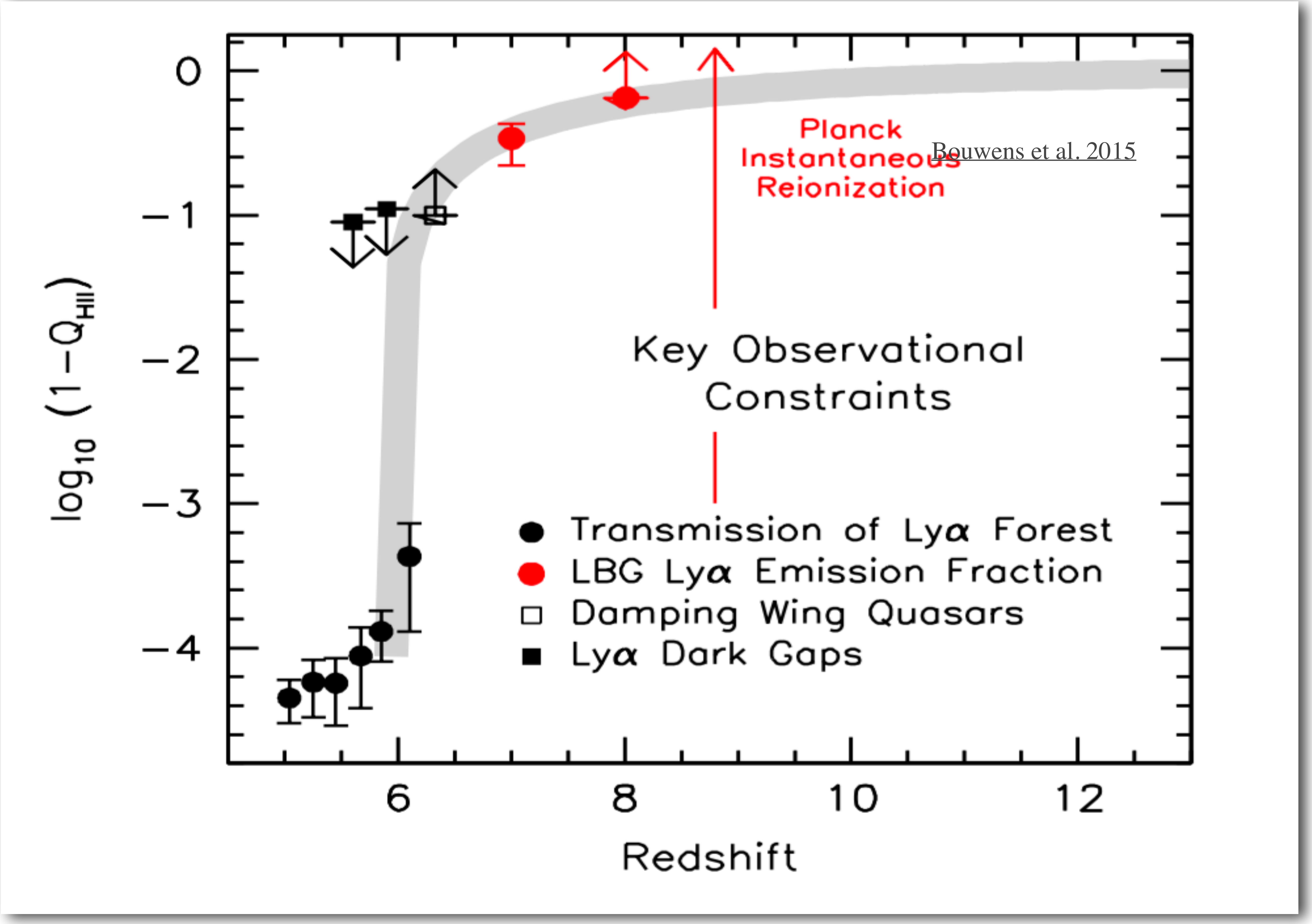
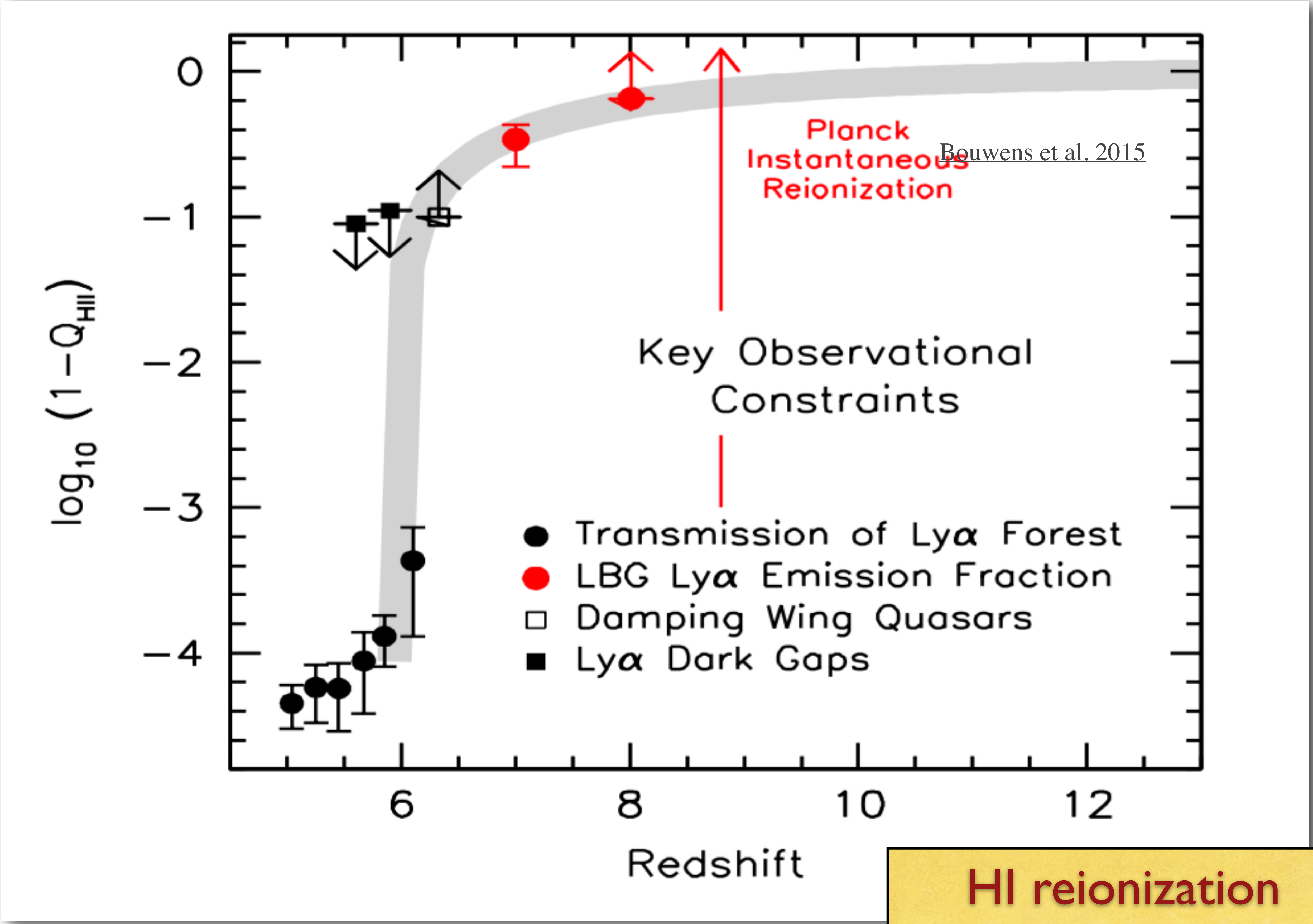


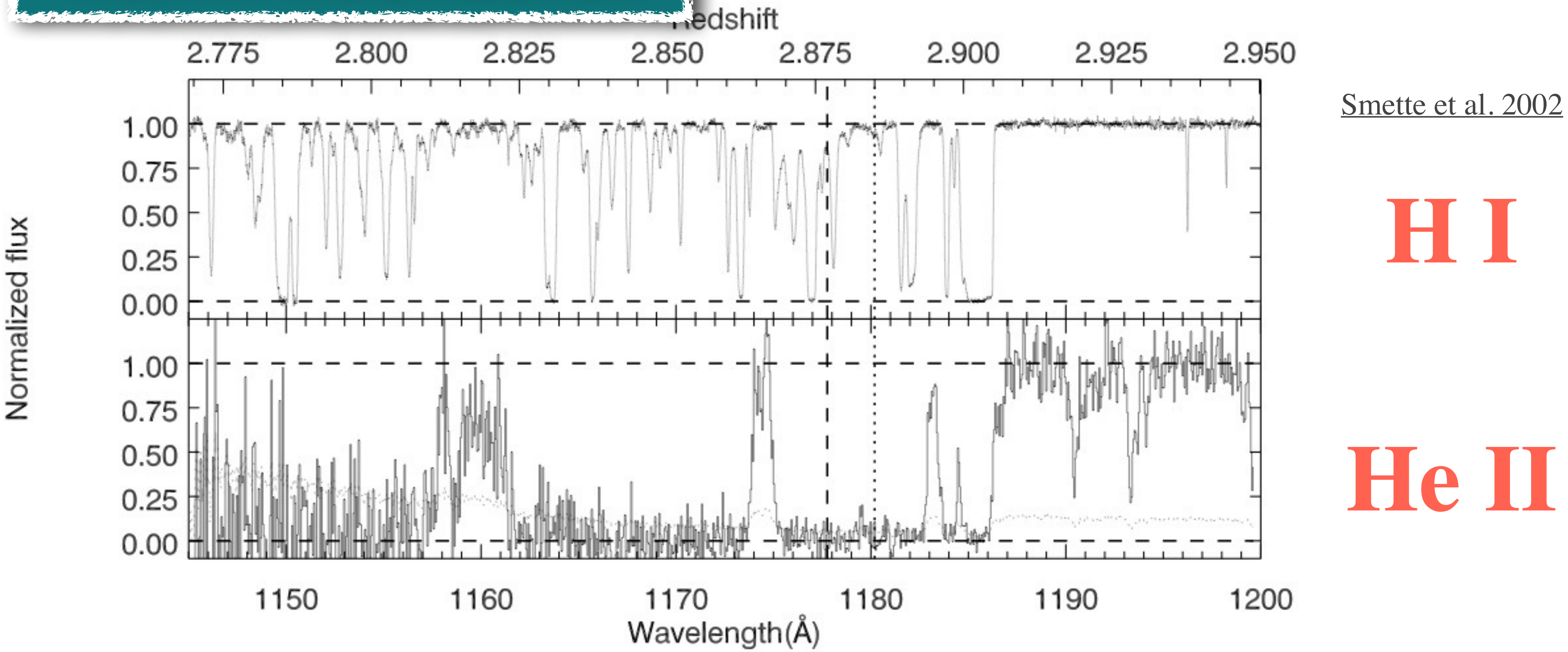
Bouwens et al. 2015



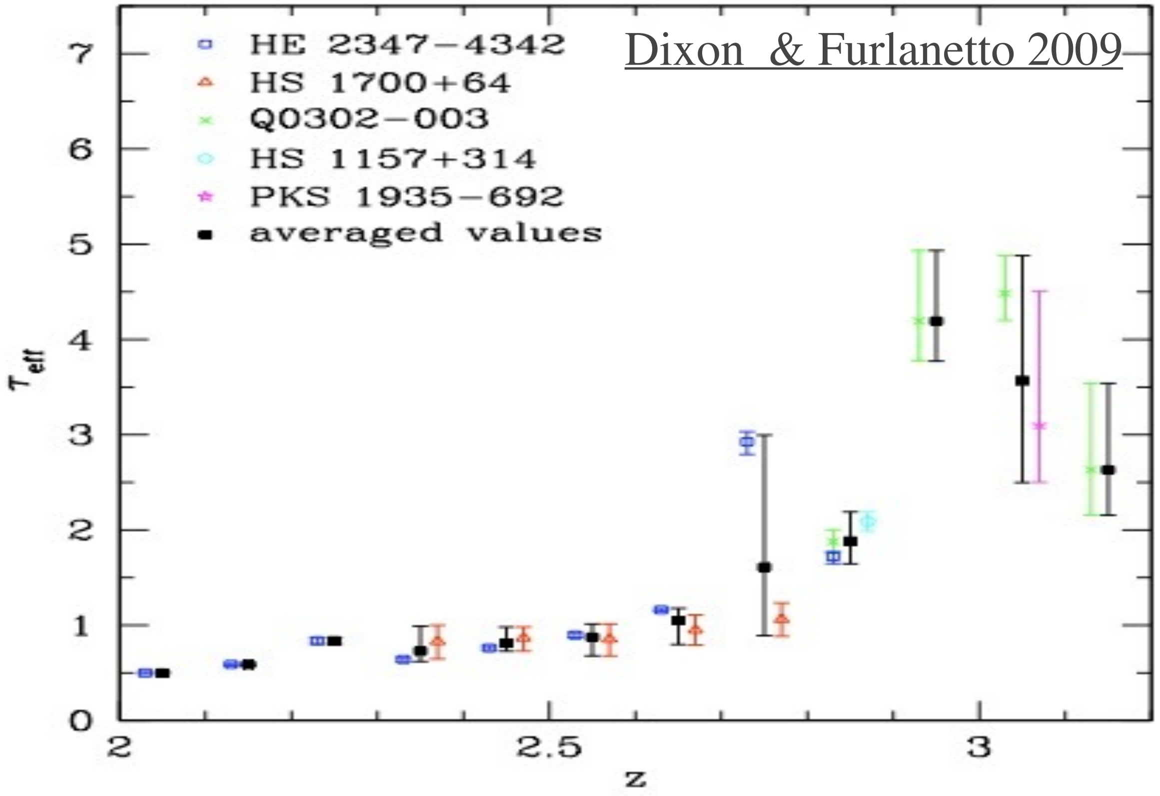
Bouwens et al. 2015

HI reionization completed at z≳6

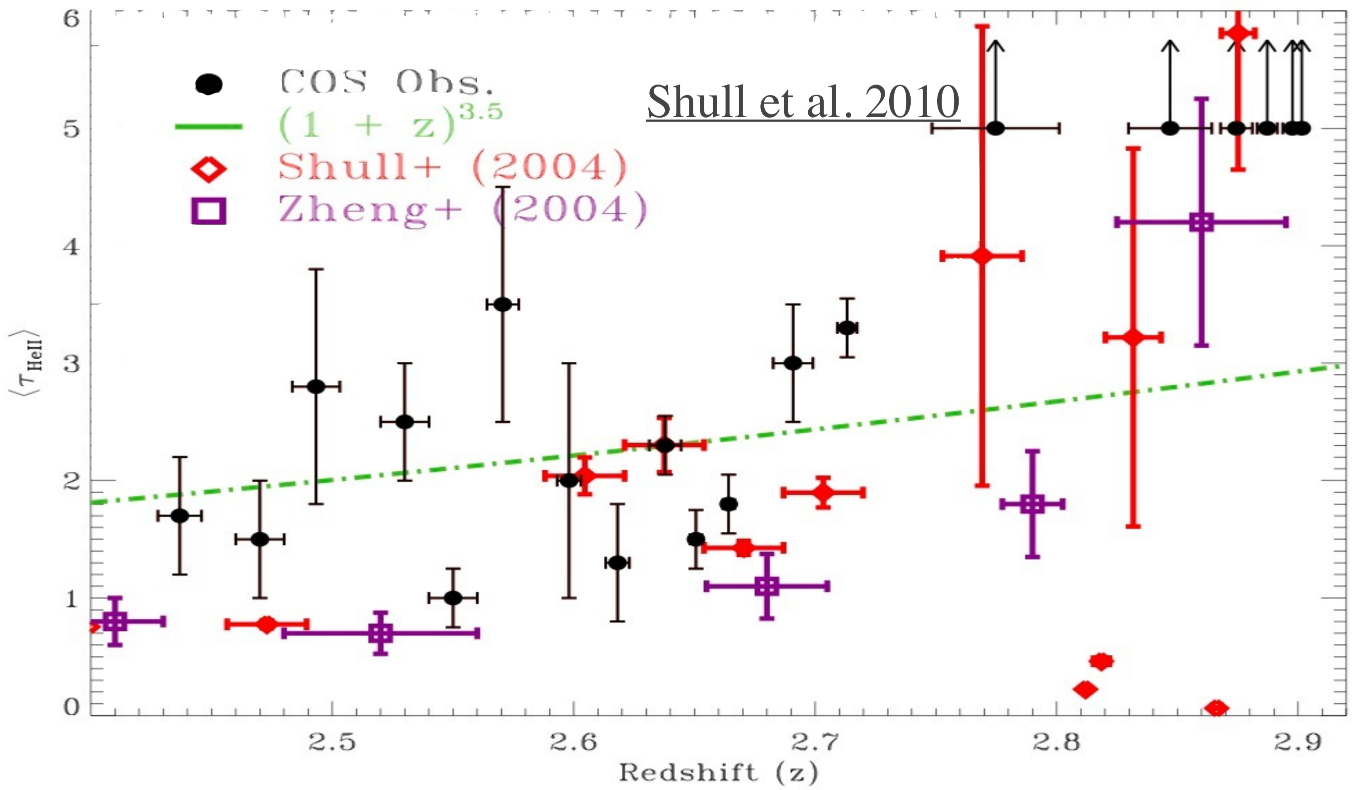
Helium Reionization



Smette et al. 2002



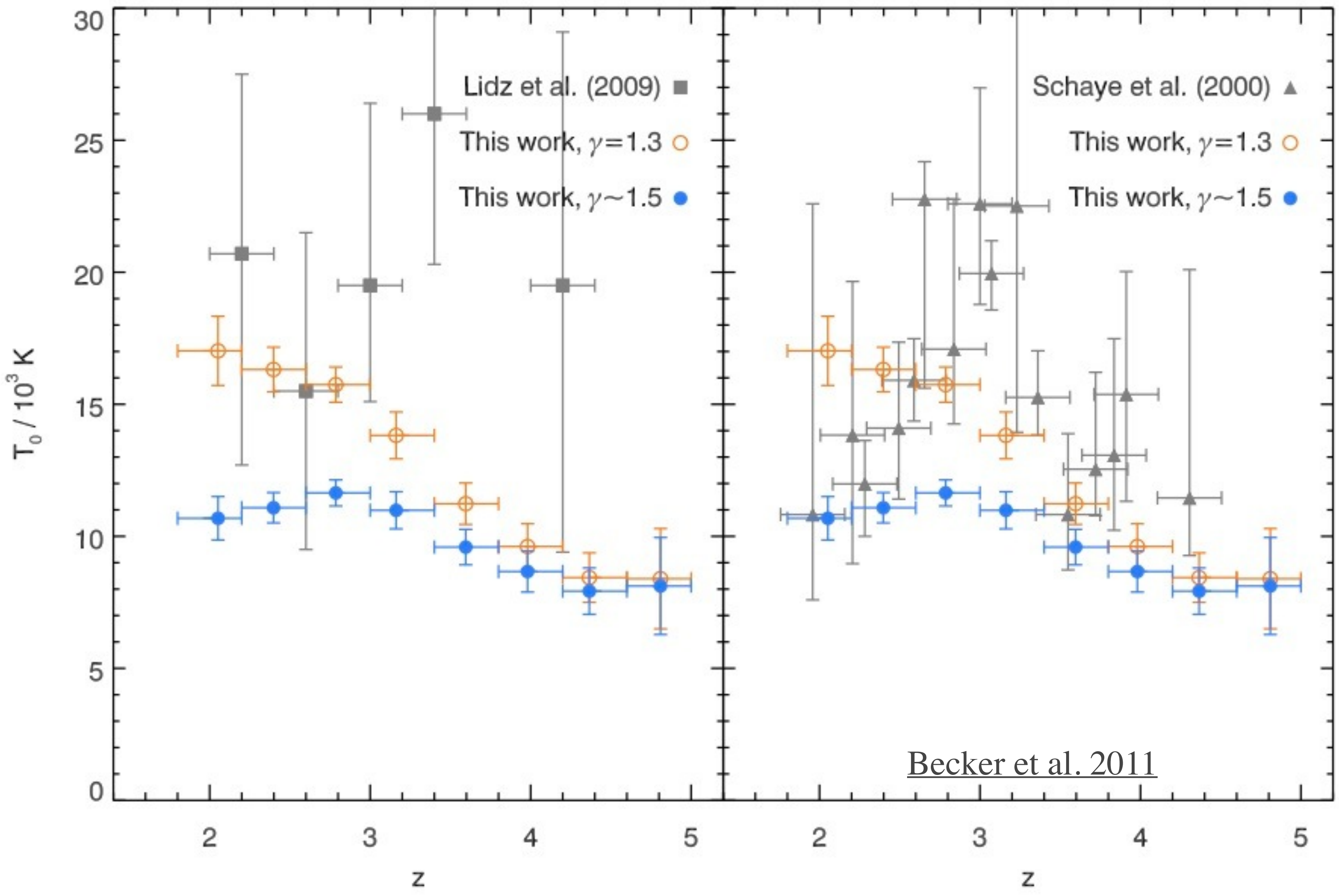
Dixon & Furlanetto 2009



Shull et al. 2010

Helium Reionization

IGM Temperatures over $2 < z < 5$



IGM temperature possibly shows a peak at z≅2.8-3 indicating He reionization then.

He reionization occurs at $z_{reion}≈3$ BUT the process is patchy. Possible indications of a delayed, slow reionization period, extending down to z<2.7
BUT Worseck et al. (2016): clean los up to z~4.5

Cosmological Radiative Transfer

The equation of cosmological radiative transfer describes the time evolution of the space/angle-averaged specific intensity J_ν

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

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

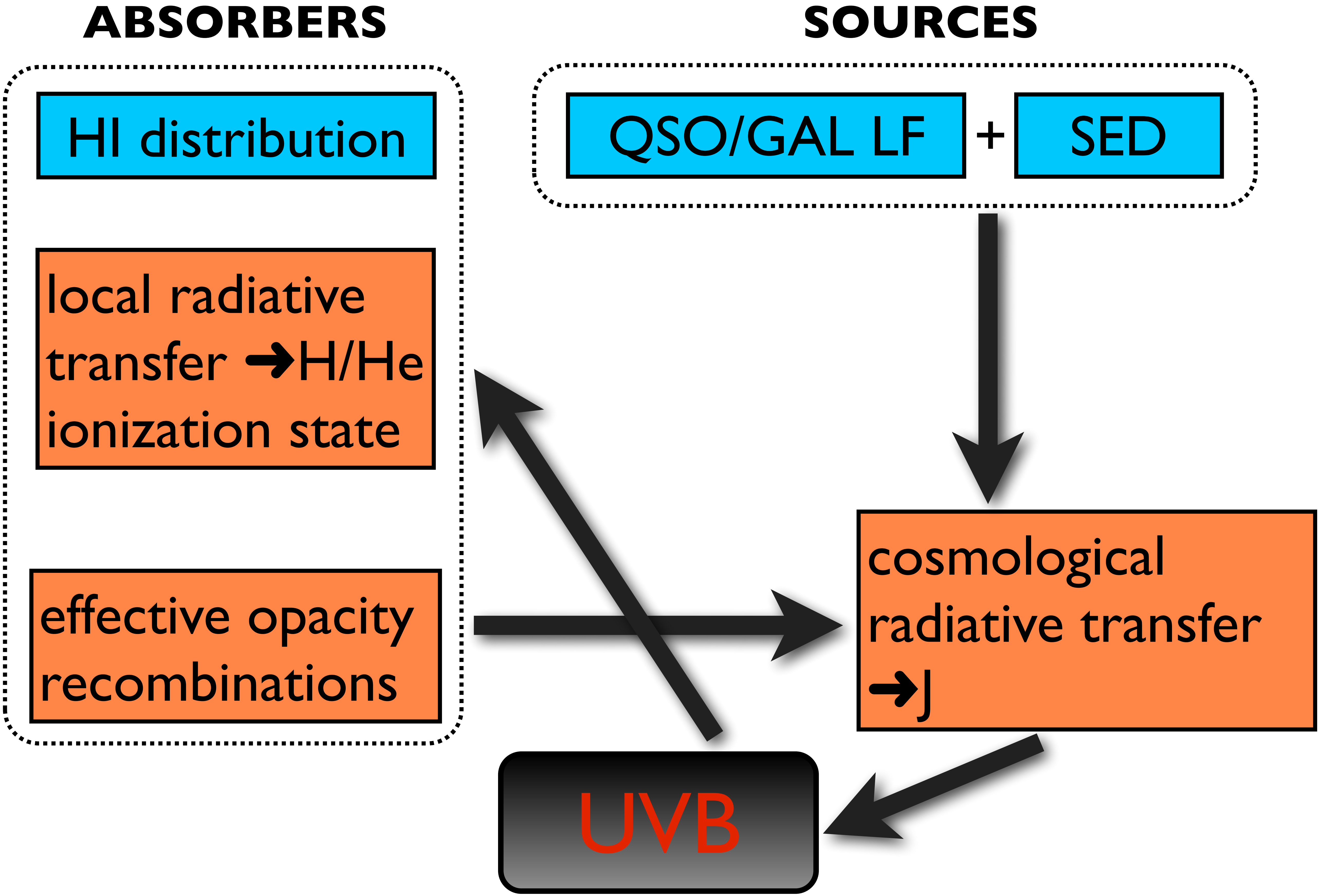
$$\nu = \nu_0(1+z)/(1+z_0)$$

$$\tau_{\rm eff}(\nu_o, z_o, z) = \int_{z_o}^{z} dz' \int_0^\infty dN_{\rm HI}\, f(N_{\rm HI}, z')(1-e^{-\tau})$$

$$\tau(\nu') = N_{\rm HI}\sigma_{\rm HI}(\nu') + N_{\rm HeI}\sigma_{\rm HeI}(\nu') + N_{\rm HeII}\sigma_{\rm HeII}(\nu')]$$

$$\nu' = \nu_0(1+z')/(1+z_0)$$

CUBA solution flow chart



ABSORBERS

HI distribution

local radiative transfer ➔H/He ionization state

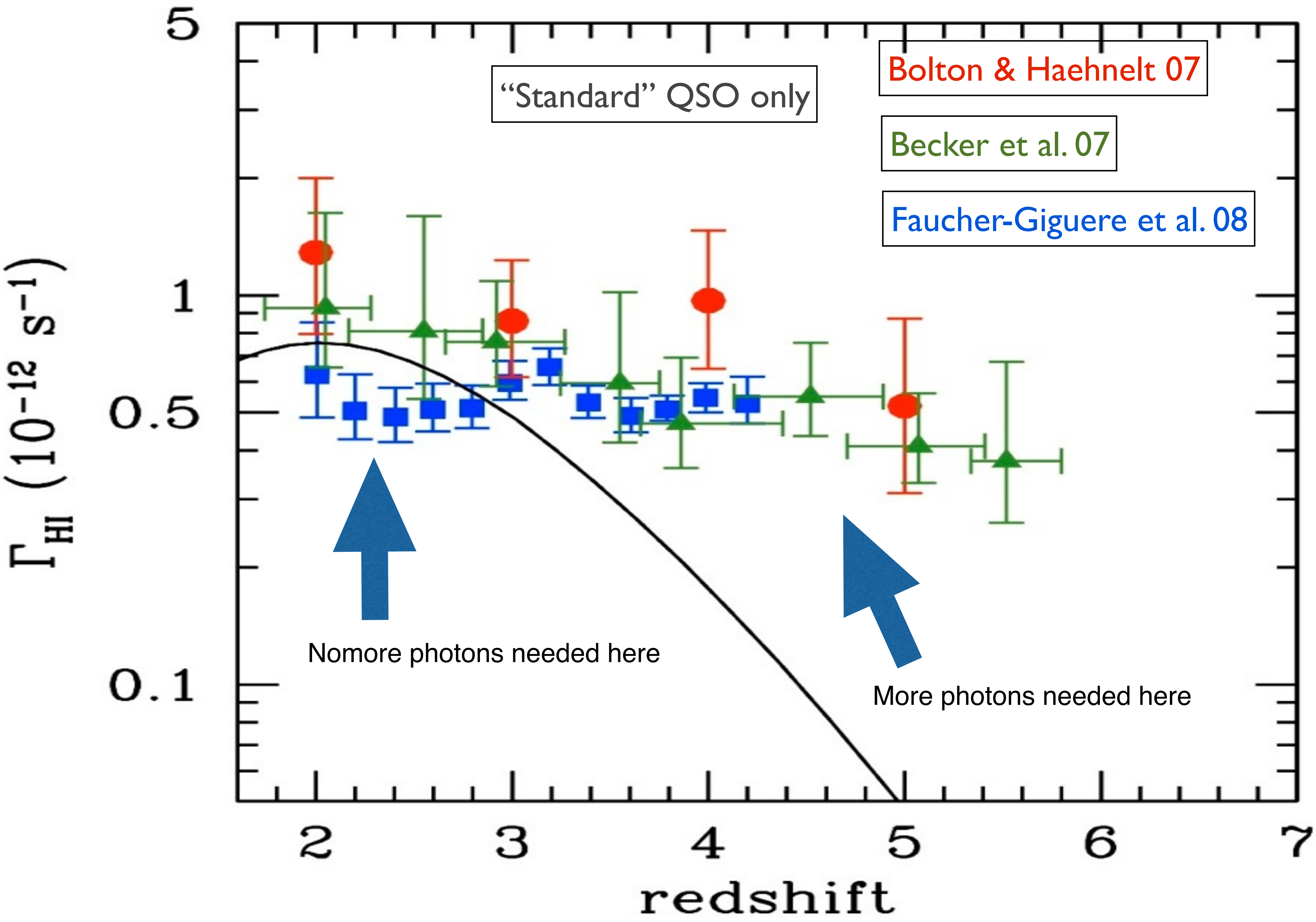
effective opacity recombinations

SOURCES

QSO/GAL LF + SED

cosmological radiative transfer ➔J

UVB



Nomore photons needed here

More photons needed here

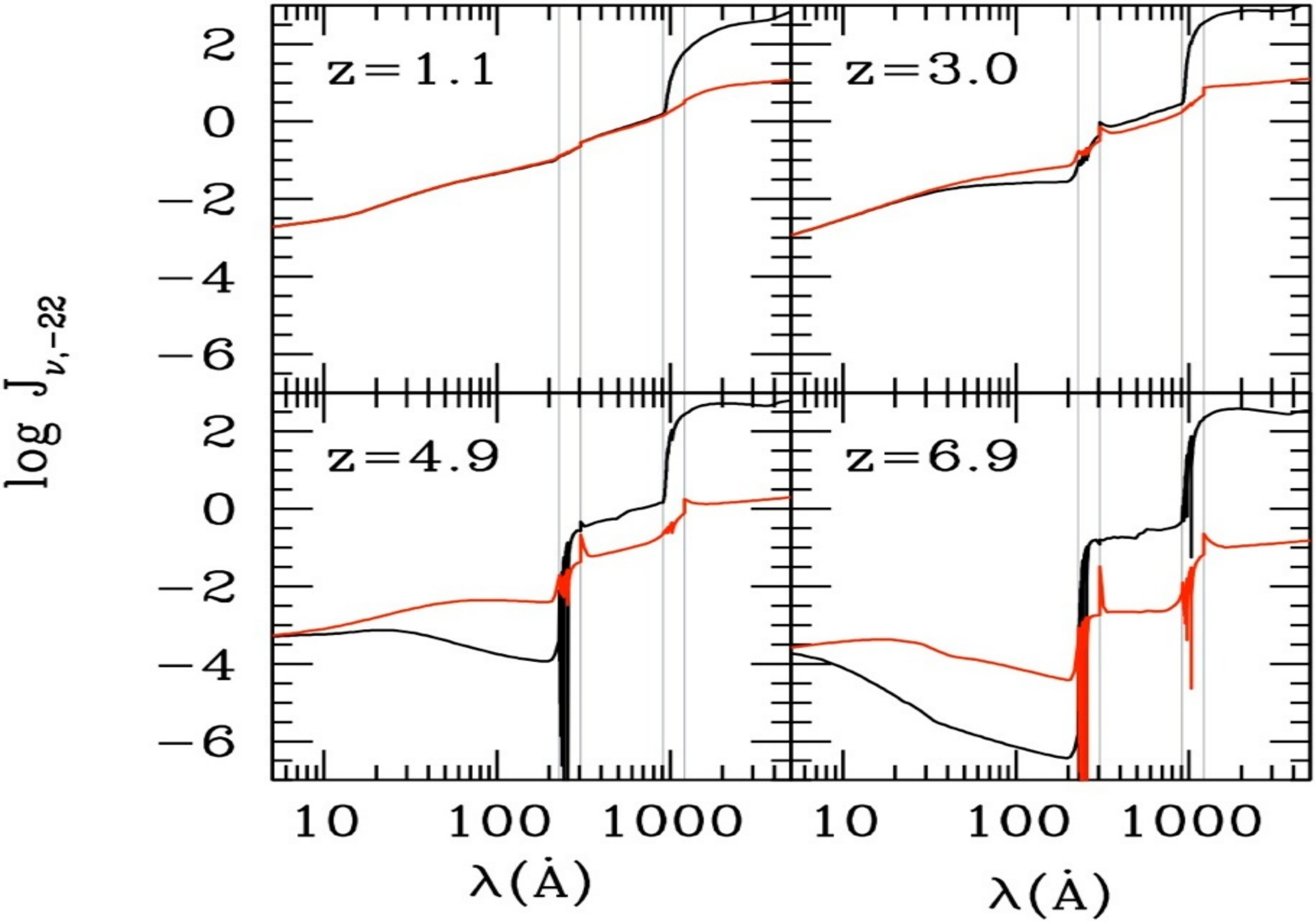
Contribution from Star Forming Galaxies

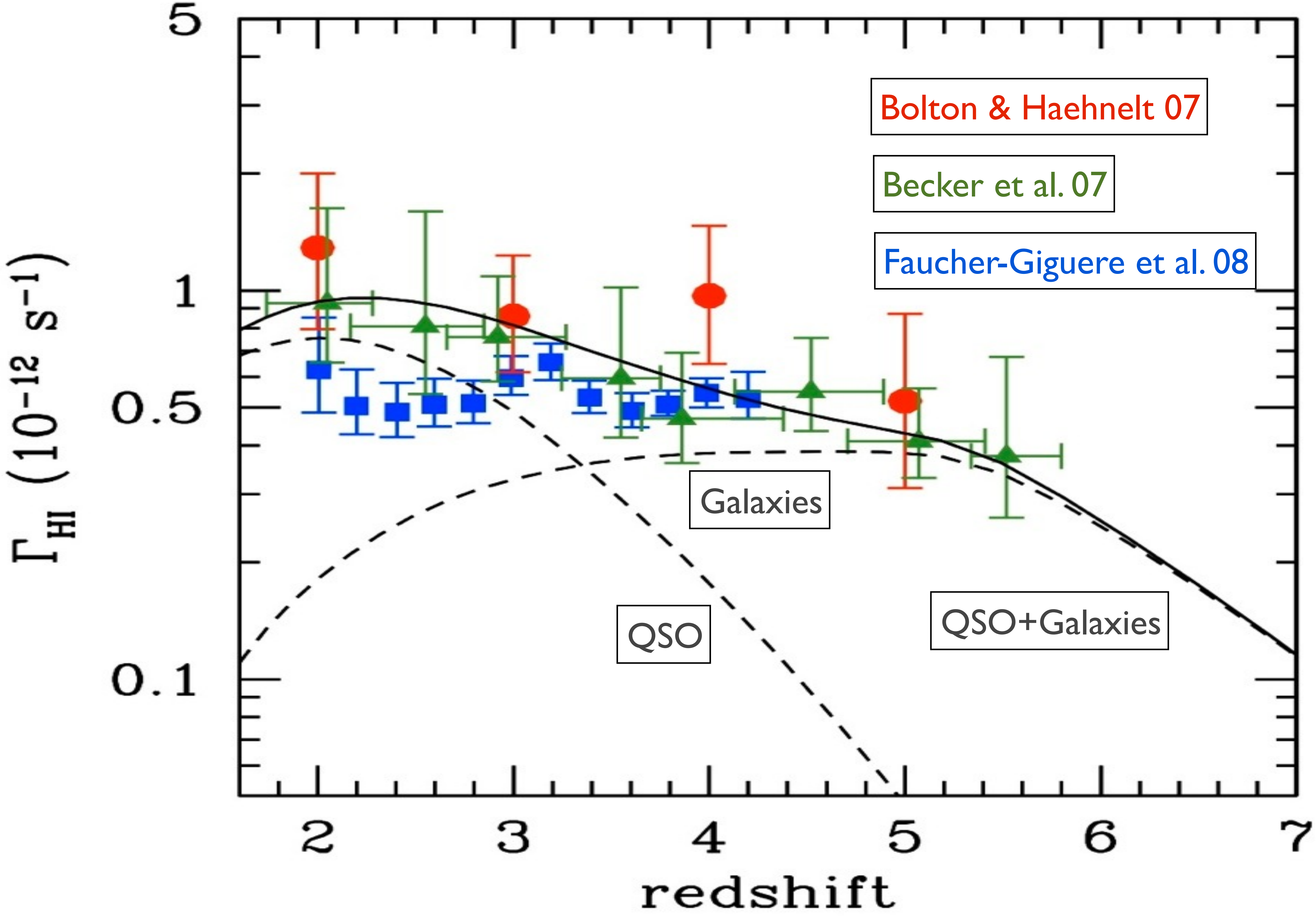
The model:
Synthetic SED (Bruzual & Charlot) with Salpeter IMF, fiducial Z vs z.

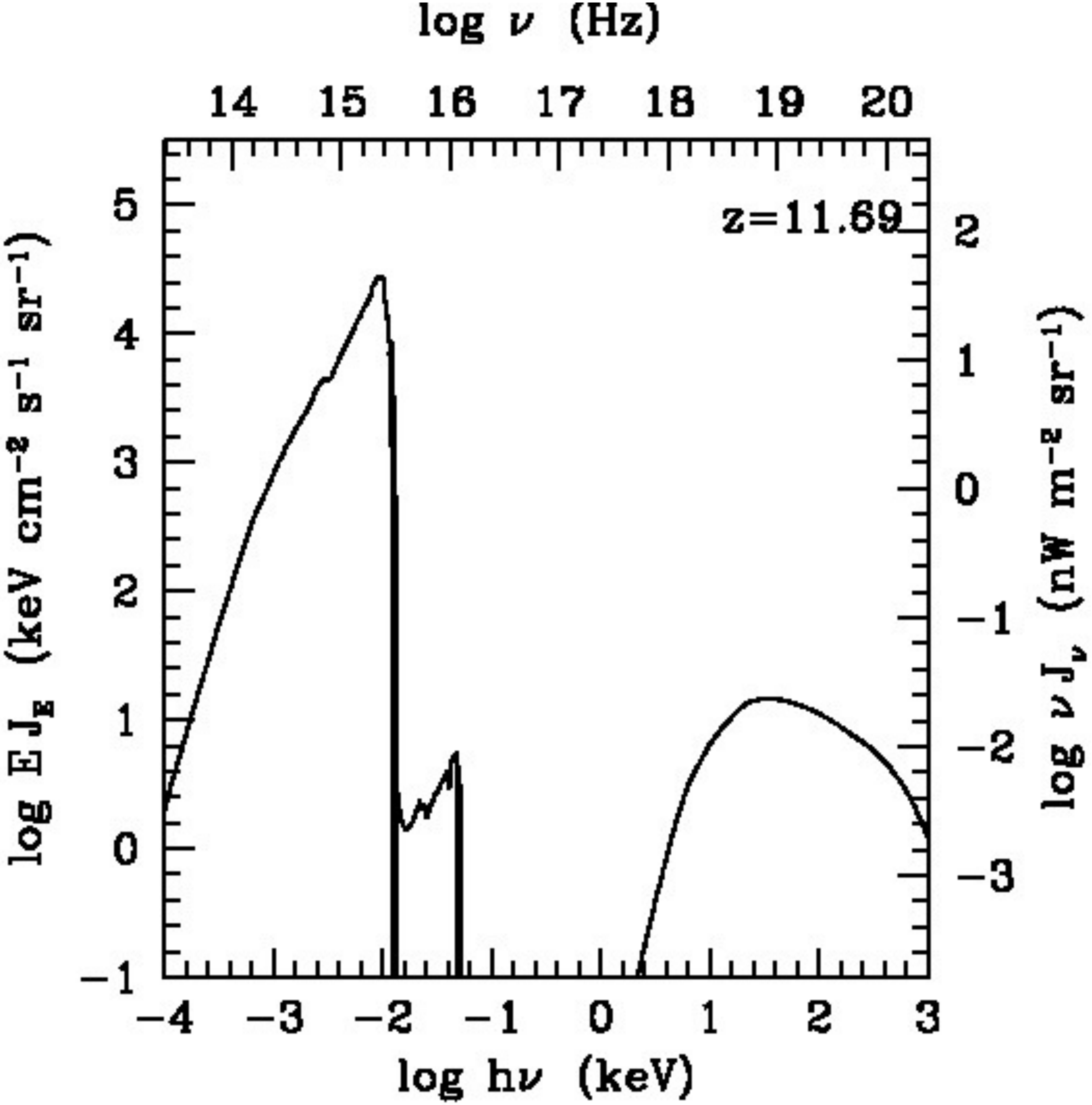
SFRD (Schiminovich et al. 2005, Reddy & Steidel 2009, Bouwens et al. 2010).
Key parameters: slope of the faint end, dust correction.

One "fitting" quantity:
redshift-dependent escape fraction (lo-to-hi with z)

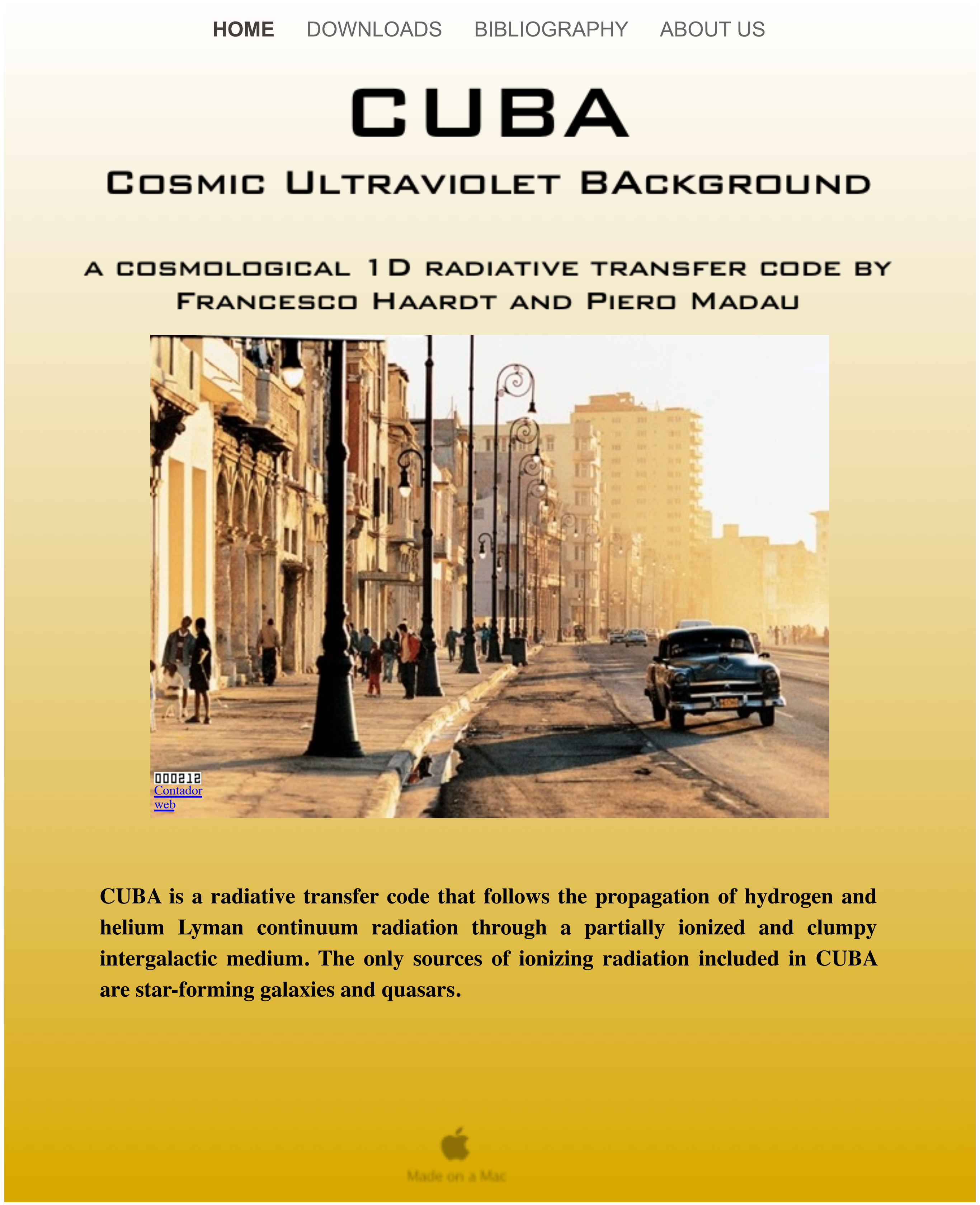
Costraints:
1) reionize HI by z=6-7, HeII by z=2.5-3.5;
2) fit ionization rate measurements.


z=1.1
z=3.0
z=4.9
z=6.9
log J_{ν,-22}
2
0
−2
−4
−6
10
100
1000
λ(Å)


Bolton & Haehnelt 07
Becker et al. 07
Faucher-Giguere et al. 08
Galaxies
QSO
QSO+Galaxies
Γ_{HI} (10^{-12} s^{-1})
5
1
0.5
0.1
2
3
4
5
6
7
redshift


log ν (Hz)
14
15
16
17
18
19
20
z=11.69
5
4
3
2
1
0
−1
log E J_E (keV cm⁻² s⁻¹ sr⁻¹)
2
1
0
−1
−2
−3
log ν J_ν (nW m⁻² sr⁻¹)
−4
−3
−2
−1
0
1
2
3
log hν (keV)

www.ucolick.org/~pmadau/CUBA/HOME.html



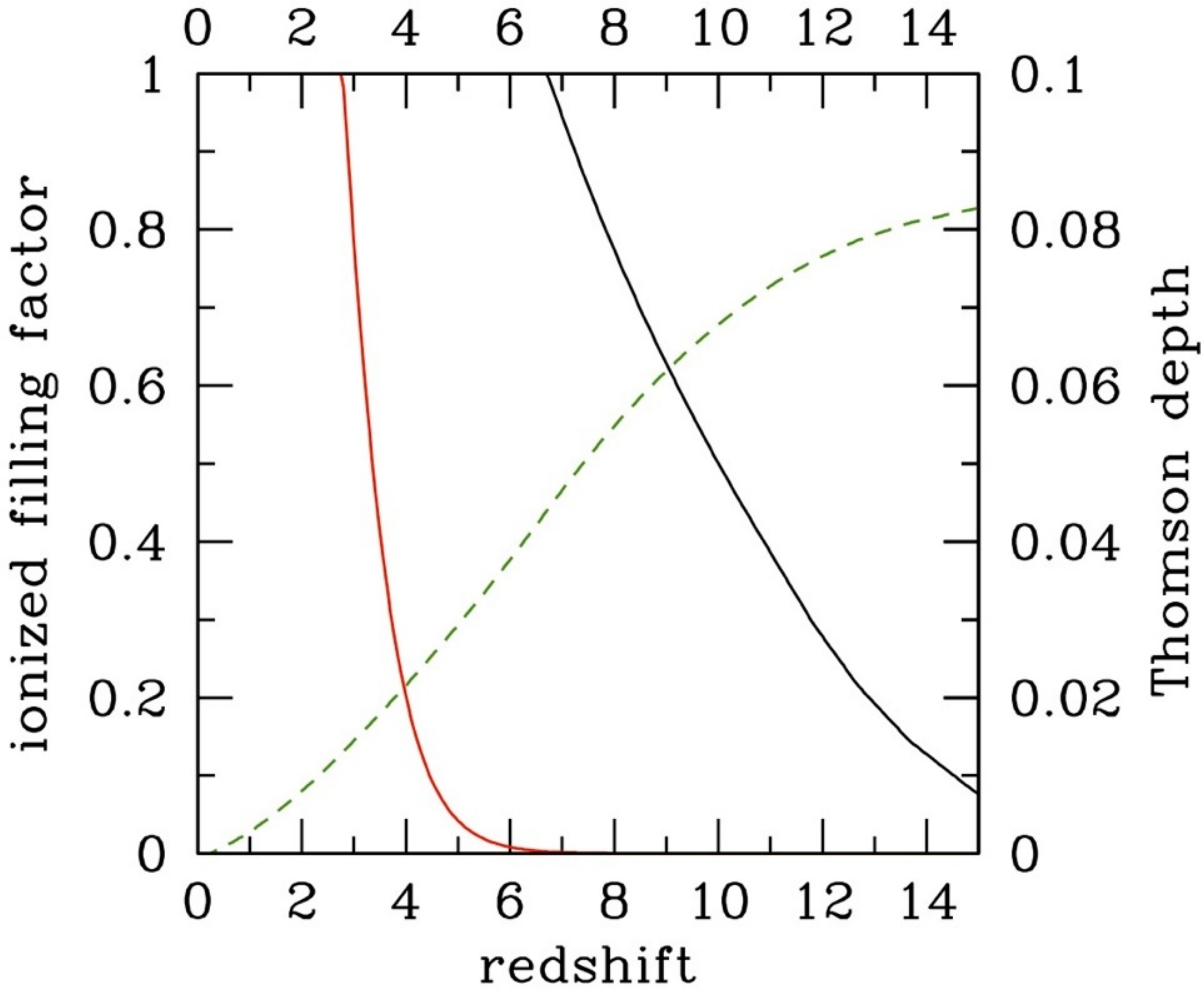
CUBA

COSMIC ULTRAVIOLET BACKGROUND

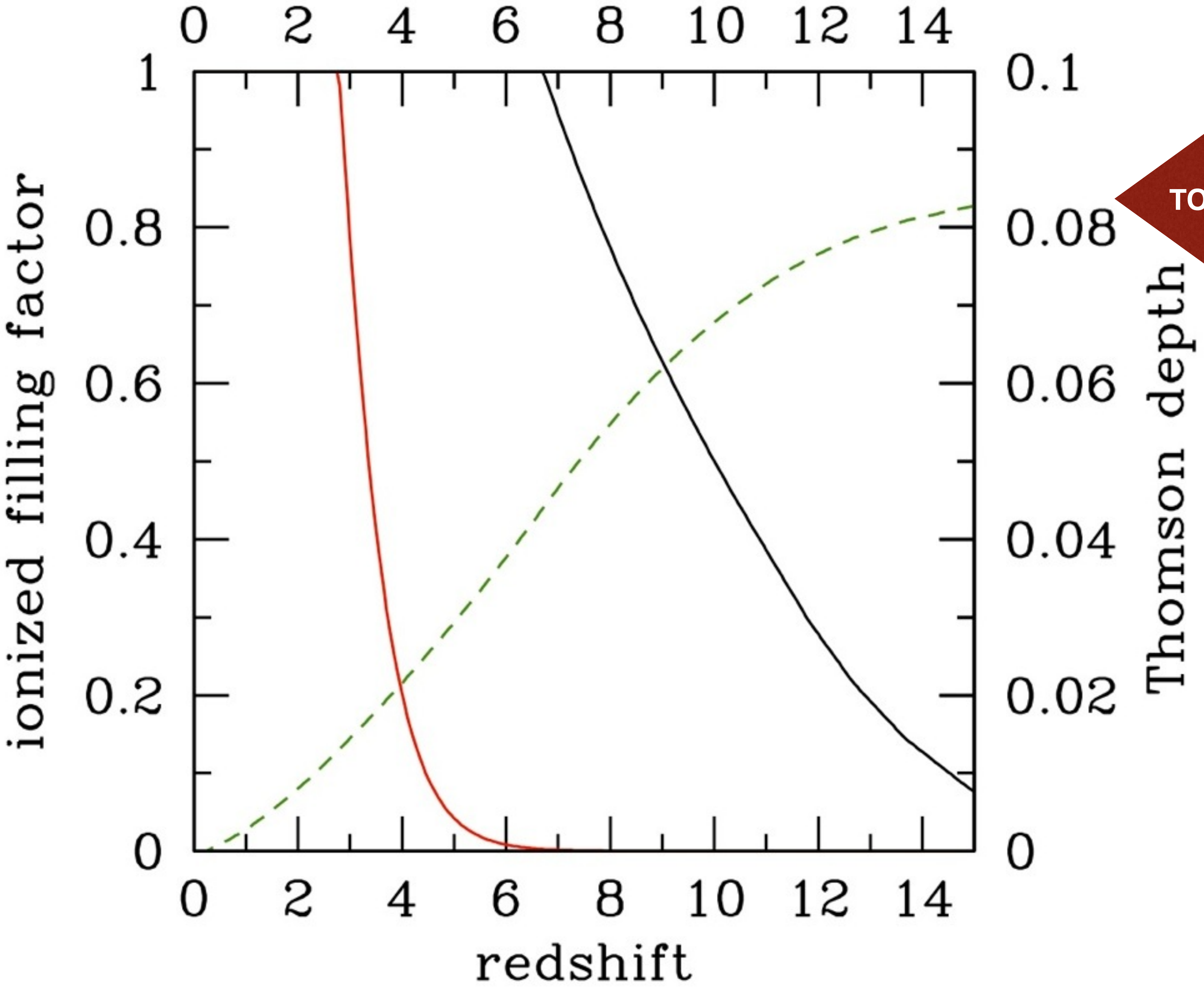
A COSMOLOGICAL 1D RADIATIVE TRANSFER CODE BY
FRANCESCO HAARDT AND PIERO MADAU

CUBA is a radiative transfer code that follows the propagation of hydrogen and helium Lyman continuum radiation through a partially ionized and clumpy intergalactic medium. The only sources of ionizing radiation included in CUBA are star-forming galaxies and quasars.

Filling factors and Thomson opacity



Filling factors and Thomson opacity



TOO HIGH!

Model Summary

HI reionized at z=6.7
HeII reionized at z=2.8
Fits HI ionization rates (flux decrement+proximity).

τ_{es}=0.083

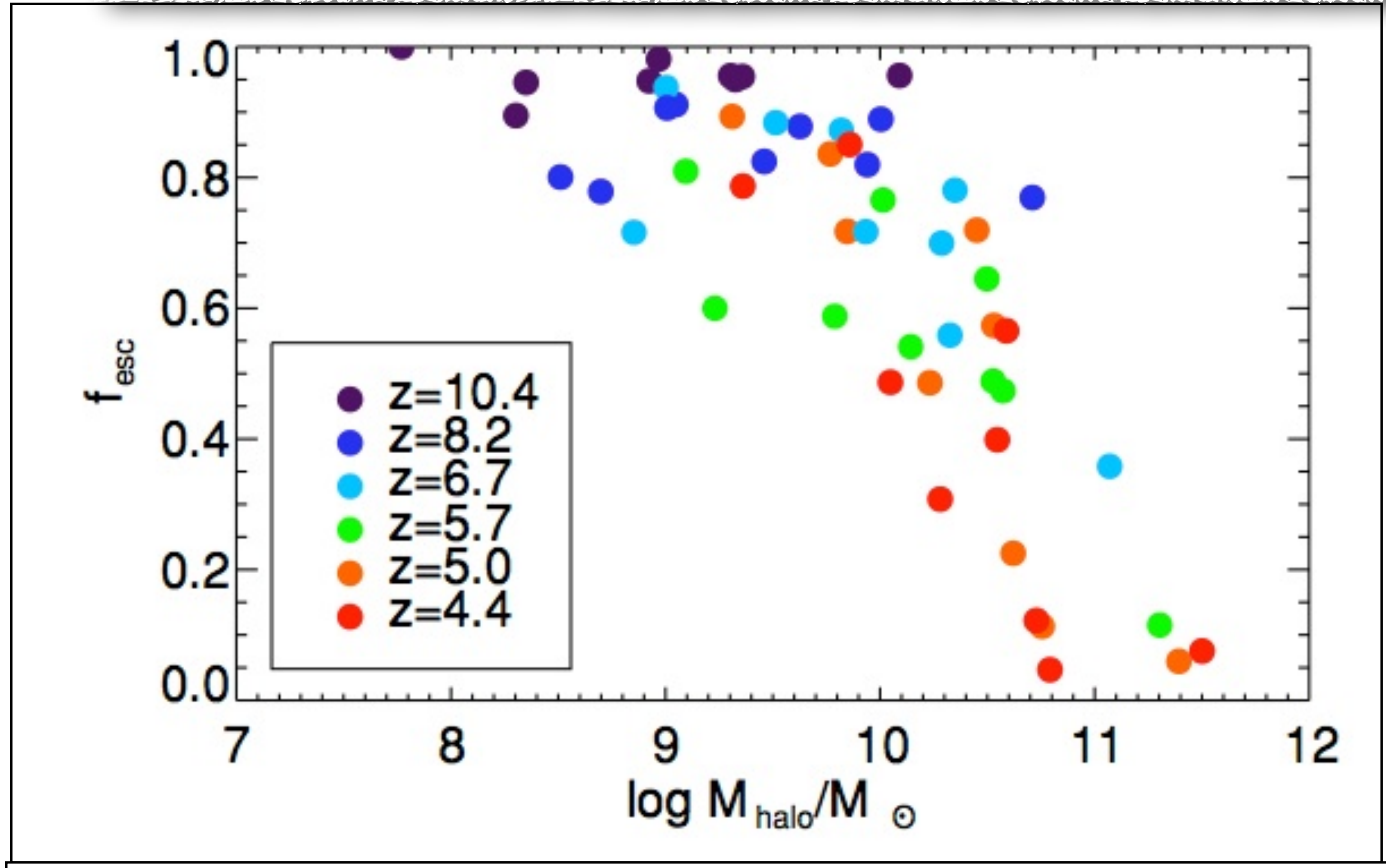
Revised now to 0.058. This implies:

1) Reionization does not necessary need to occur later, rather, it must be a bit faster than thought before Planck results.

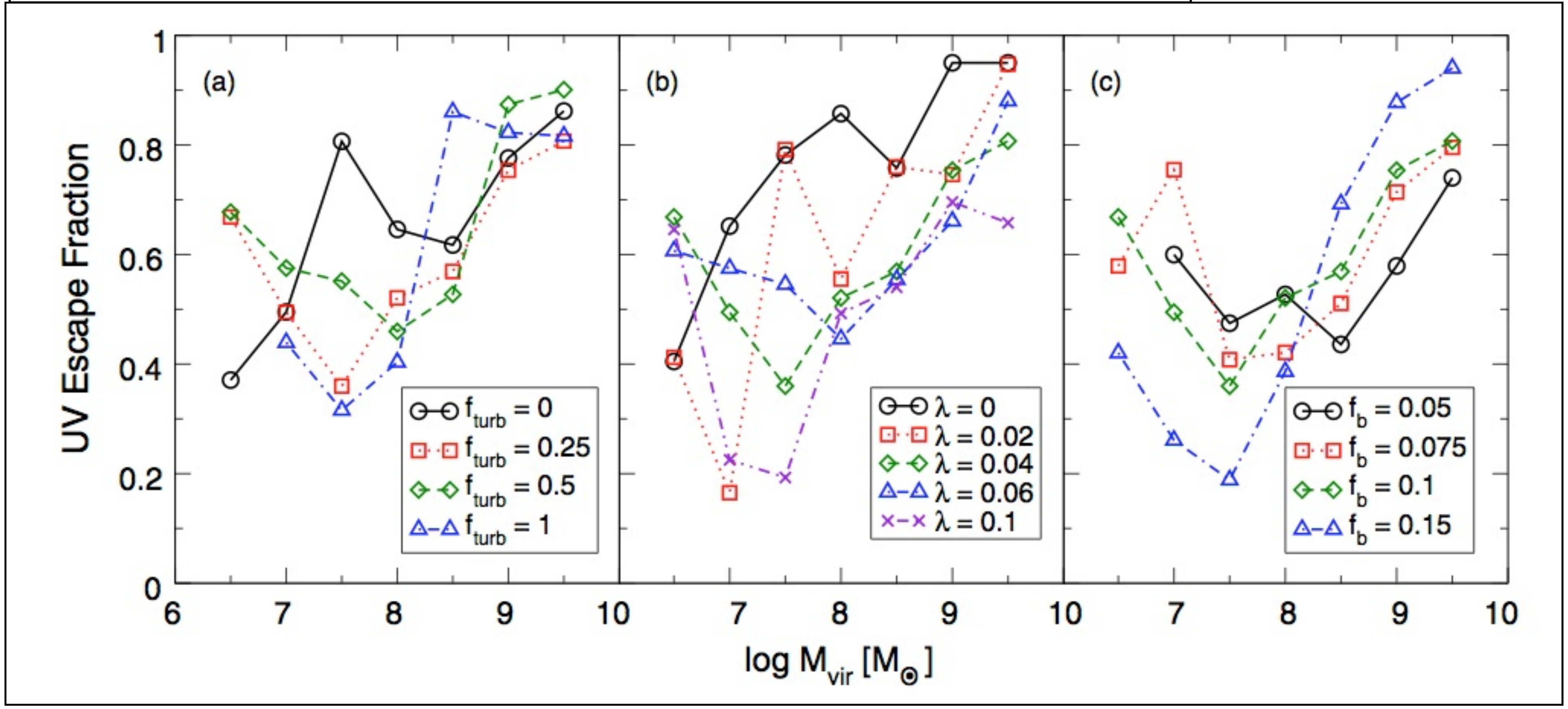
Model needs some revision (work in progress…)

Crucial parameters to fit all constraints:
1) **faint-end** of the luminosity functions.
2) **escape fraction** of Lyman continuum photons.

L-z Dependent Escape Fraction?

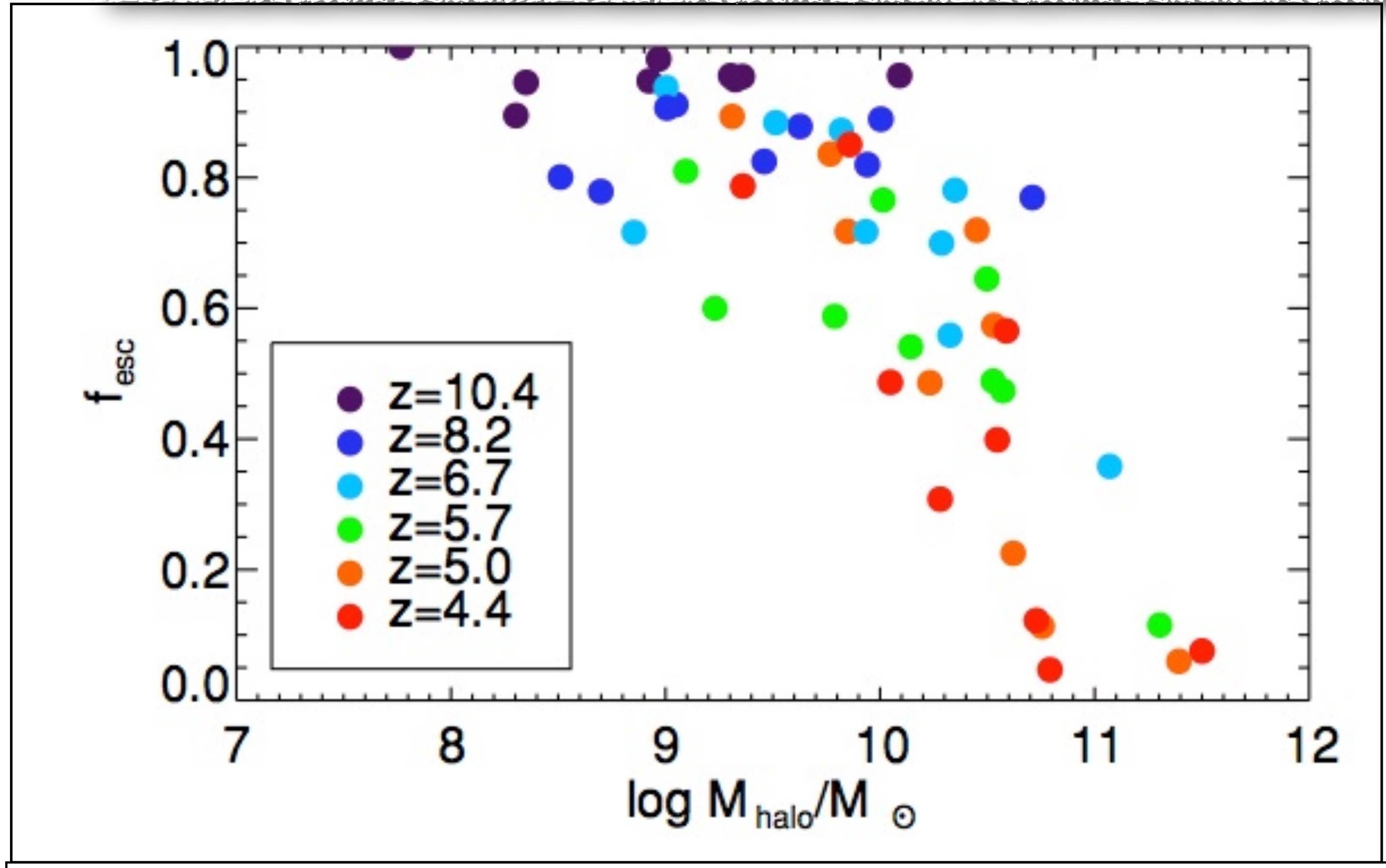


Razoumov & Sommer-Larsen 2010



Wise & Cen 2009

L-z Dependent Escape Fraction?



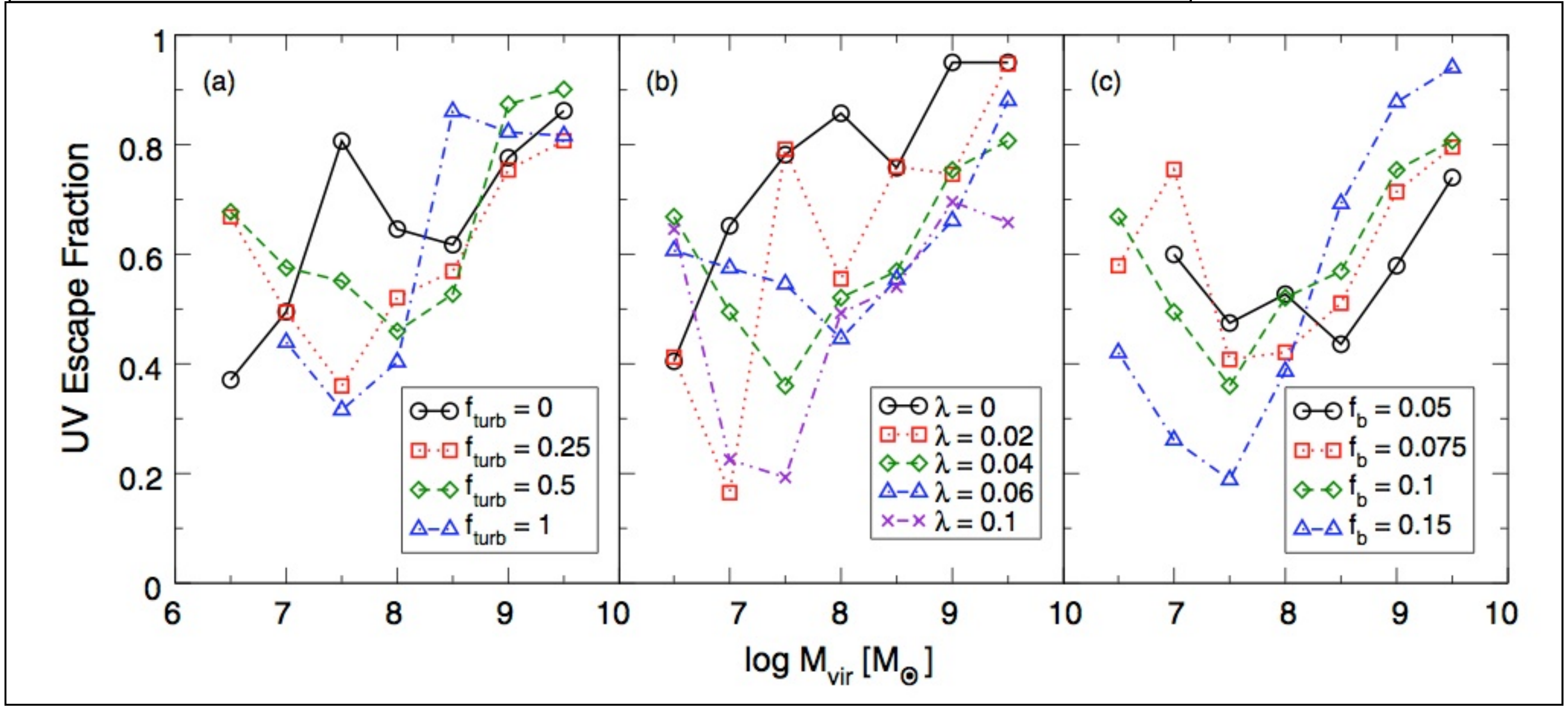
Razoumov & Sommer-Larsen 2010

Contradictory Results from Simulations

Low f_{esc} from observations:
f_{esc}<5% at z~3 from L~L*
(Vanzella et al. 2012)

No LyC emitters in bright LBG (z~3)
(Siana et al. 20150

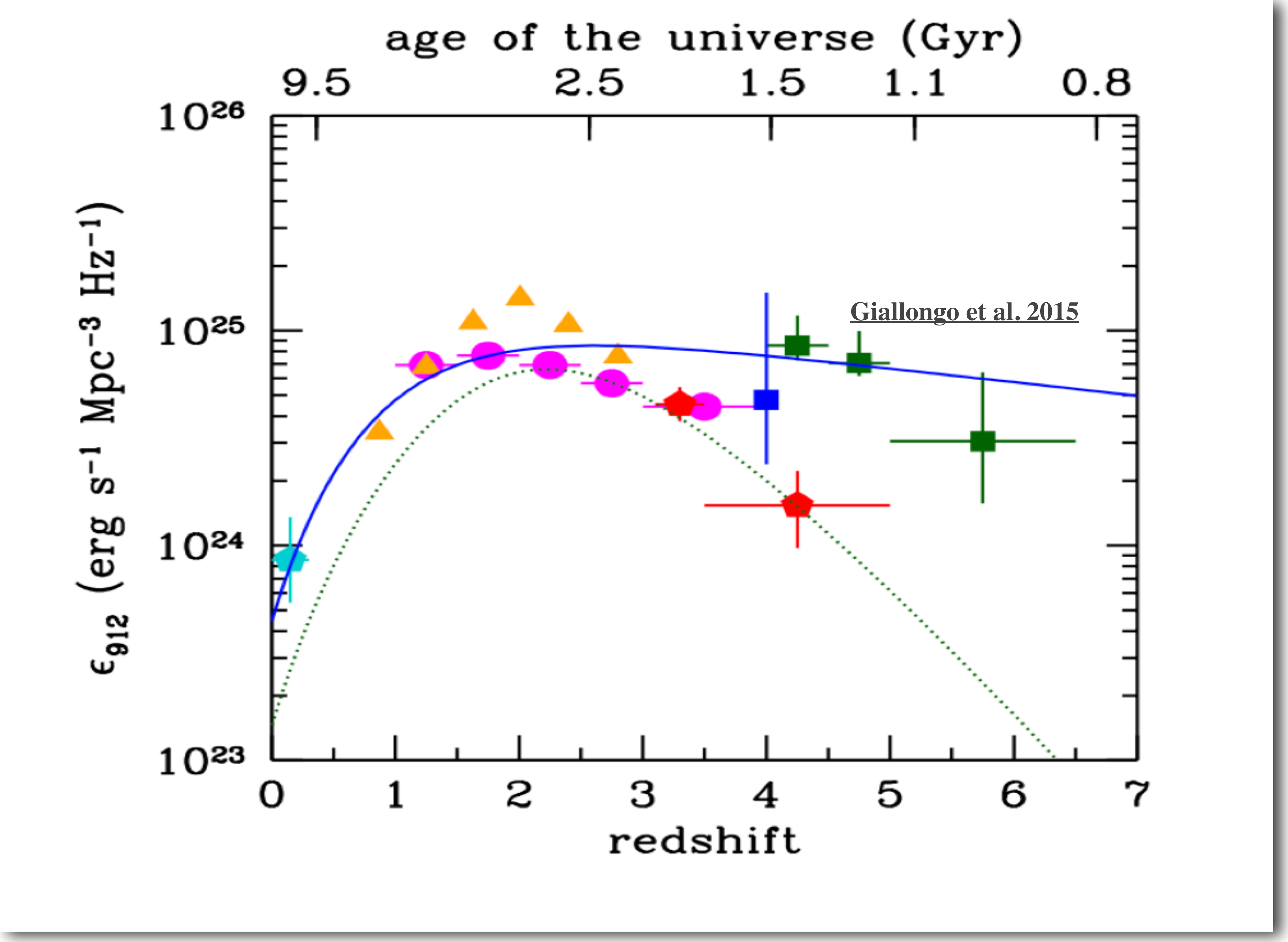
f_{esc}<5% at z~1 from 10^{9-10} M_{sun} galaxies
(Rutkowski et al., 2016).



Wise & Cen 2009

HI Reionization Driven by faint AGNs?

Madau & FH 2015



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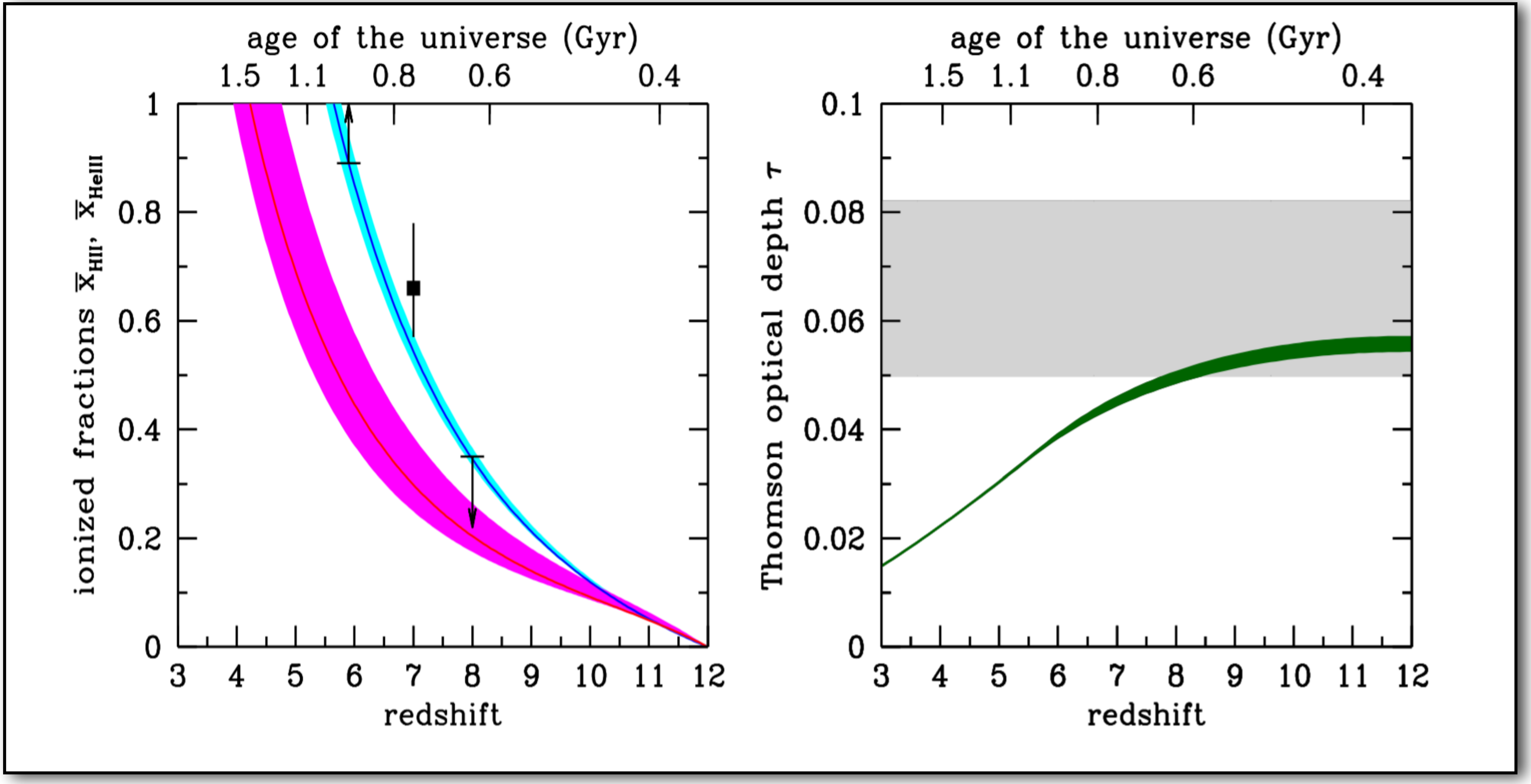
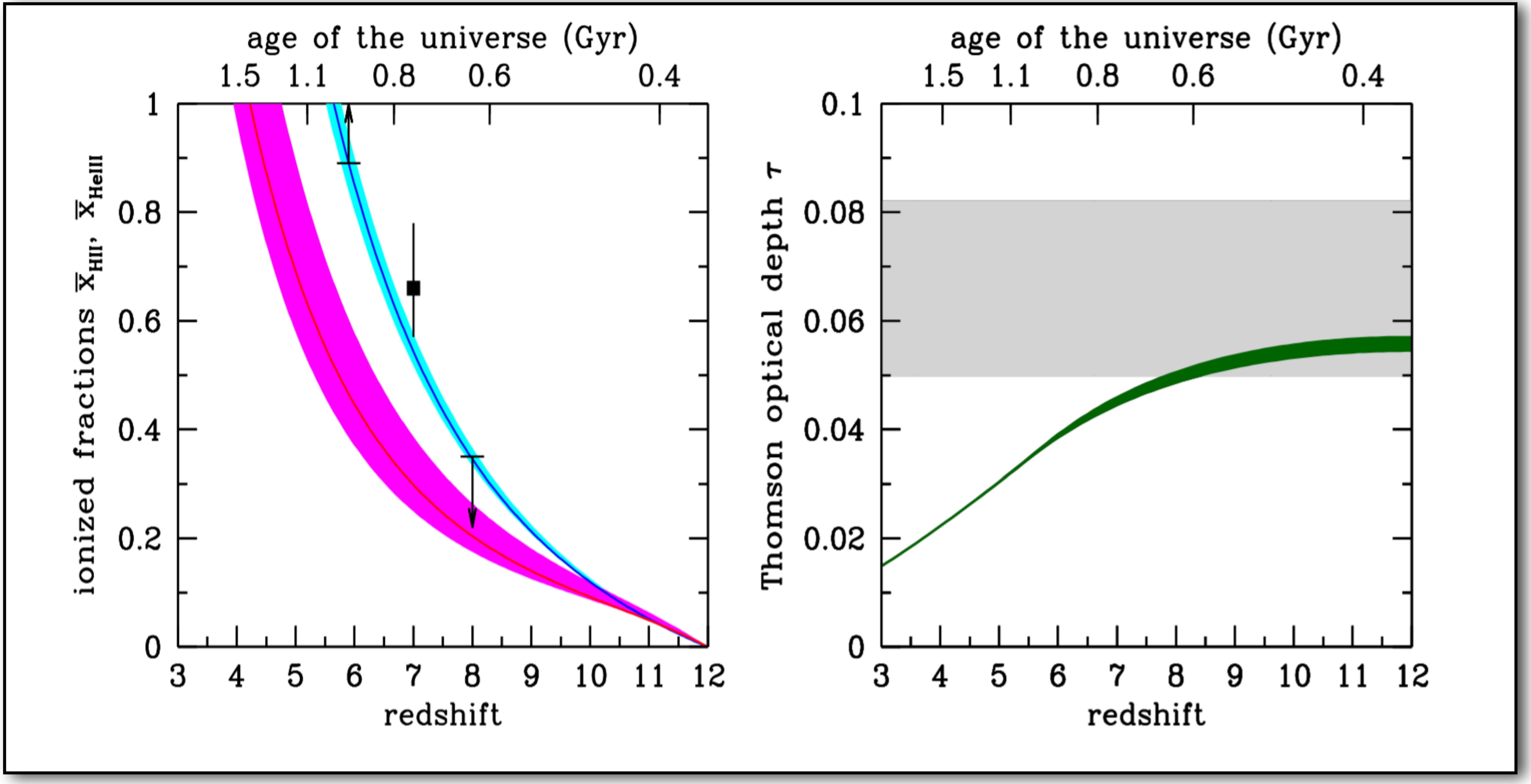


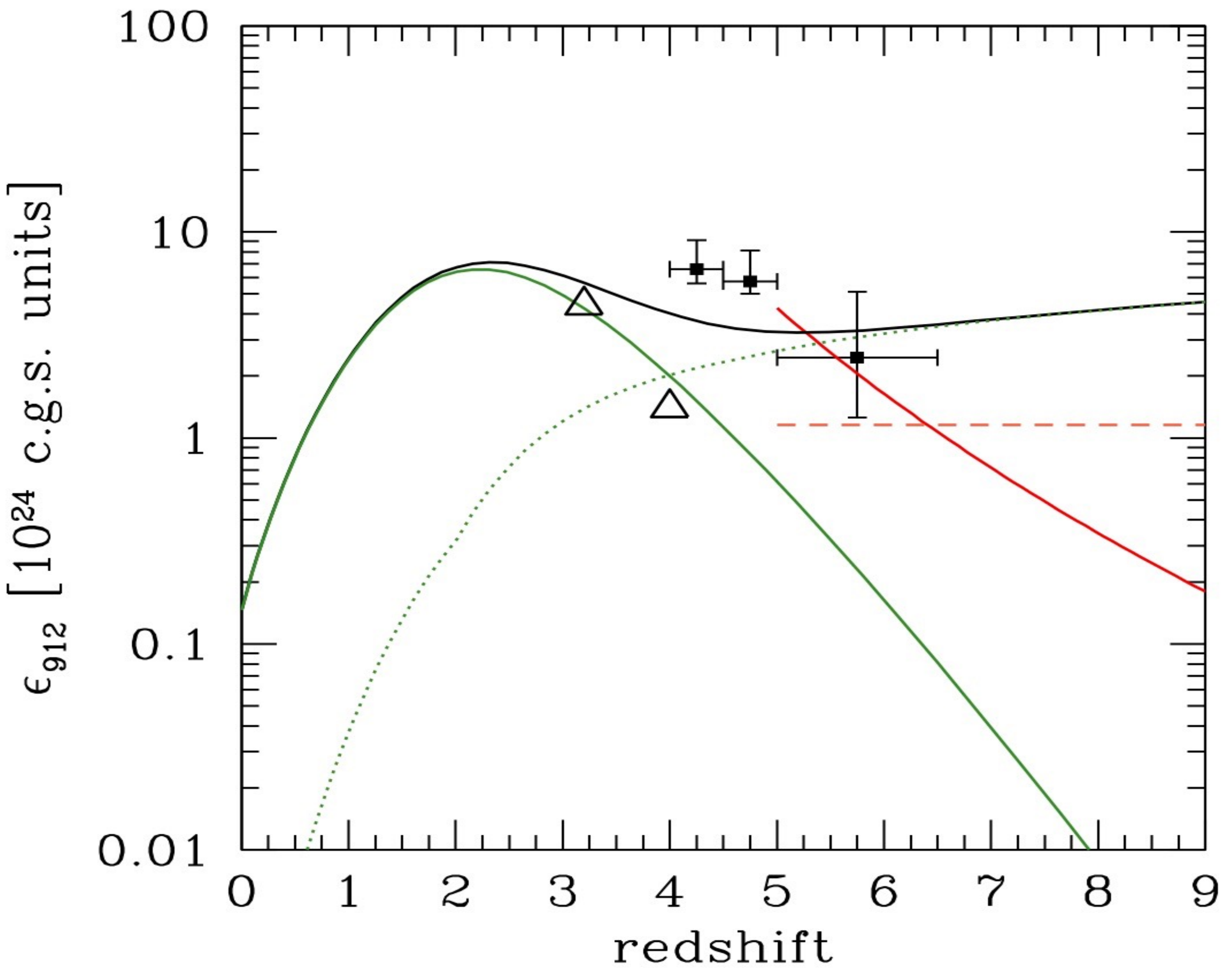
HI Reionization Driven by faint AGNs?

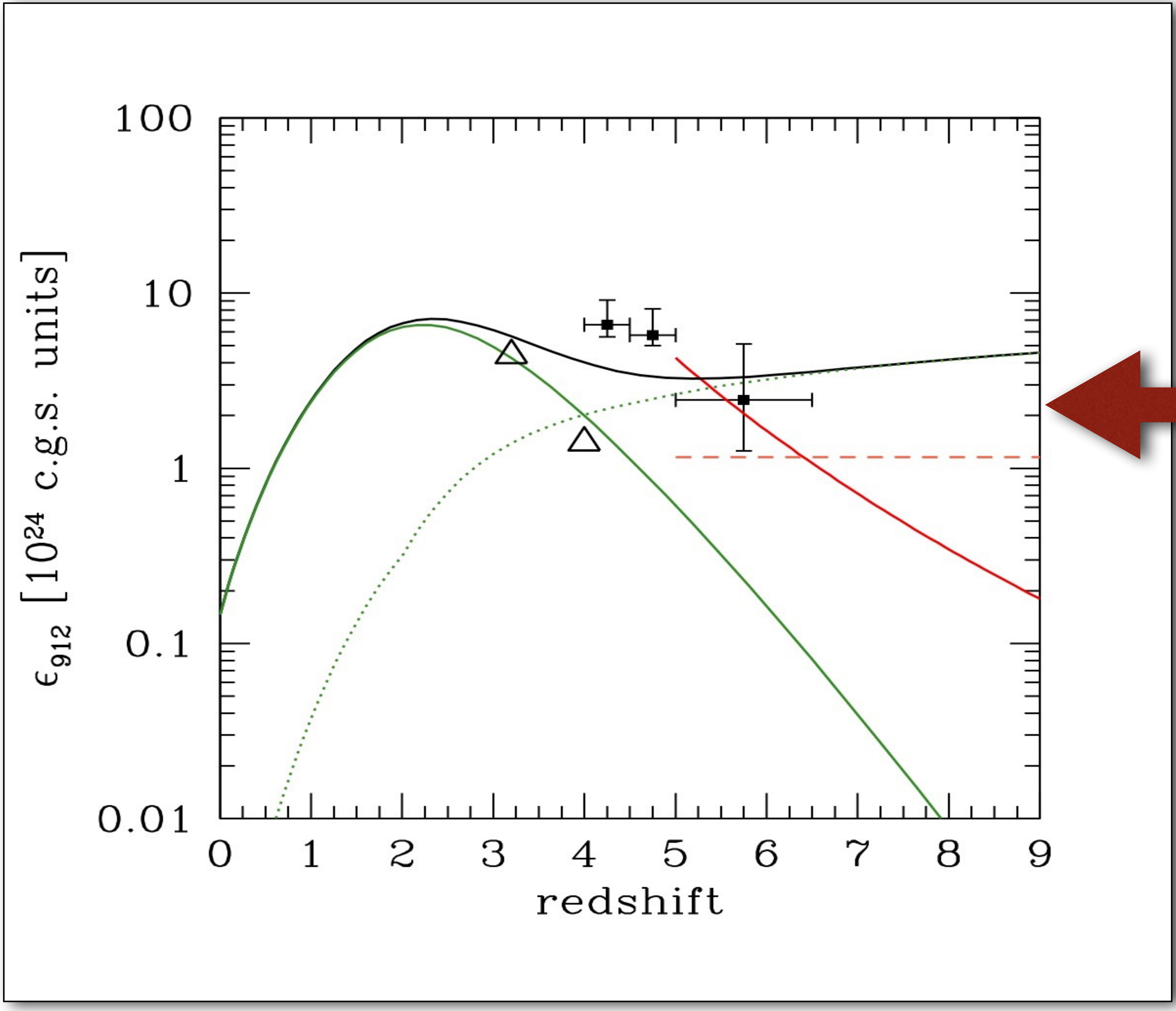
Madau & FH 2015



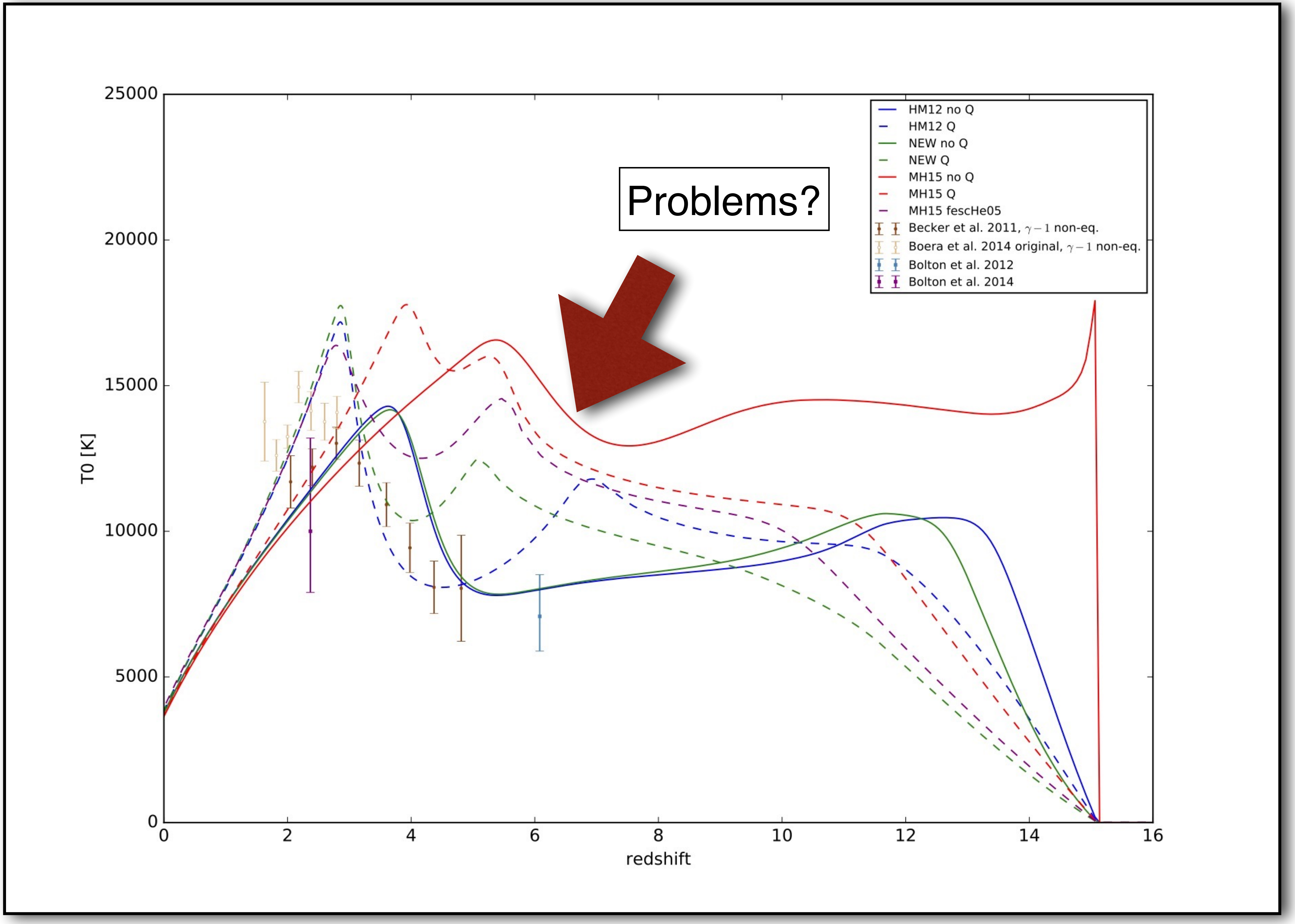
AGNs emissivity must be consistent with:

1) XRB unresolved fraction
2) Thermal history of the IGM


ϵ_{912} [10^{24} c.g.s. units]
100
10
1
0.1
0.01
0
1
2
3
4
5
6
7
8
9
redshift



Low typeII/typeI ratio required



Problems?

AGN driven reionization: so cool, and yet too hot?

Open Issues

Large uncertainties in almost all input quantities: hi-z LFs, SEDs, escape fraction, IGM clumpiness, etc.

HI:

1. When did reionization occur? How fast was it?
2. Can AGNs alone really do it?
3. Star forming galaxies can do it, but the observed escape fraction in bright galaxies at z~3 seems too low. Is it much larger (possibly 100%!) in faint/dwarf galaxies? Is it an increasing function of redshift?
4. Is there a photon budget shortage at z~0?

HeII:

1. Are indications of z=3 reionization real? (Contradictory results).
2. Are there other possible sources (e.g., X-ray binaries, blazars, decaying exotic particles)?