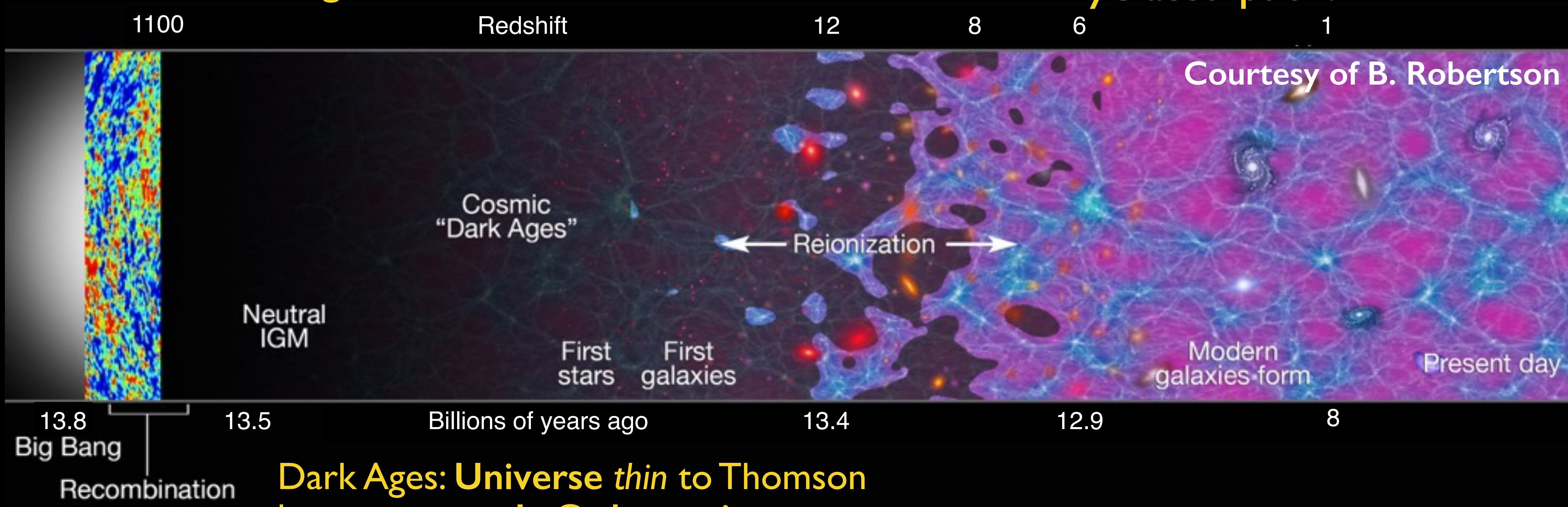
COSMIC REIONIZATION AFTER *PLANCK*: PROGRESS AND CHALLENGES

Universe *opaque* to Thomson scattering

Strikly speaking, Universe still not *transparent* to LyC absorption!



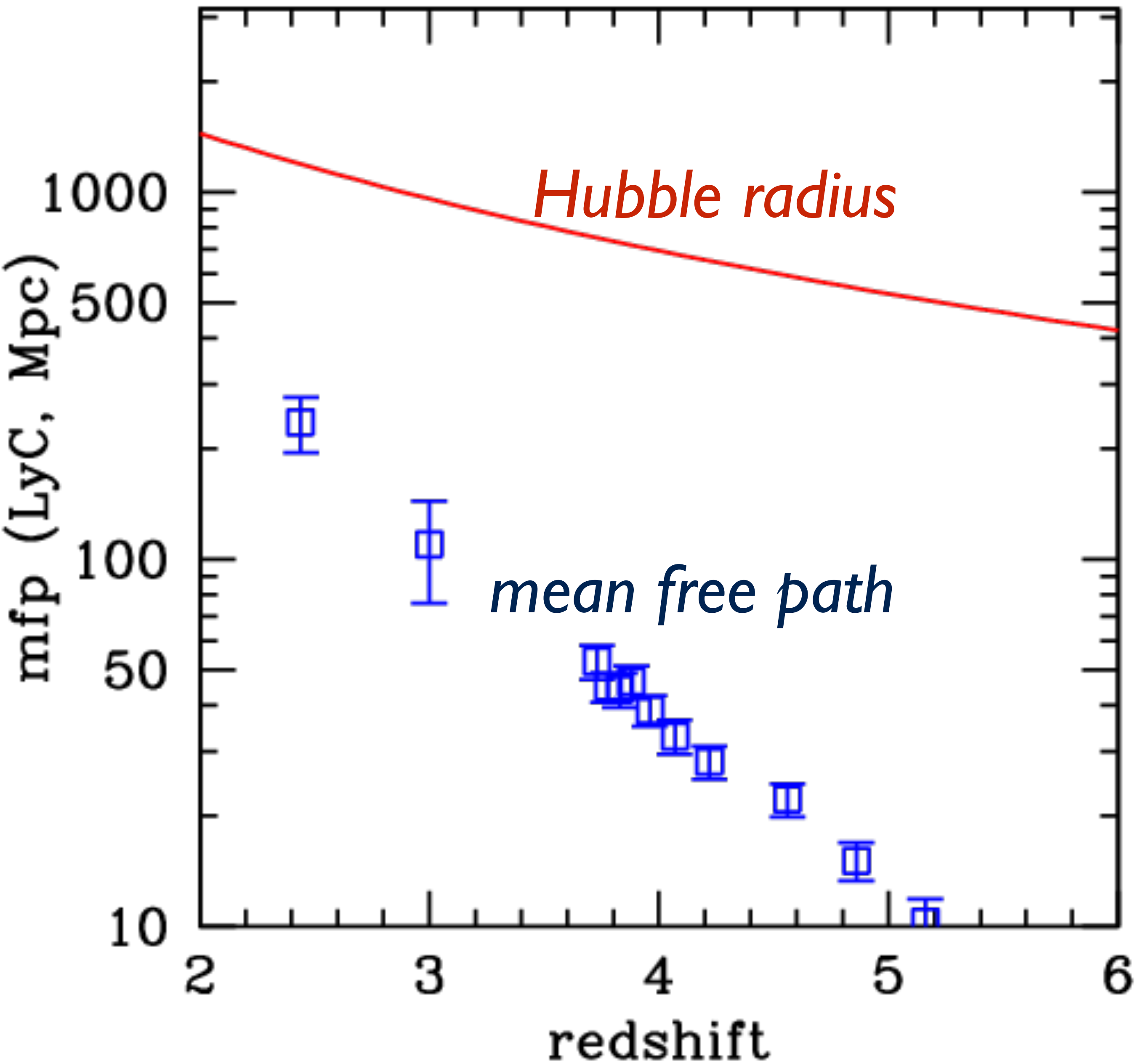
Courtesy of B. Robertson

Dark Ages: **Universe *thin*** to Thomson but ***opaque* to LyC absorption**

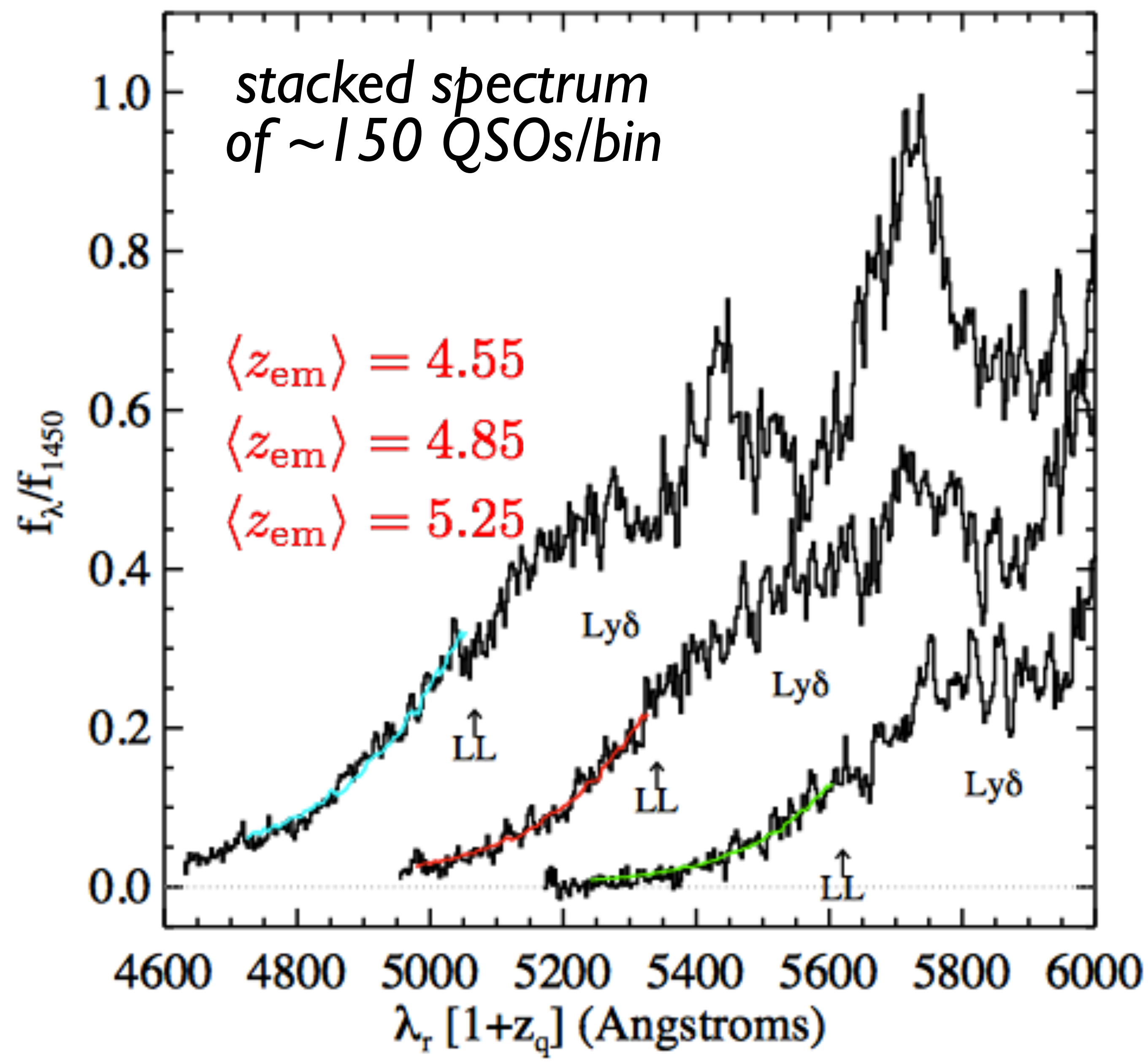
PIERO MADAU
UCSC

EDINBURGH 2016

Hydrogen Lyman Continuum Opacity



Prochaska et al 2009



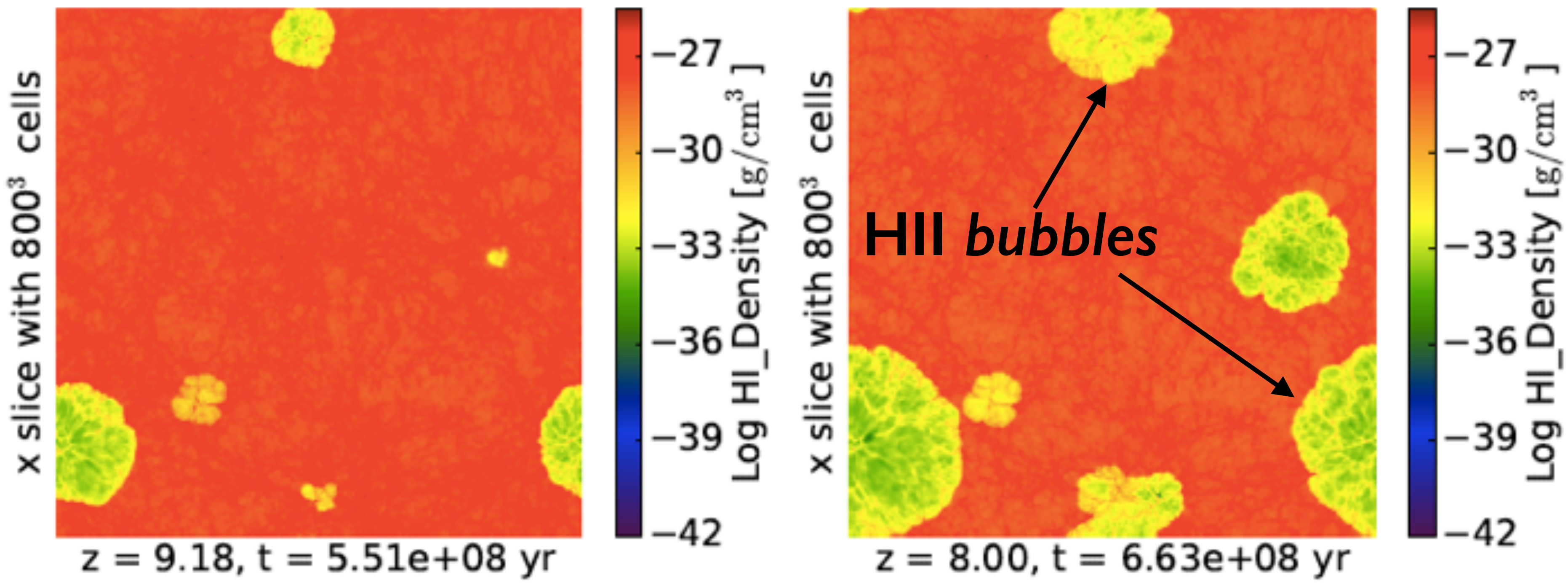
z>1.5 mfp < c/H

☞ ***Universe is optically thick to LyC even after reionization!***

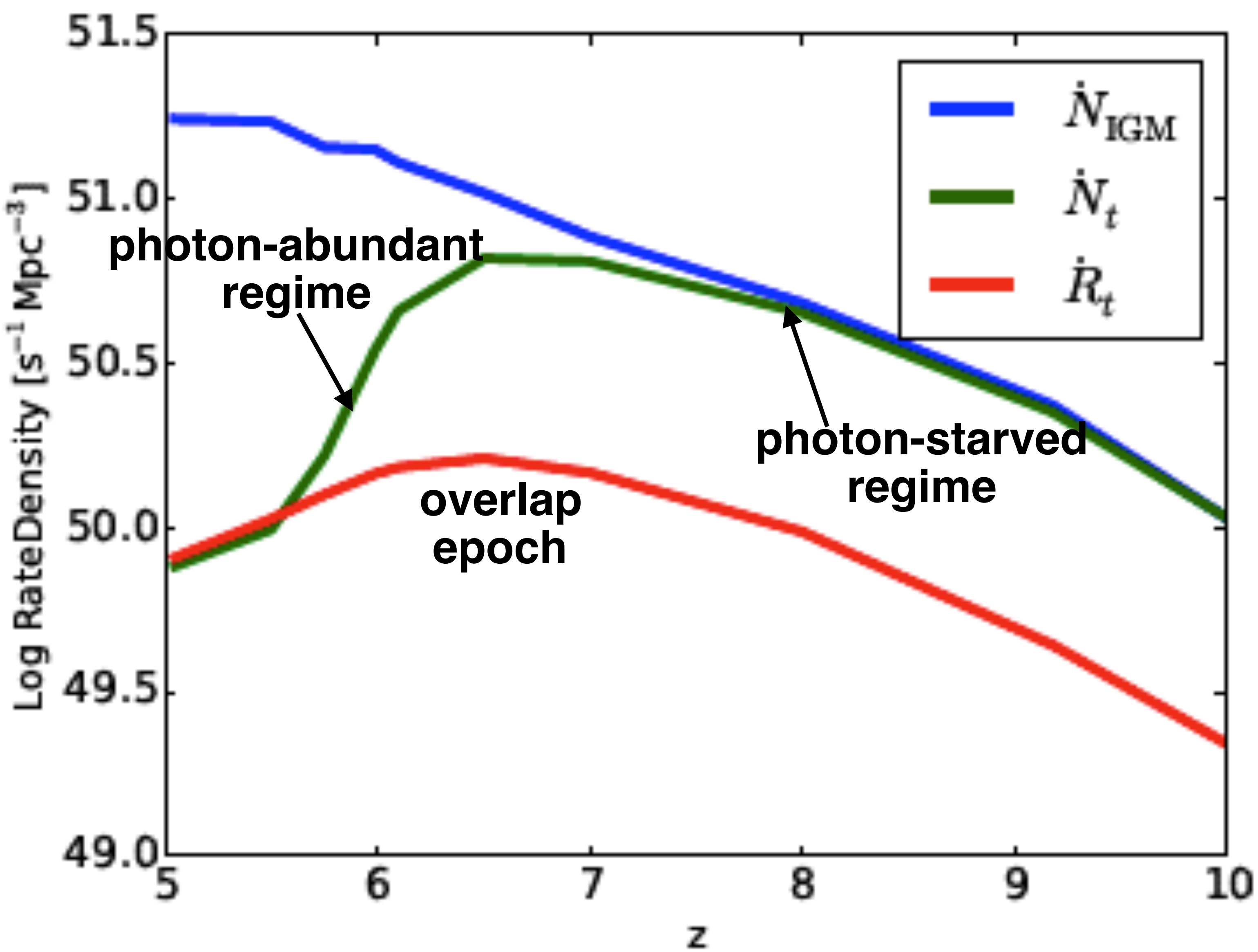
$$\tau_{\rm LyC}(z_{912}, z) = c\int_{z_{912}}^{z} \frac{dz'}{(1+z')H(z')\,{\rm mfp}(\lambda', z')}$$

$$\lambda' = 912\,\text{Å}(1+z_{912})/(1+z')$$

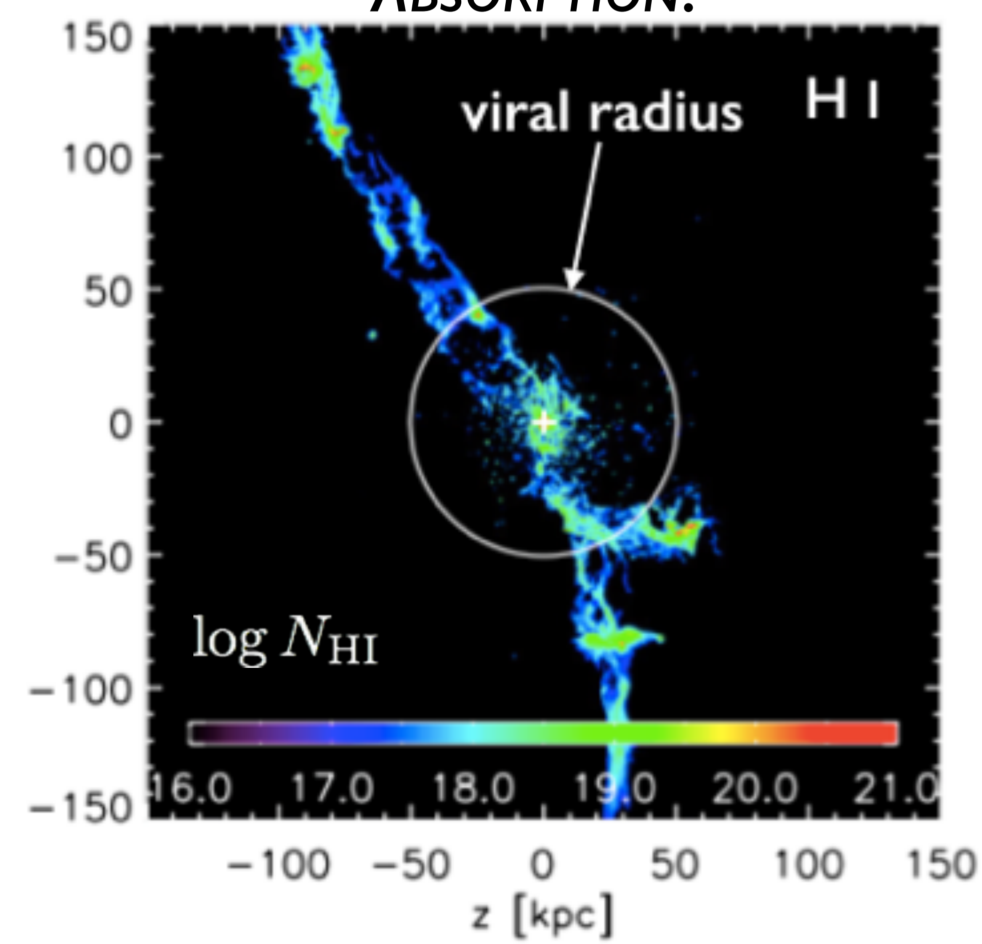
Reionization at PFLOPS Speed



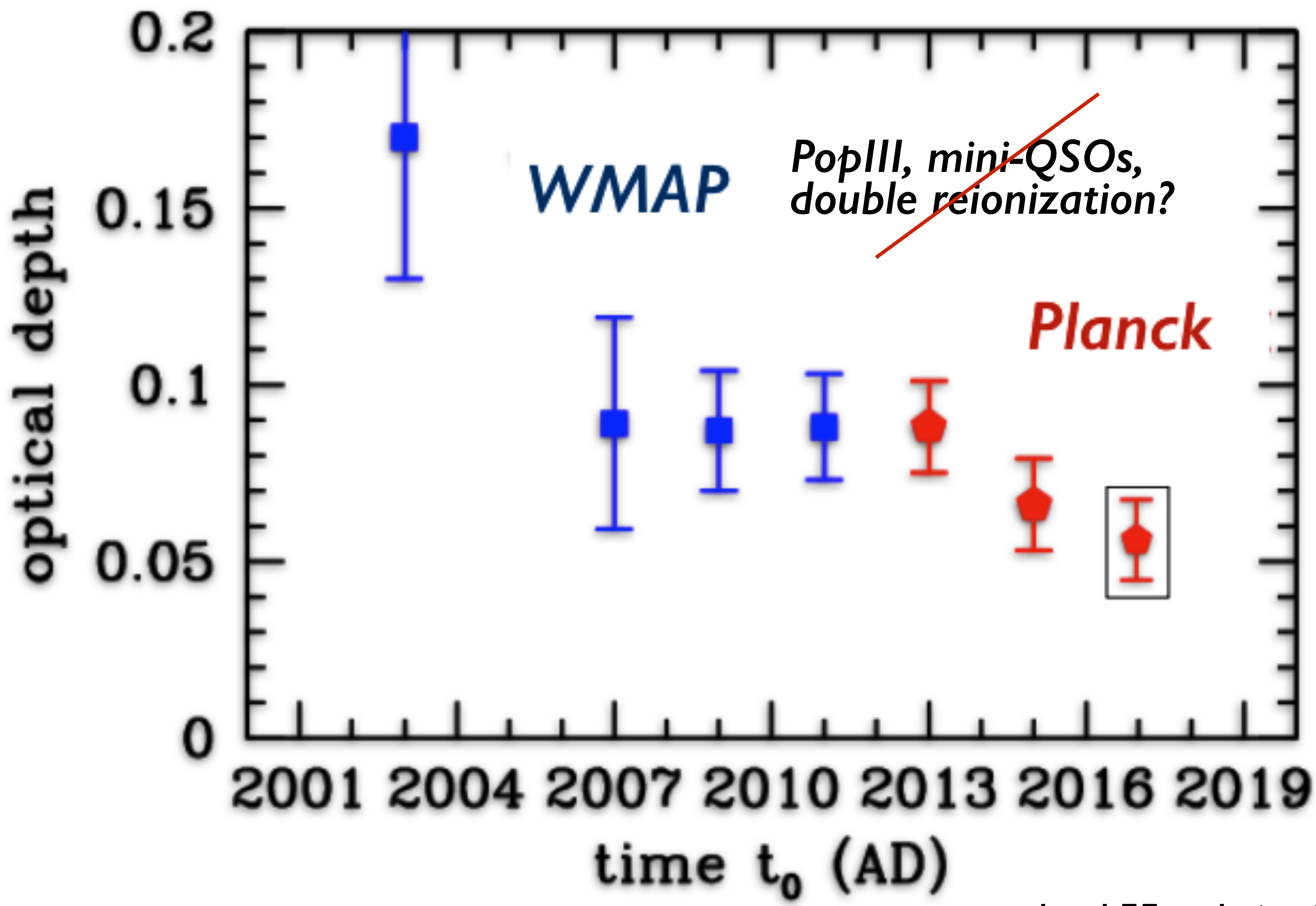
Radiative transfer simulations of reionization by So et al 2015 (box=20 cMpc)



MISSING OPTICALLY THICK ABSORPTION?



Thomson Opacity vs. Observer Time



low-l EE polarization likelihood

$$\tau(t_0) = \int_{t_0}^{t} c n_e \sigma_T dt' = 0.054 \pm 0.012$$

lollipop +*Planck*TT +VHL

high-l likelihood (ACT+SPT) measurements

Planck/ACT/SPT Constraints on Reionization History

CMB Polarization+ kinetic Sunyaev-Zeldovich

(95% CL, uniform prior)

$$z_{\rm re} \equiv z_{50\%} = 7.2^{+1.2}_{-1.2}$$

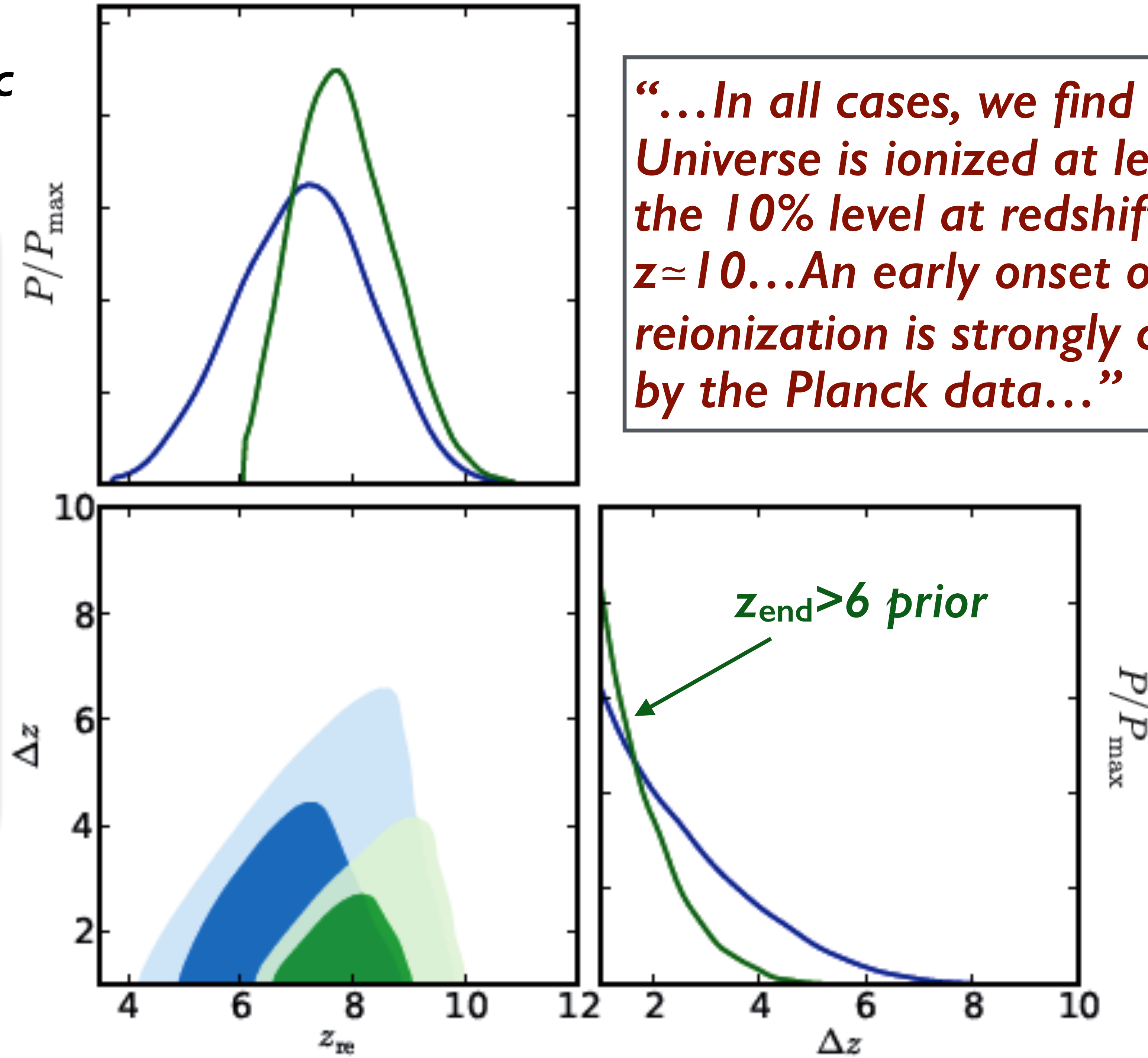
$$\Delta z < 4.8$$

(95% CL, $z_{\rm end}$>6 prior)

$$z_{\rm re} = 7.8^{+1.0}_{-0.8}$$

$$\Delta z < 2.8$$

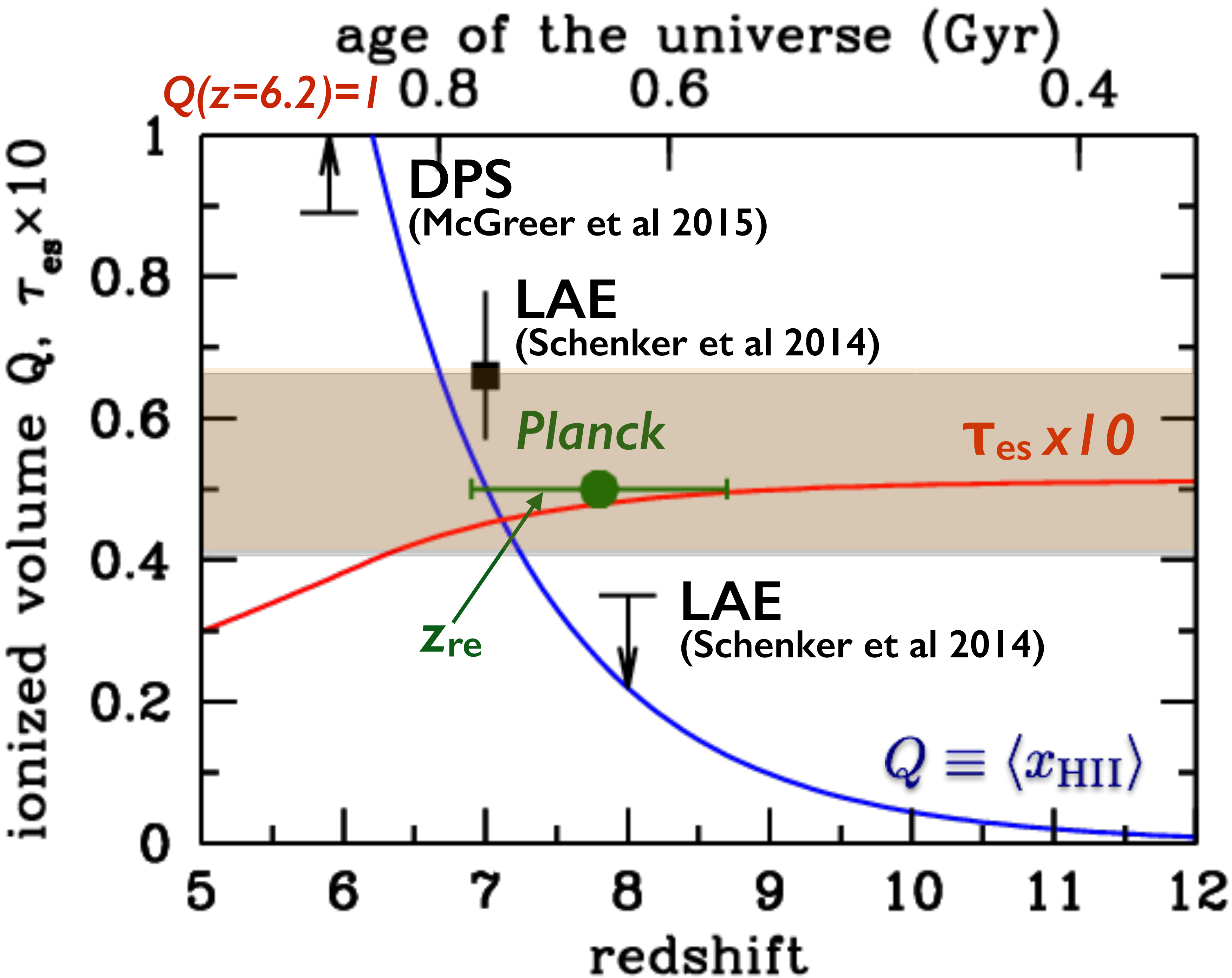
reionization is short-lived!



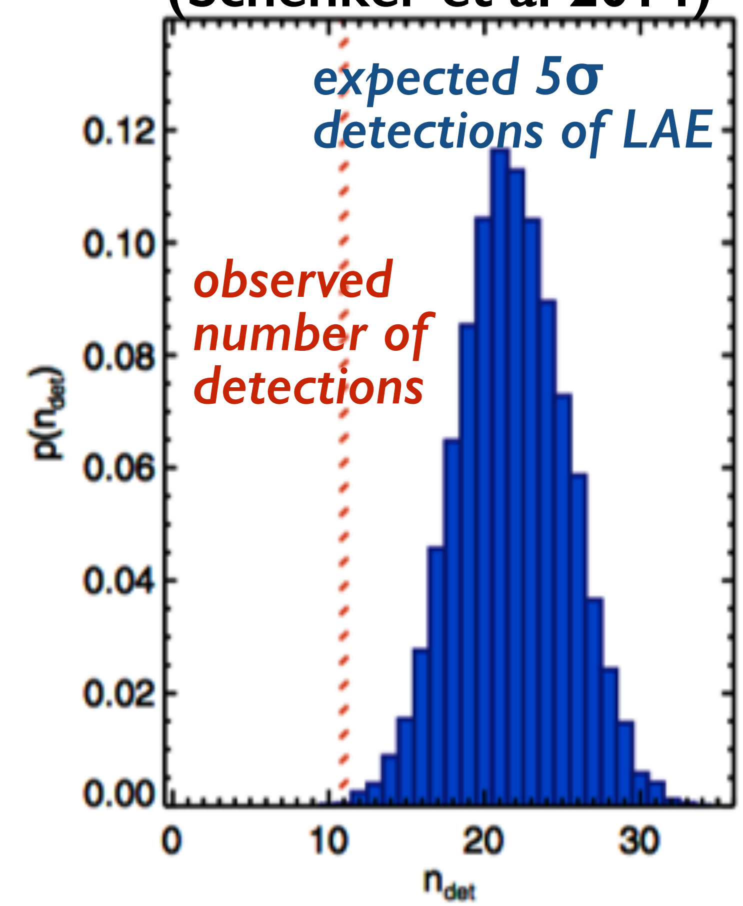
"…In all cases, we find that the Universe is ionized at less than the 10% level at redshifts above z≃10…An early onset of reionization is strongly disfavored by the Planck data…"

Fig. 14. Posterior distributions on the duration Δz and the redshift $z_{\rm re}$ of reionization from the combination of CMB polarization and kSZ effect constraints without (blue) and with (green) the prior $z_{\rm end} > 6$.

A Concordance Reionization History?



(Schenker et al 2014)



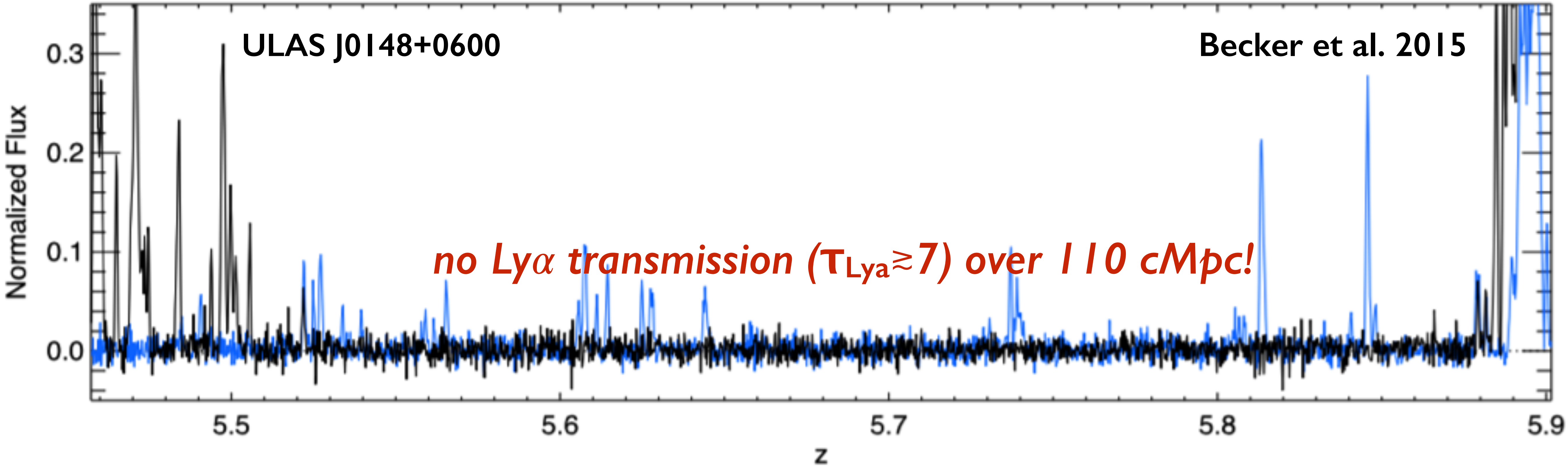
duration of reionization

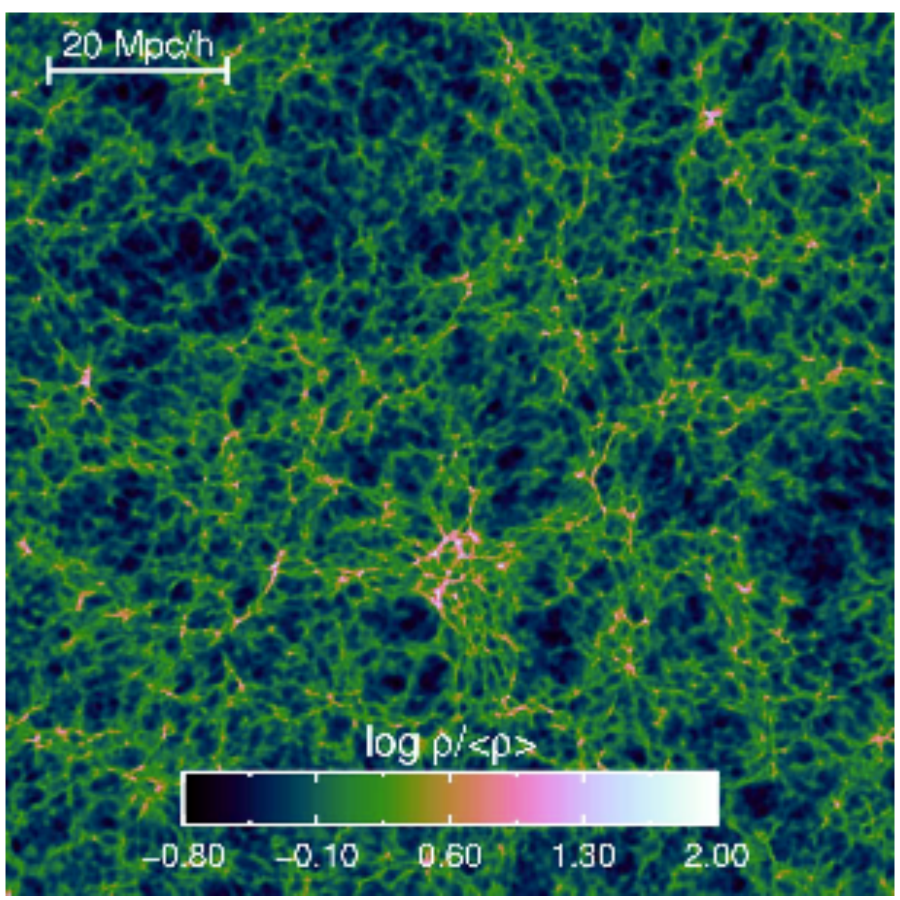
$$\Delta z \equiv z_{10} - z_{99} = 2.7$$

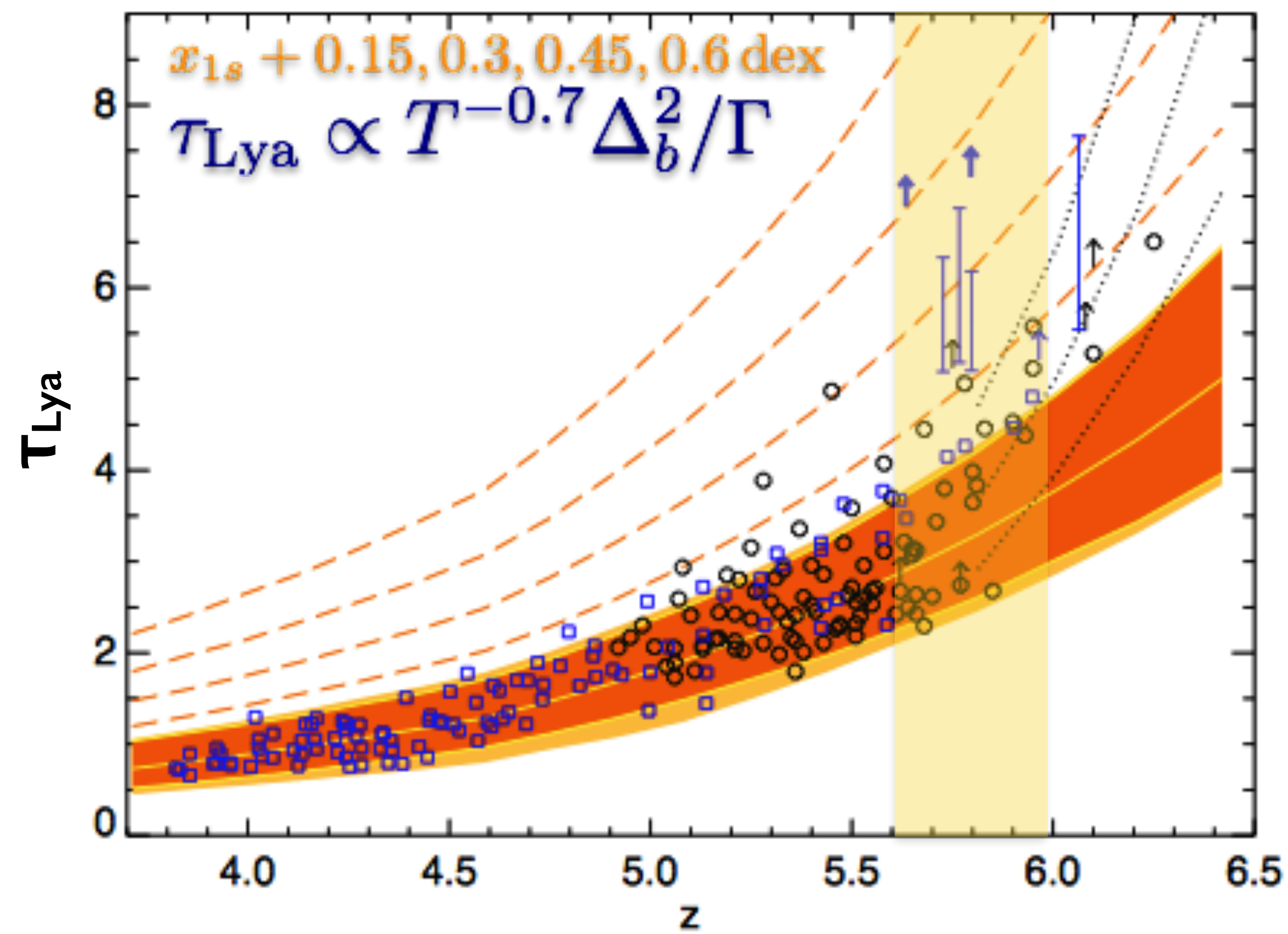
$$\tau_{\rm es} = c\sigma_T n_0 \int_0^\infty \frac{(1+z')^2 dz'}{H(z')} Q(1+\eta y)$$

$$\log \dot{n}_{\rm ion} = 50.544 - 0.25(z-8)$$
$$[\rm phot\ s^{-1}\ Mpc^{-3}]$$

Does Reionization End at z<6?

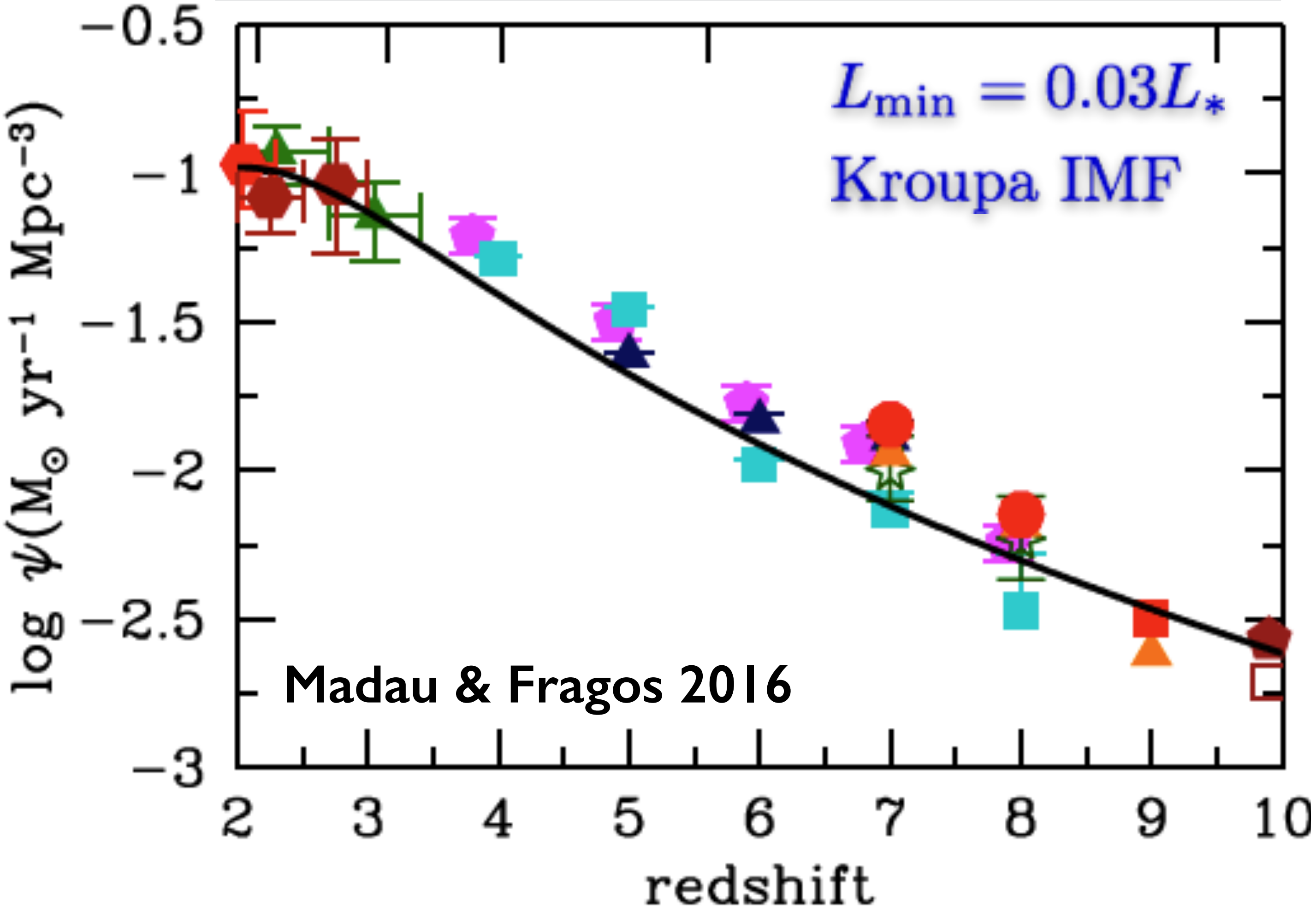




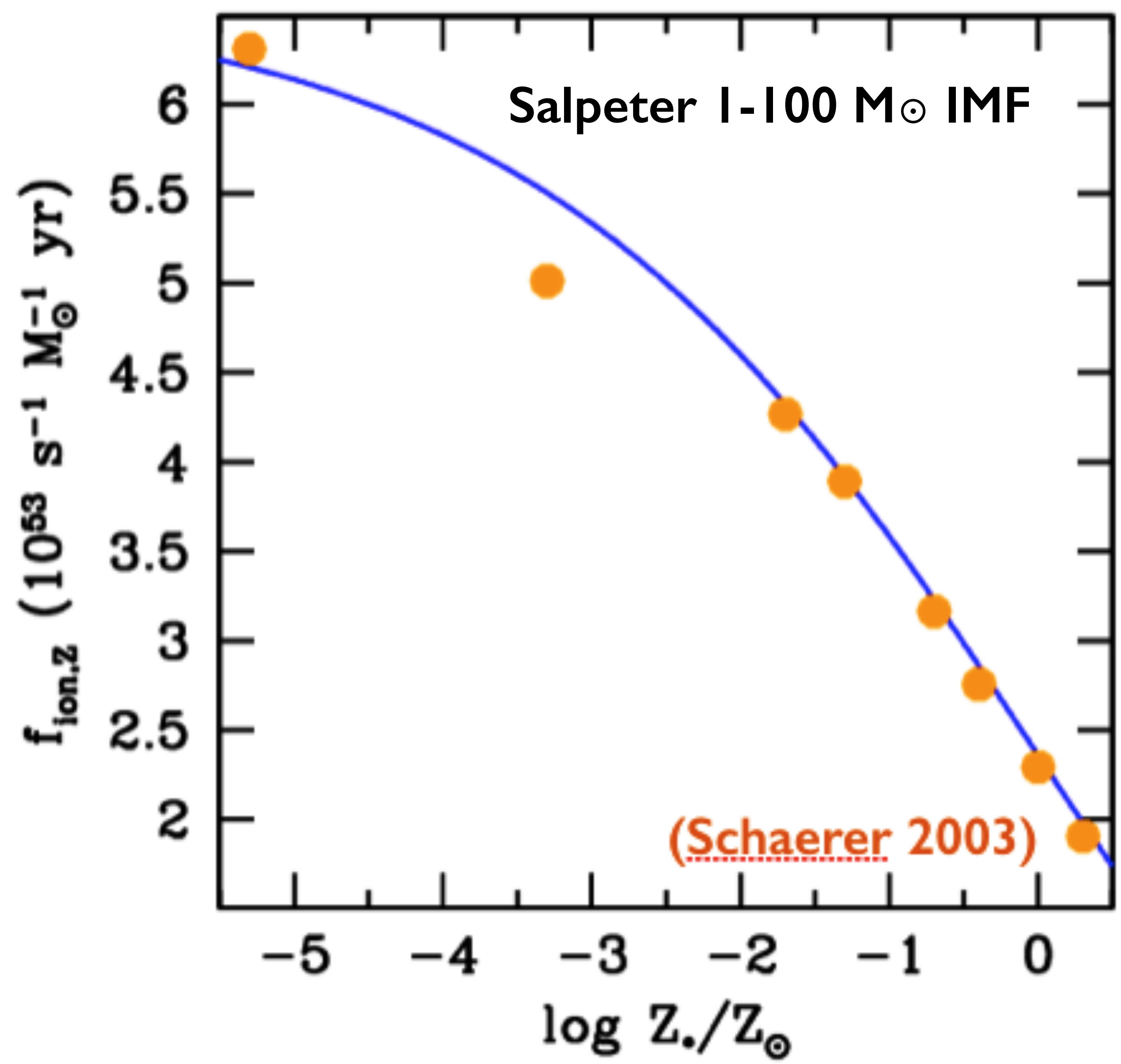


Galaxy-Dominated Reionization

History of cosmic star formation from FUV+ IR rest-frame measurements.



Metallicity dependence of ionizing photon yield



$M_{AB} > -17$

$f_{\rm esc} \equiv \langle f_{\rm esc} \rangle$

$$\dot{n}_{\rm ion} = f_{\rm esc}({\rm SFRD} \times 10^{0.2}) \times \xi_{\rm ion,Z}$$

$$\xi_{{\rm ion,Z}_\odot/20} \simeq 10^{53.365} \text{ phot yr/s/M}_\odot$$

Kroupa IMF
no binaries

Reionization at ~ FLOPS Speed

ionized volume fraction $Q \equiv \langle x_{\mathrm{HII}} \rangle$

ionizing photon production rate/V

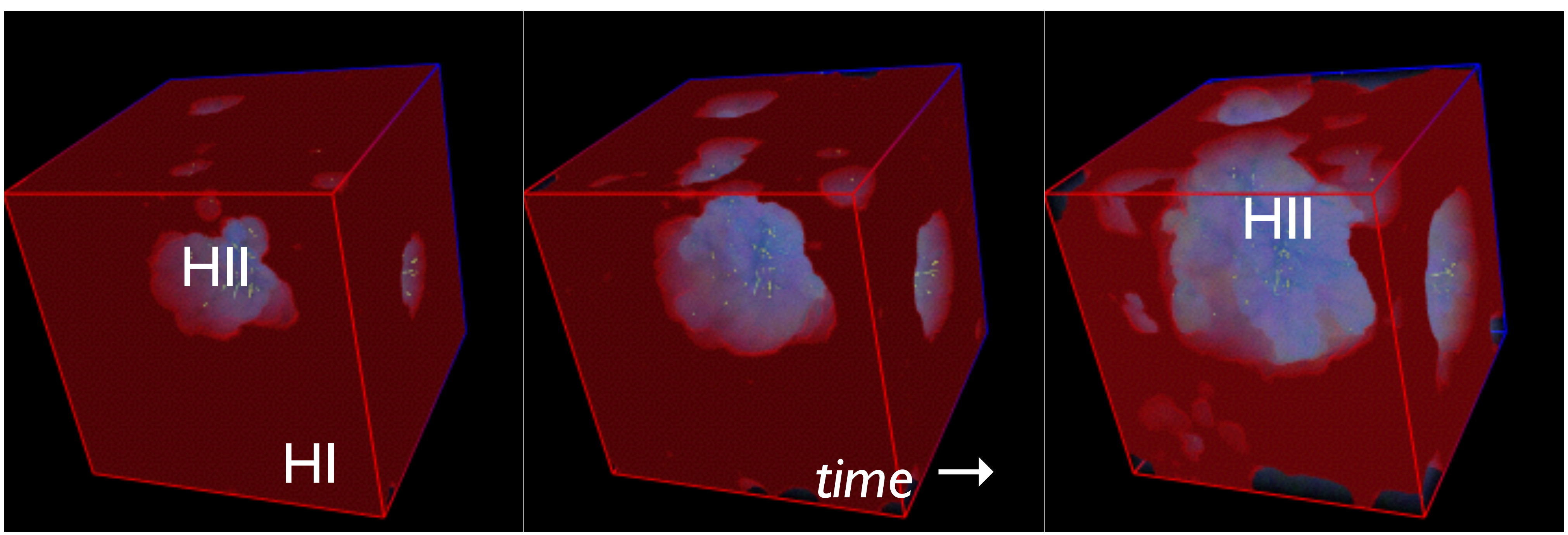
$$\frac{dQ}{dt} = \frac{\dot{n}_{\mathrm{ion}}}{n_0} - \frac{Q}{t_{\mathrm{rec}}}$$

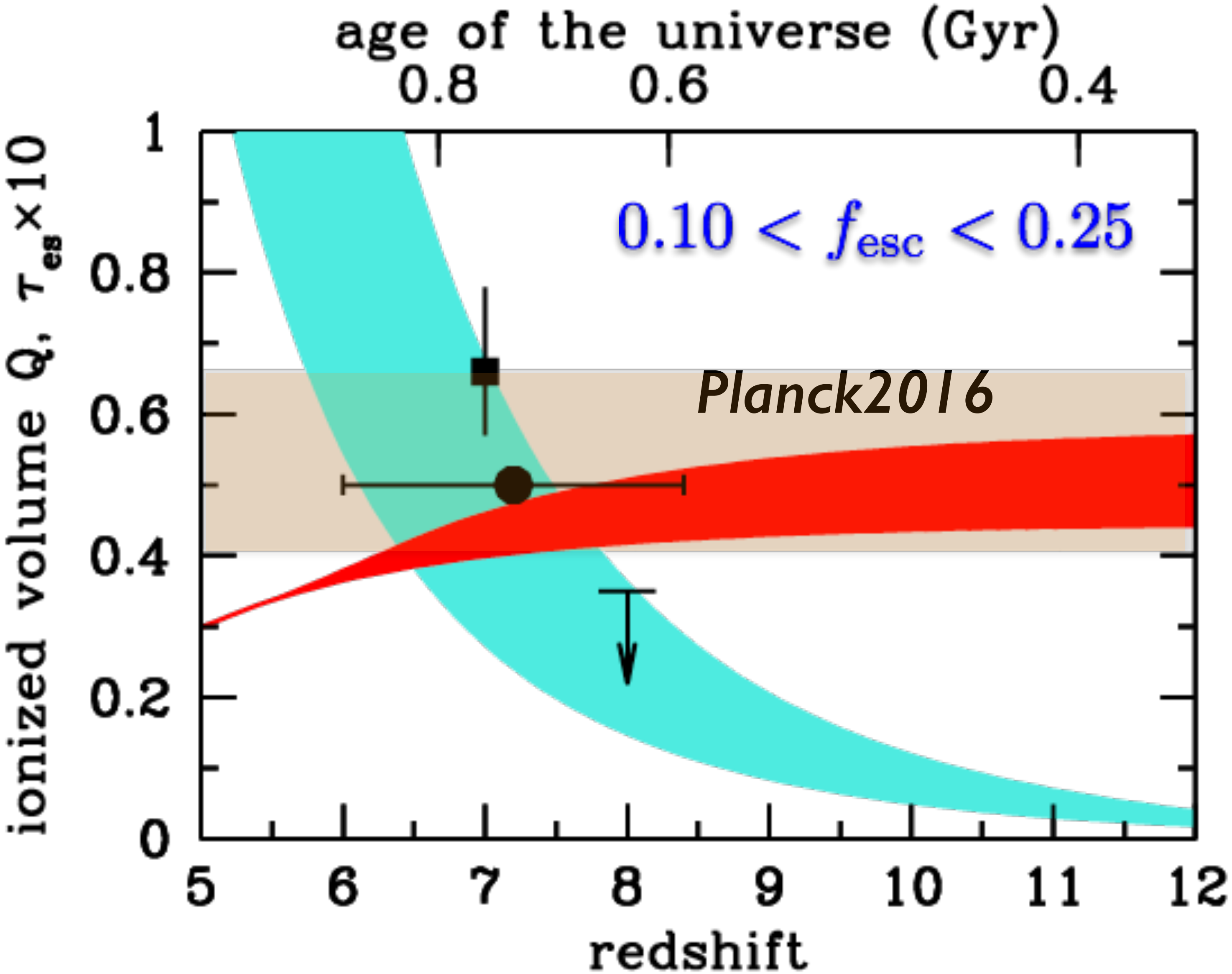
comoving H *density*

radiative recombination timescale = f (T,C)

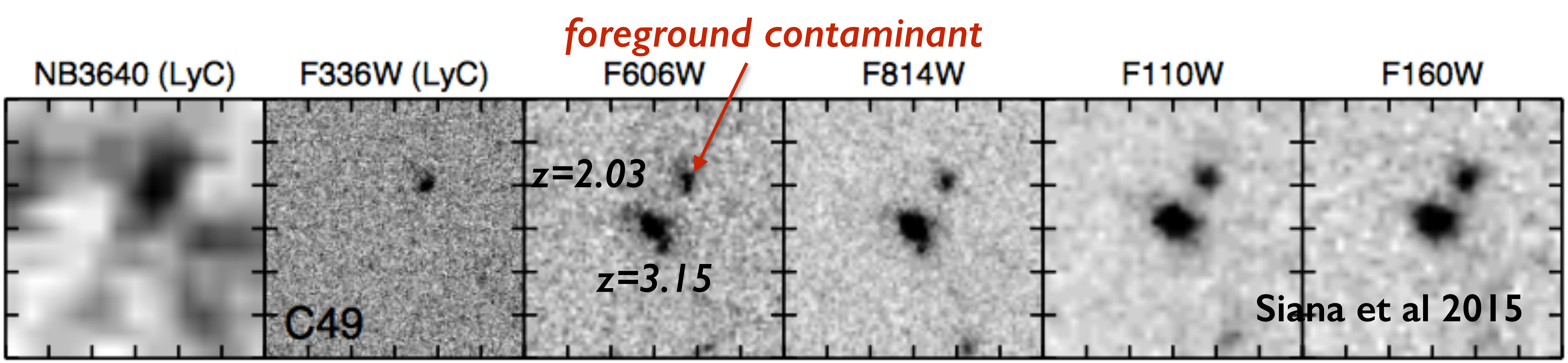
Reionization Eq:

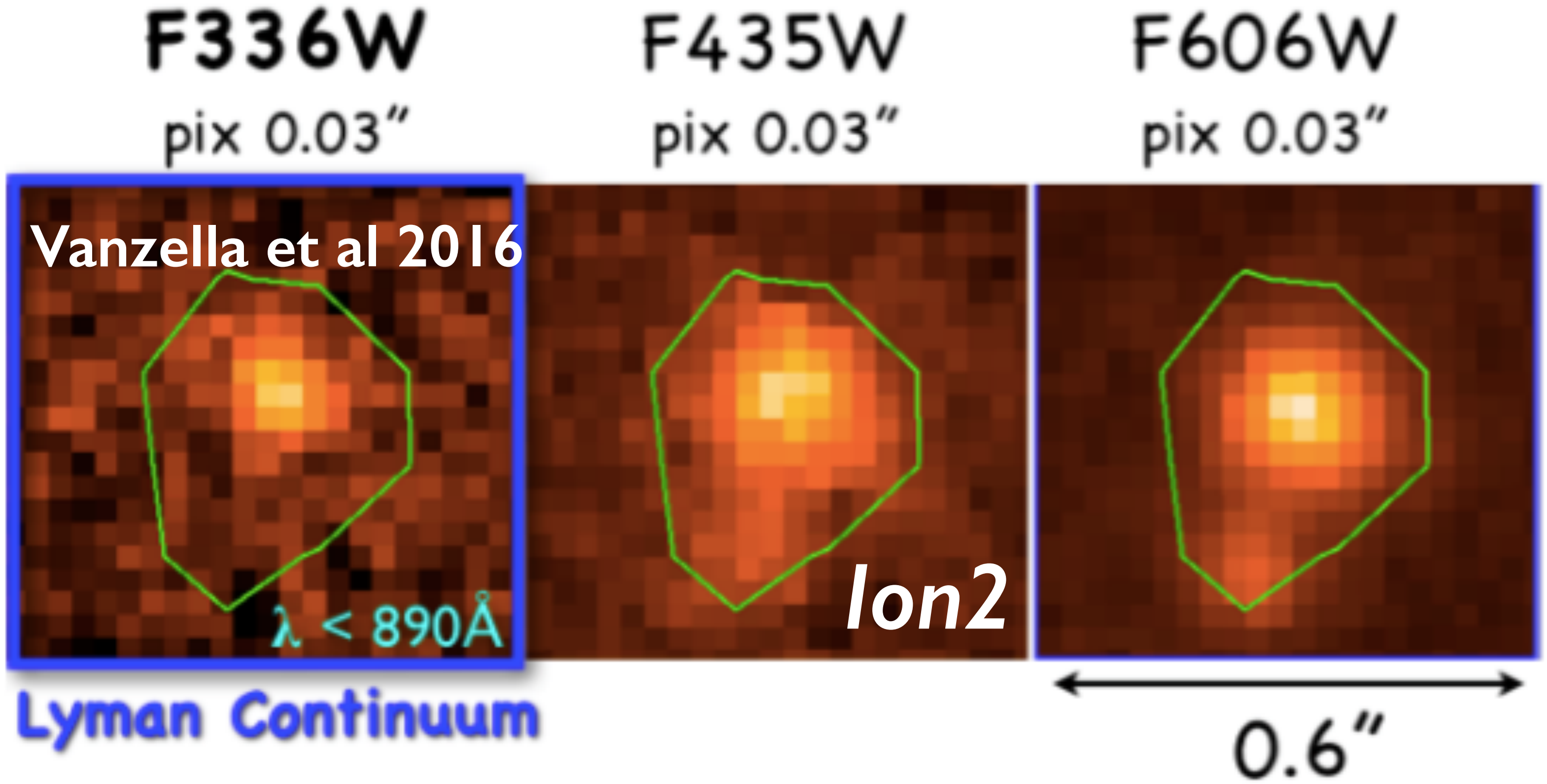
1. *UV photon counting*
2. *assumes mean free path << c/H*
3. *does not explicitly account for the presence of LLSs*
4. *allows, mathematically, for Q > 1, which is physically impossible.*





Large leakage values, f_{esc}~0.15 - 0.2, required for star-forming galaxies to reionize the universe are higher than typically inferred from observations of LBGs at z~3–4 (Mostardi et al 2013, Vanilla et al 2012). Grazian et al 2016 (VUDF): f_{esc}< 0.02 R< 26.5 z=3.3!





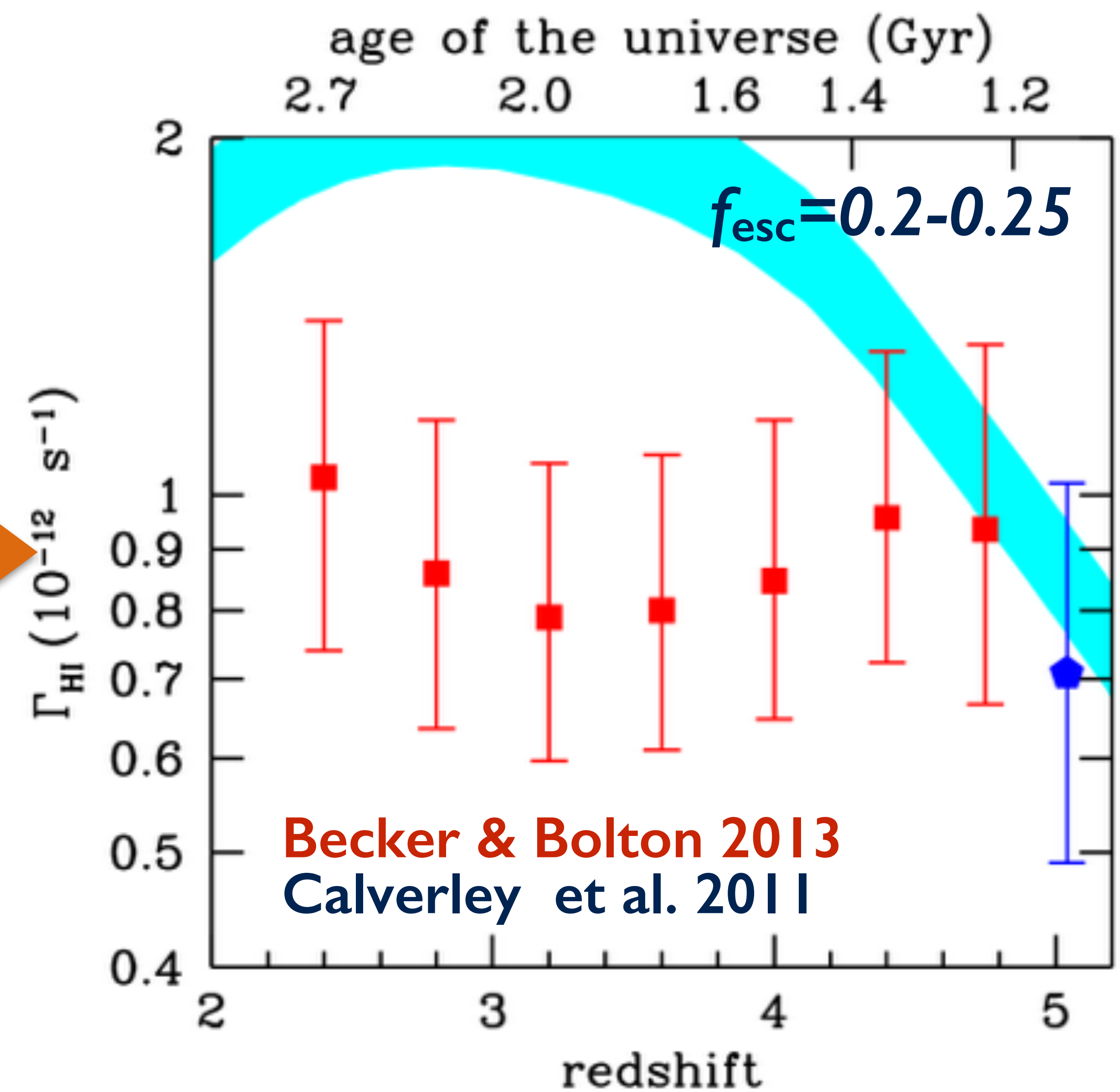
z=3.2 galaxy with f_{esc}>50%

LyC emission is spatially unresolved, with an effective radius <200 pc. Strong [OIII]!

hydrogen photo-ionization rate

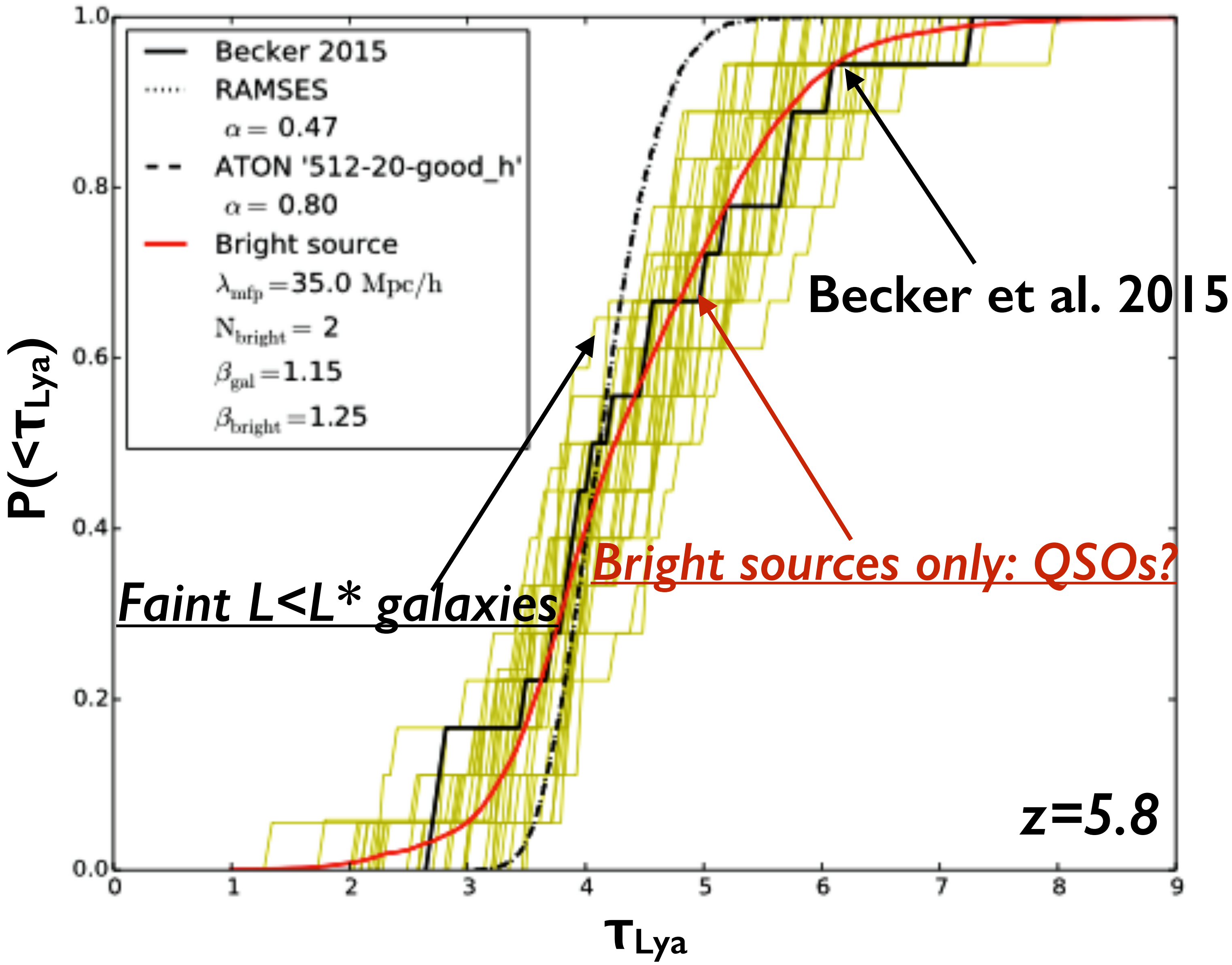
$$\Gamma_{\rm HI} = \int \frac{4\pi J_\nu}{h\nu}\sigma_\nu d\nu$$

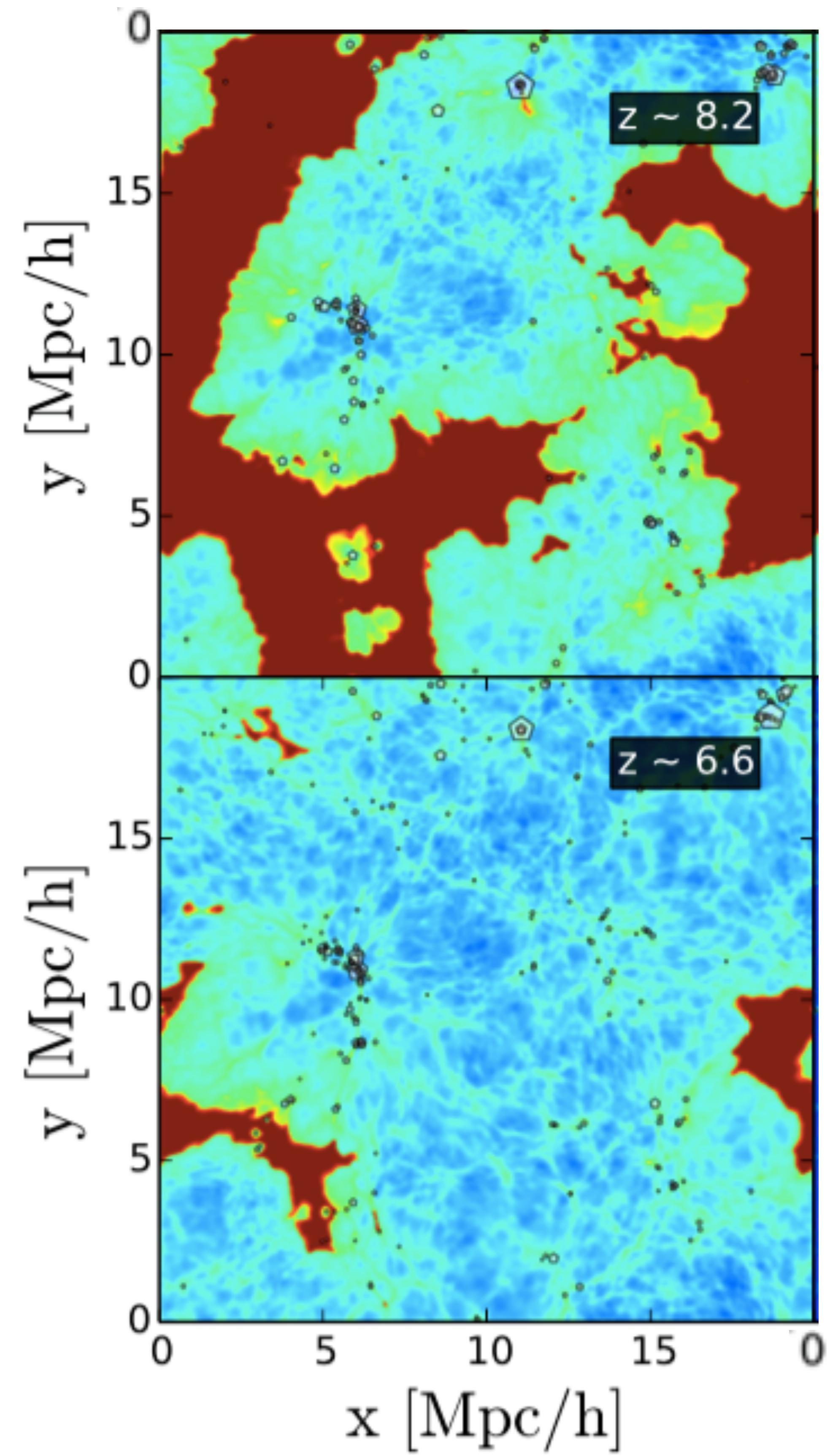
inferred from the mean opacity and temperature of IGM



What's Wrong with Faint Galaxies?

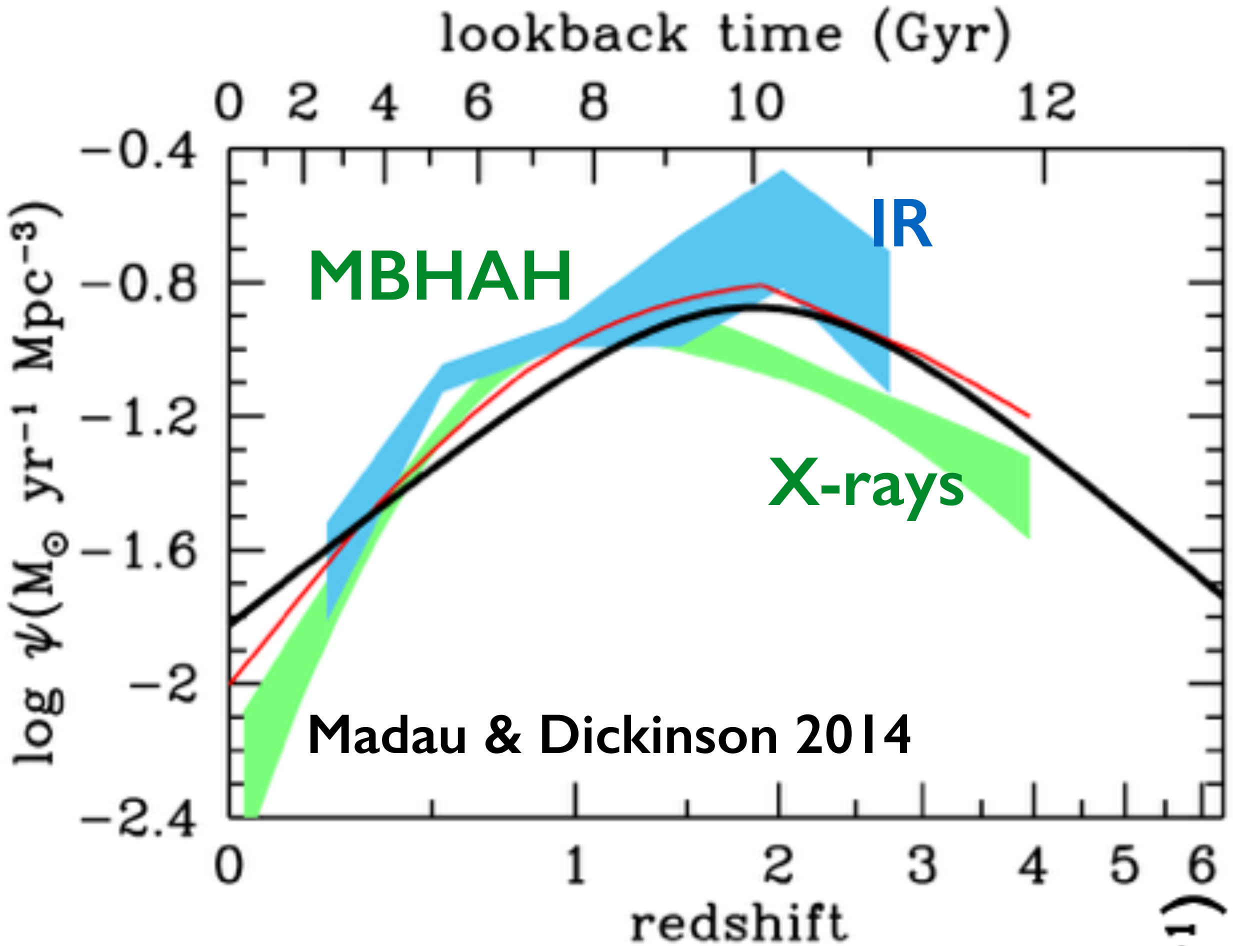
Chardin et al. 2015, 2016





Spatial UV fluctuations in full radiative transfer simulations of faint galaxy-dominated reionization are insufficient to explain the observed wide distribution of Lyα optical depths at $5 < z < 6$: QSOs ($\Gamma_{QSO} > 0.5\ \Gamma_{tot}$)!

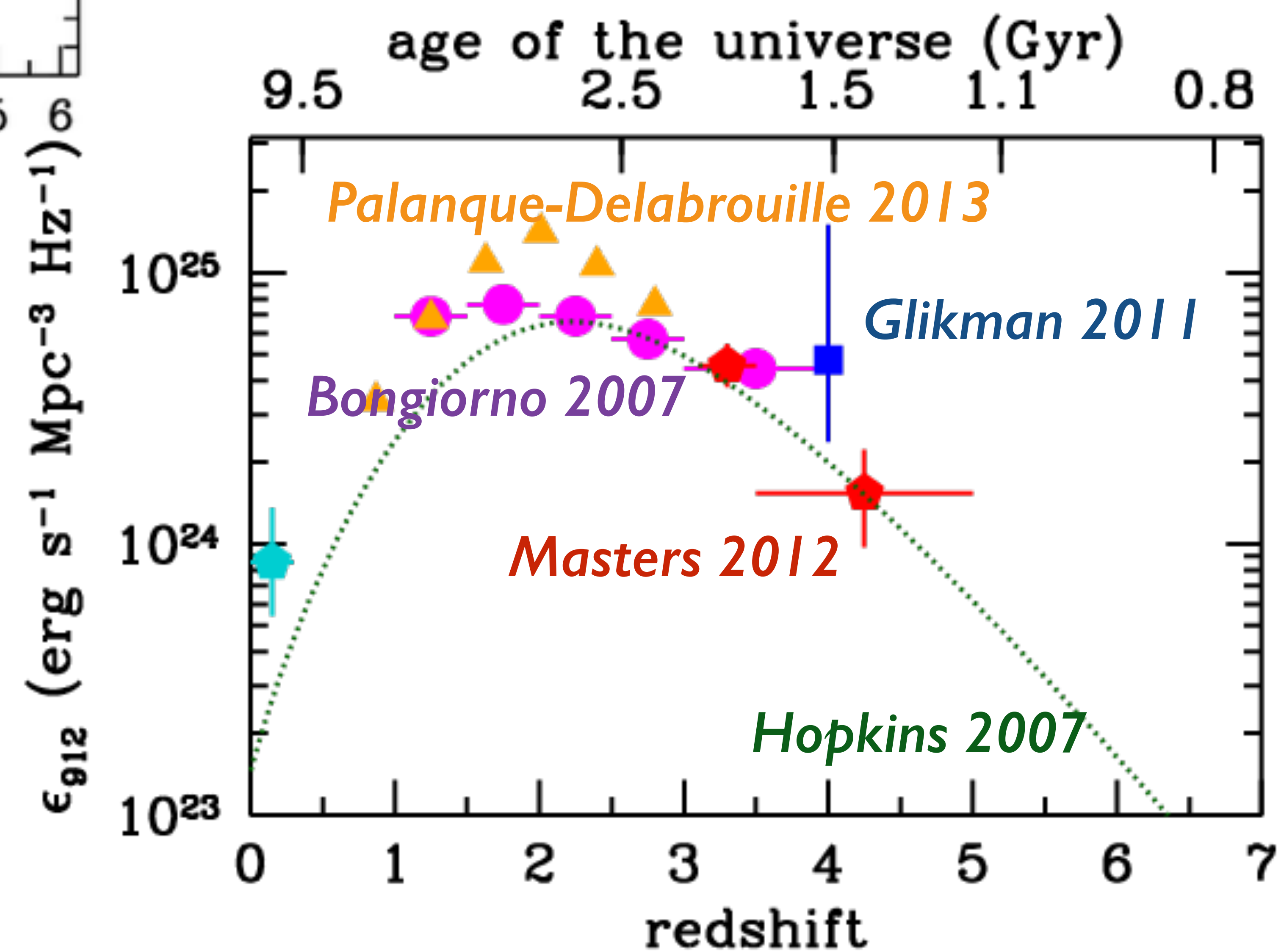
AGN-Dominated Reionization



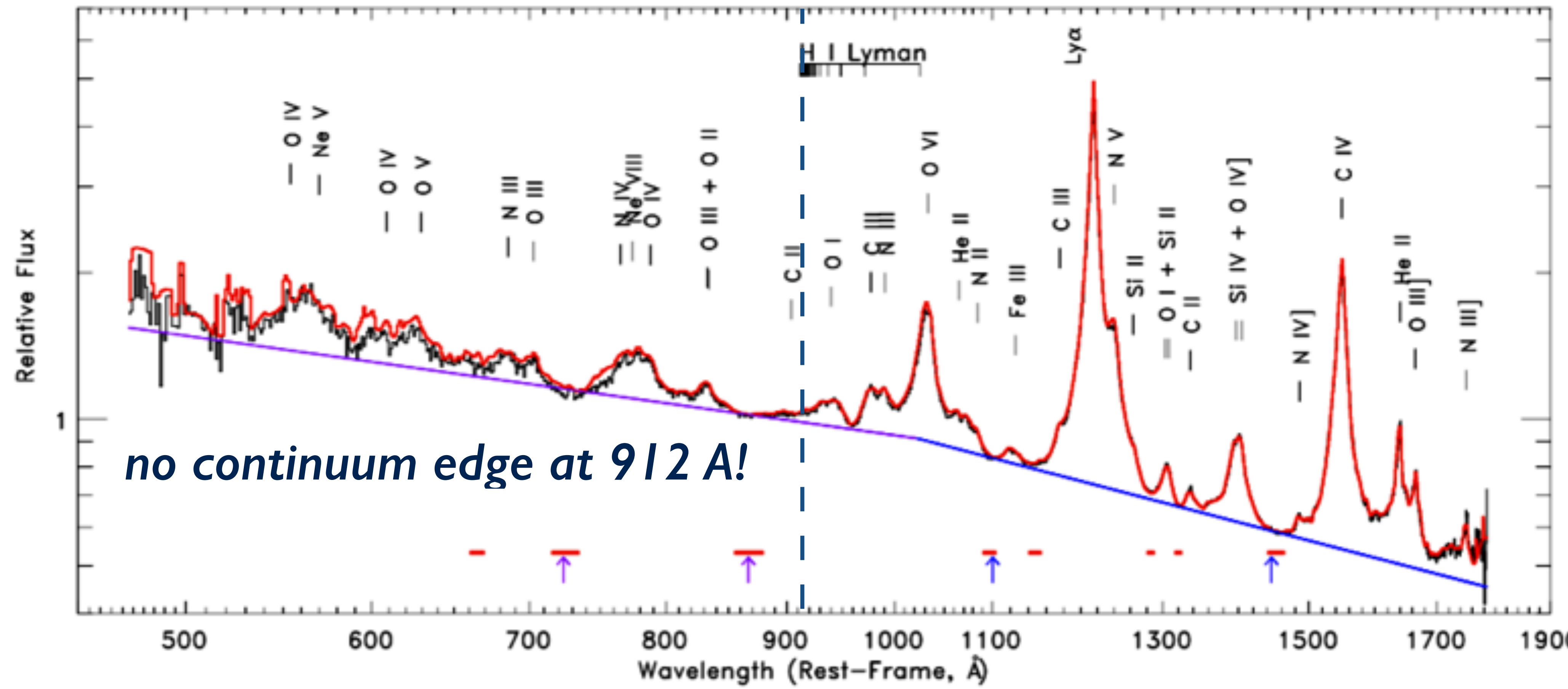
CSFH

Cosmic SF and MBH Accretion History

AGN Ionizing Emissivity

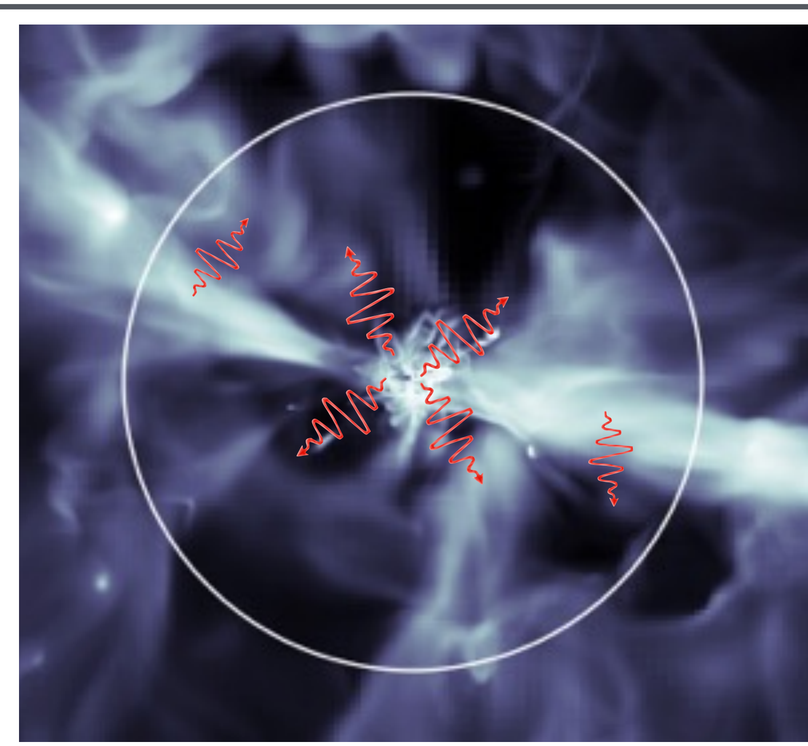


HST-COS Observations of 159 *0<z<1.5* AGNs

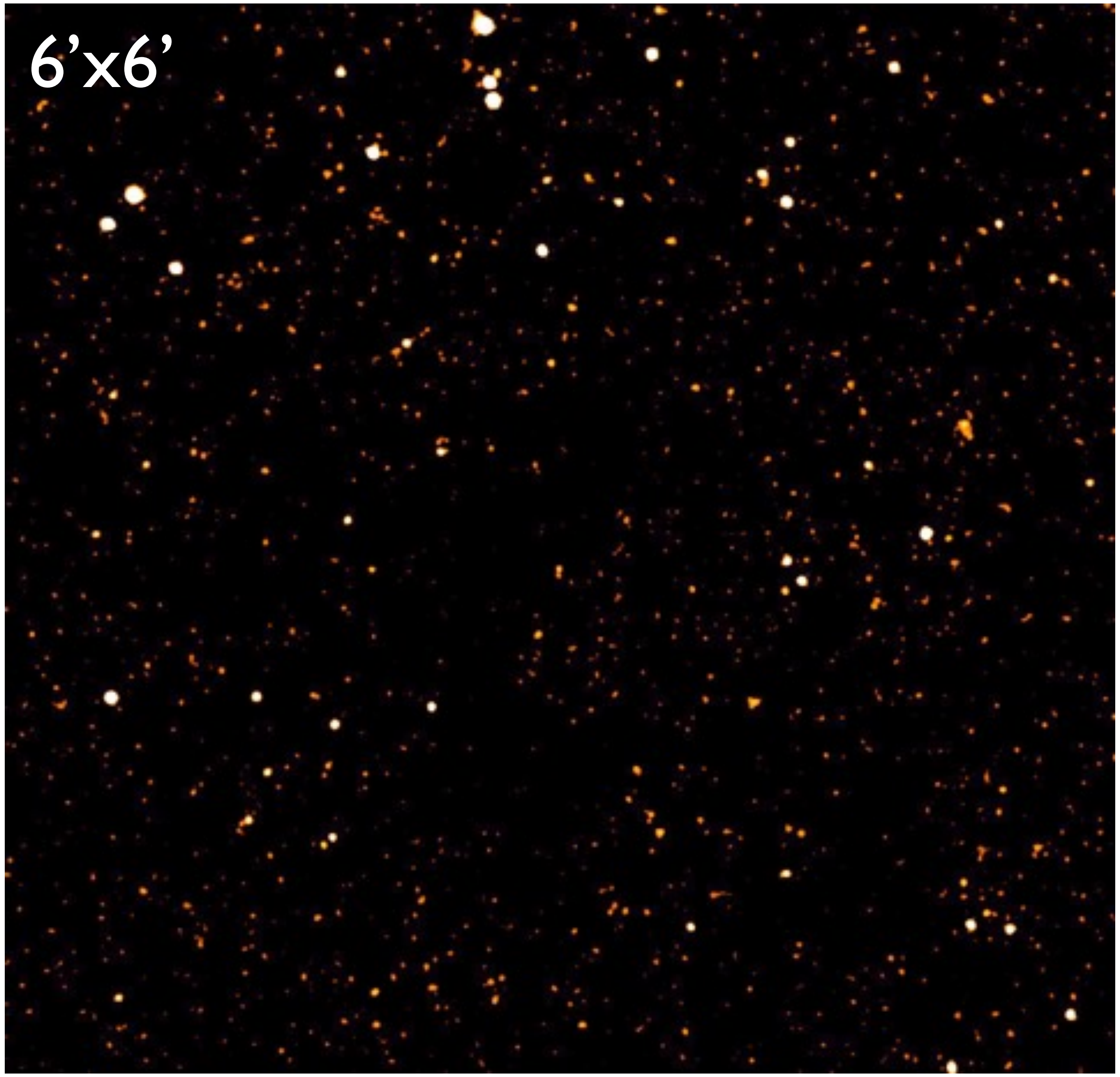


Composite spectra with rest-frame wavelengths 465–1750 Å, normalized to unit flux at 1100 Å (Stevans et al. 2014).

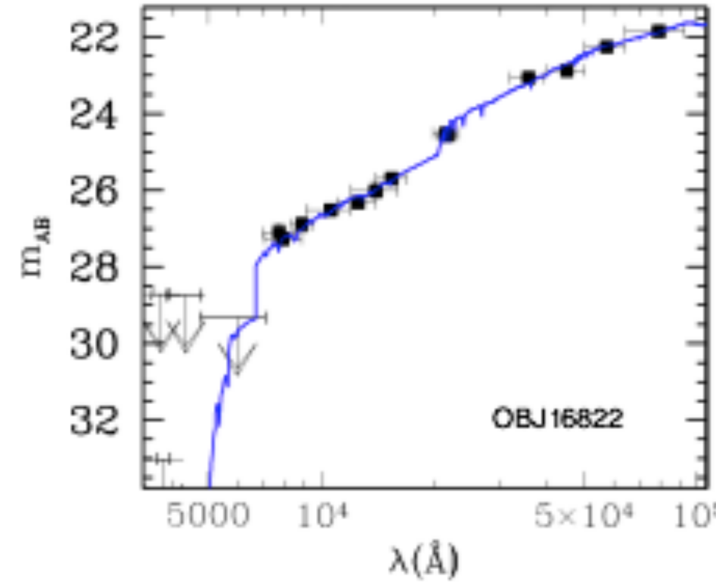
$z \simeq 0$ $f_{esc,AGN}=1$ $f_{esc,GAL} \simeq 0$
➪ AGN activity is a prerequisite for large UV leakages!

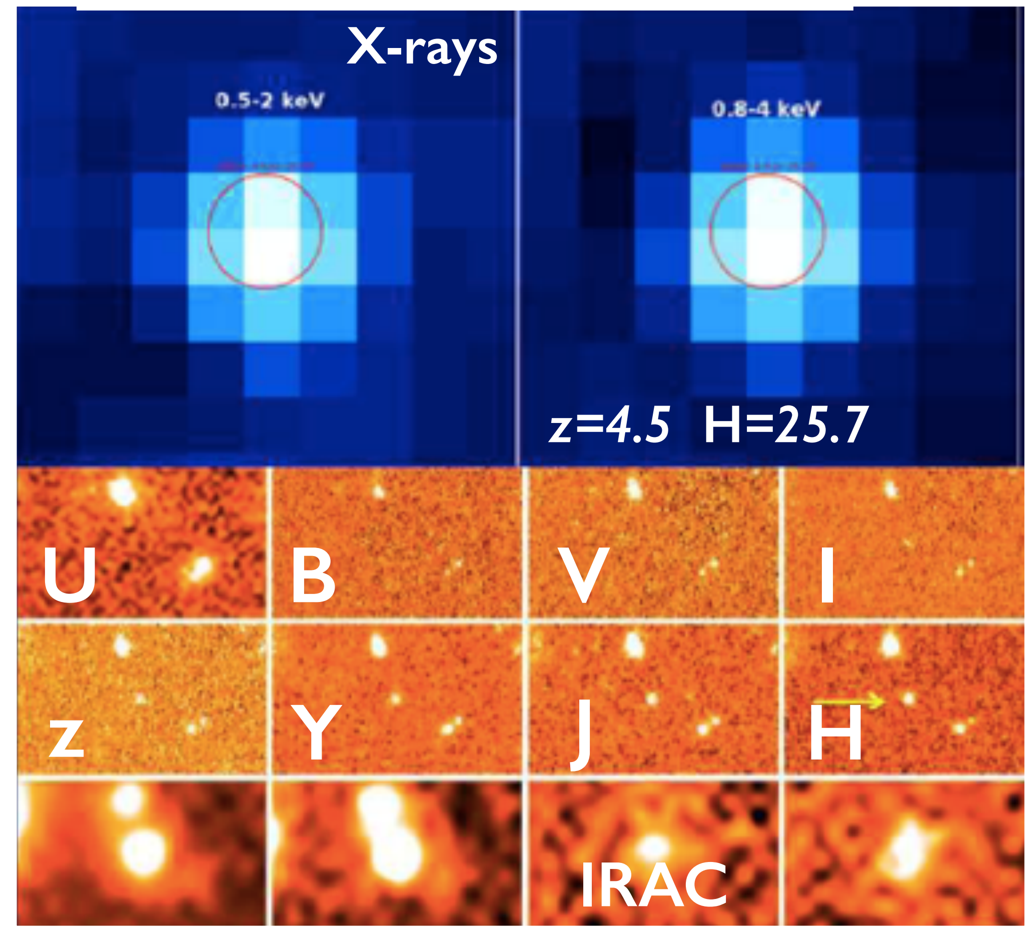


New 7 Ms Chandra Deep Field-South



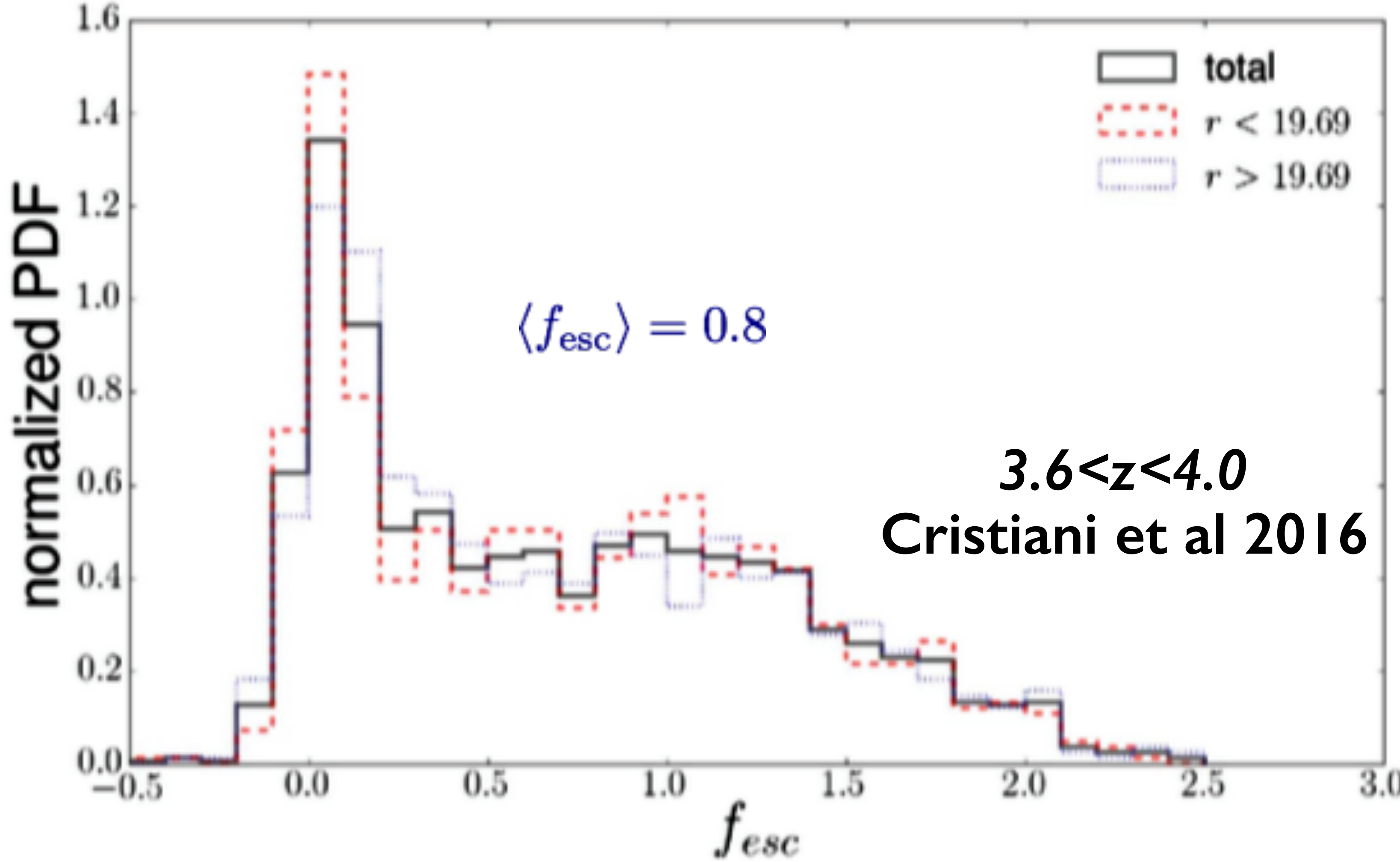
Giallongo et al 2015, 2016: 19 faint AGNs in CDF-S $4.1 < z_{photo} < 9.7$
24<H<27 mag





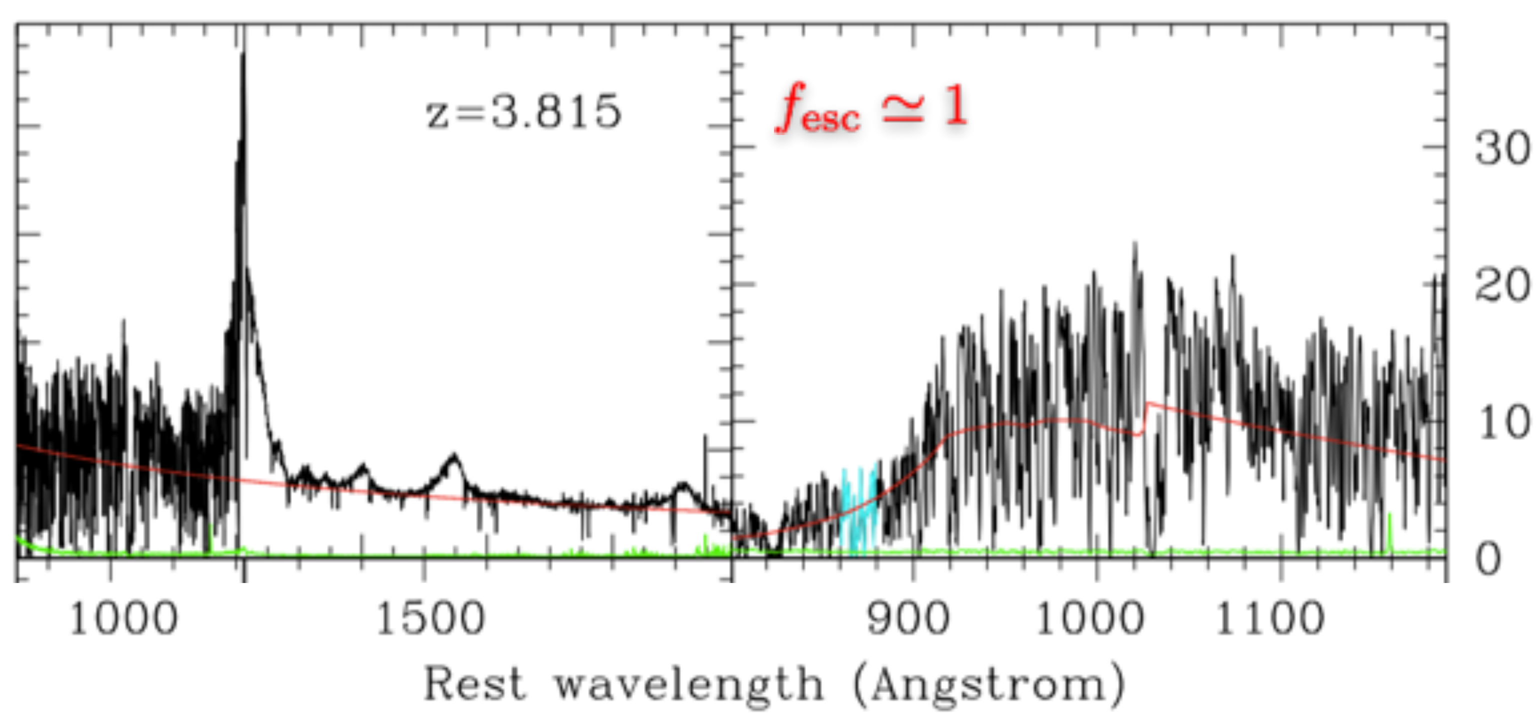
Push the formal detection limits of 4/7 Ms Chandra X–ray data using O-NIR images as priors. This increases the detection rate of faint AGNs relative to blind searches.

1669 QSOs (r < 20.15) from BOSS

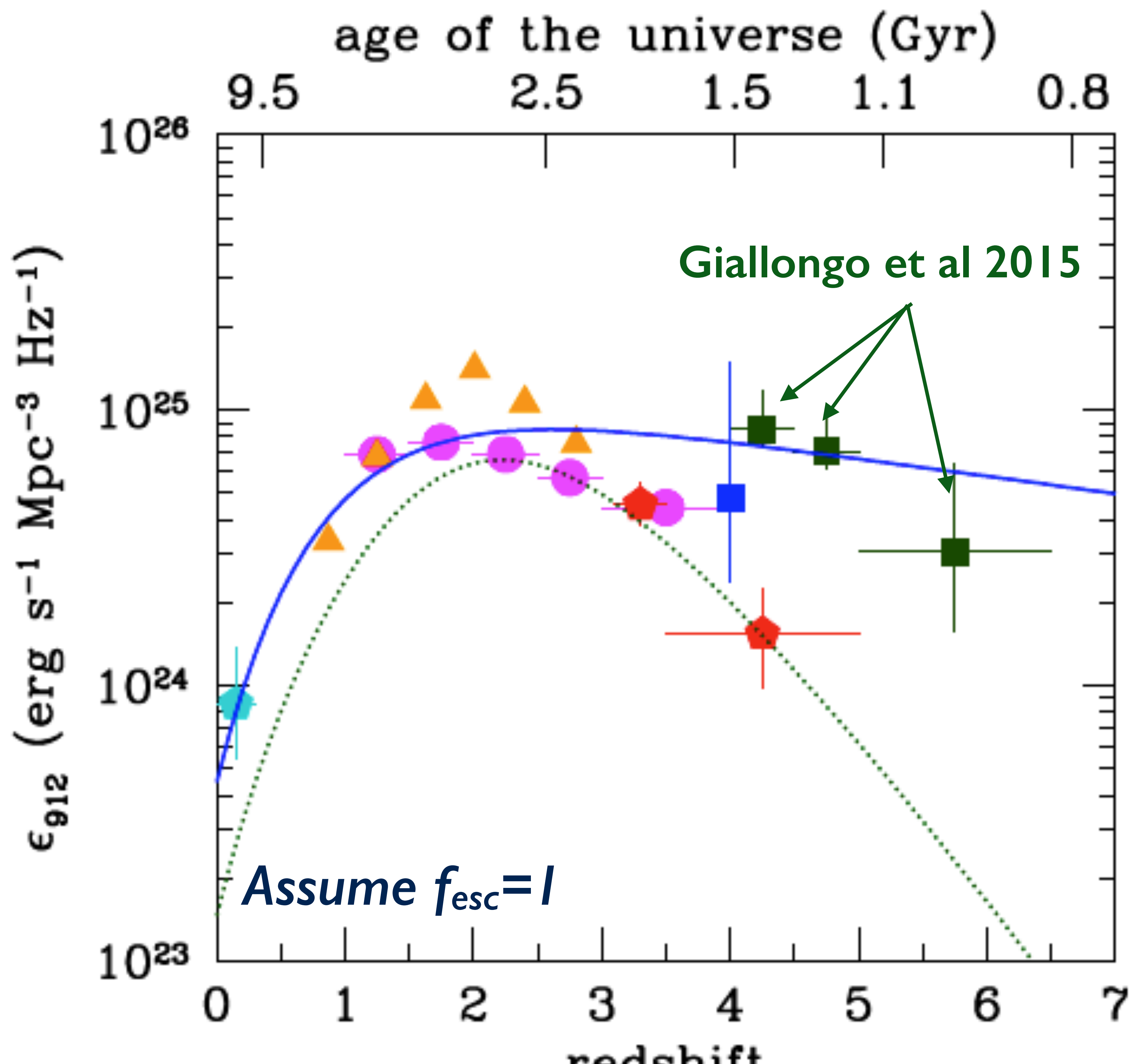


3.6<z<4.0

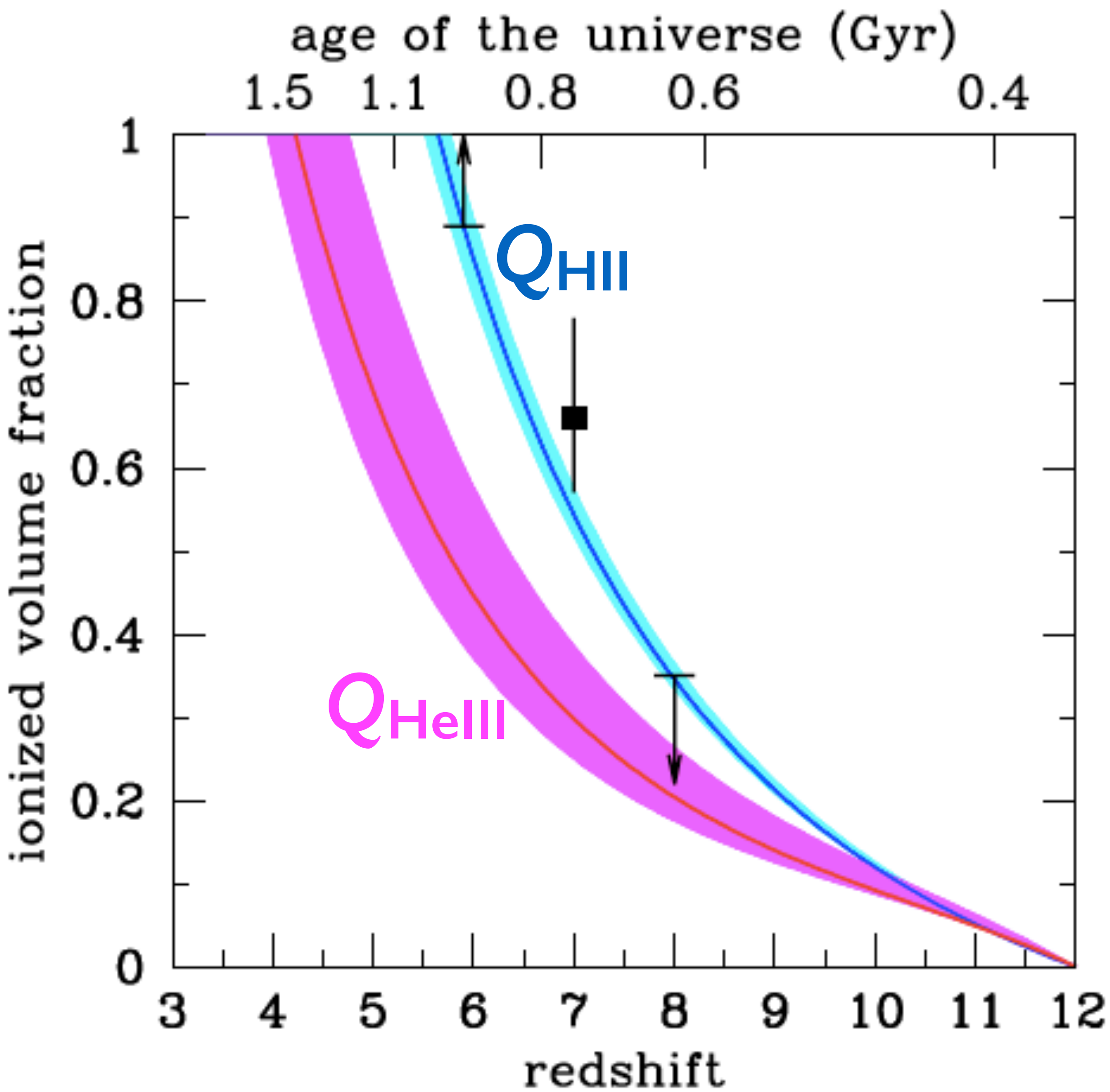
Cristiani et al 2016

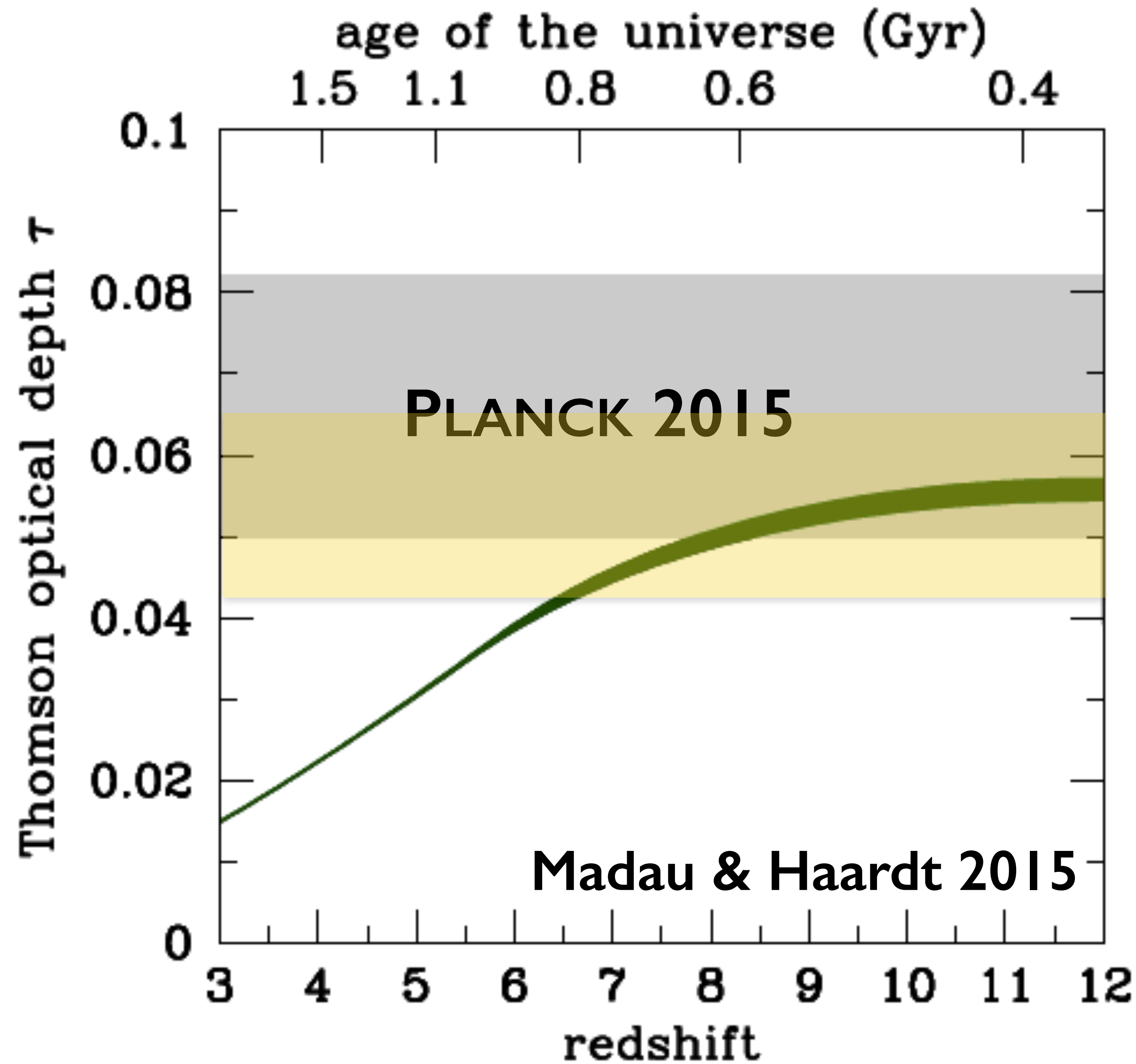


AGN Comoving Ionizing Emissivity



Q_{HII}=1 at z=5.7
Assume f_{esc}=1 at 4 Ryd:
Q_{HeIII}=1 at z=4.2

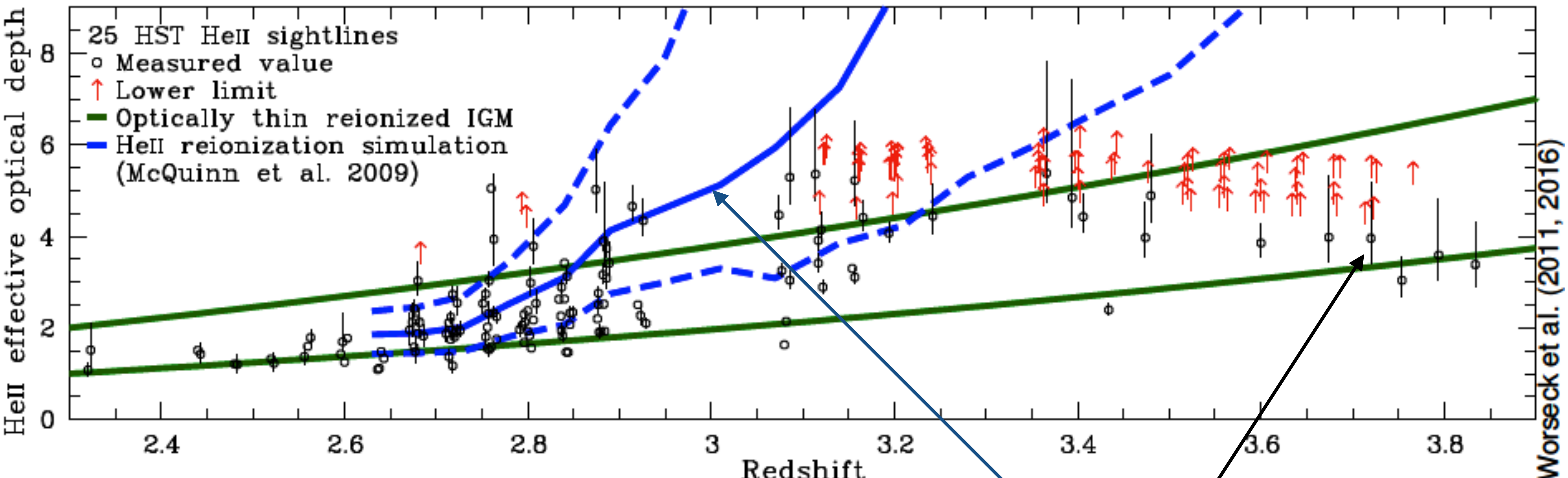




$$\tau(z) = c\sigma_T \langle n_{\rm H}\rangle \int_0^z \frac{(1+z')^2 dz'}{H(z')} [Q_{\rm HII}(1+\chi) + \chi Q_{\rm HeIII}]$$

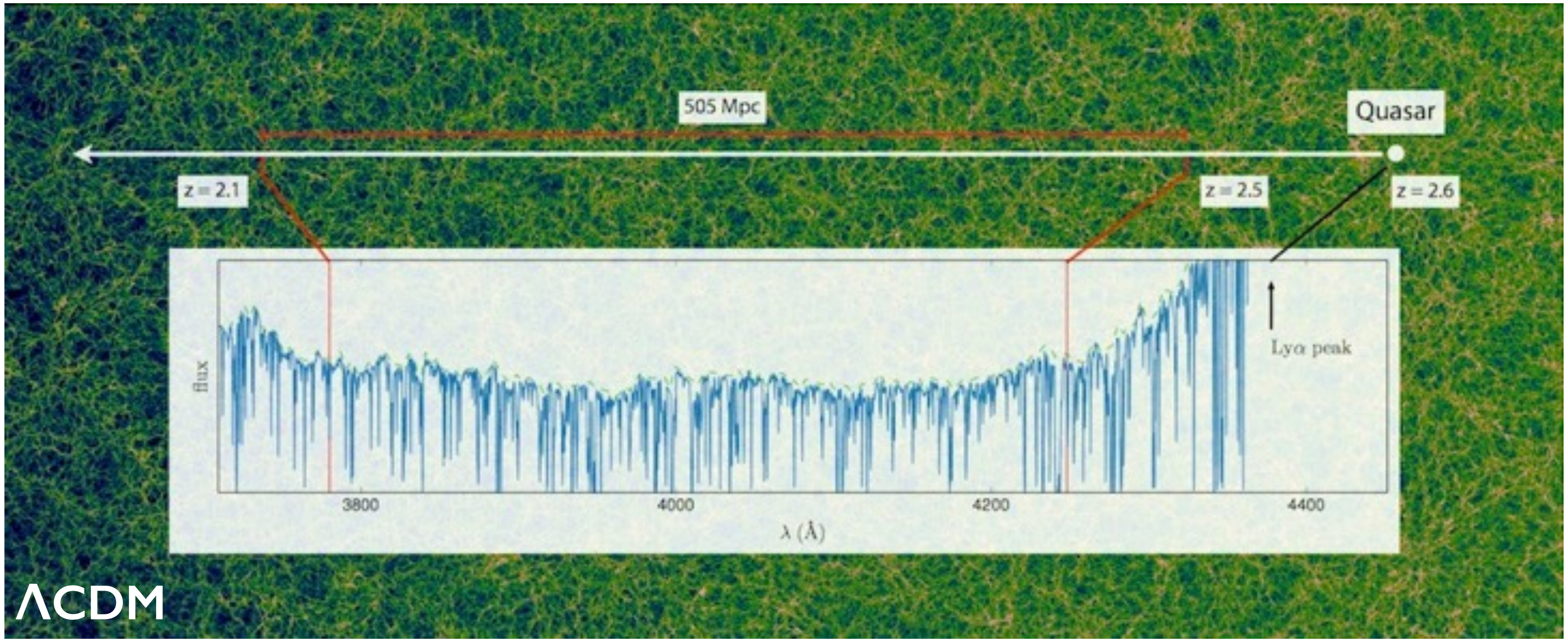
Very Extended HeII→HeIII Reionization

He II Lyα optical depth on 10 pMpc scales

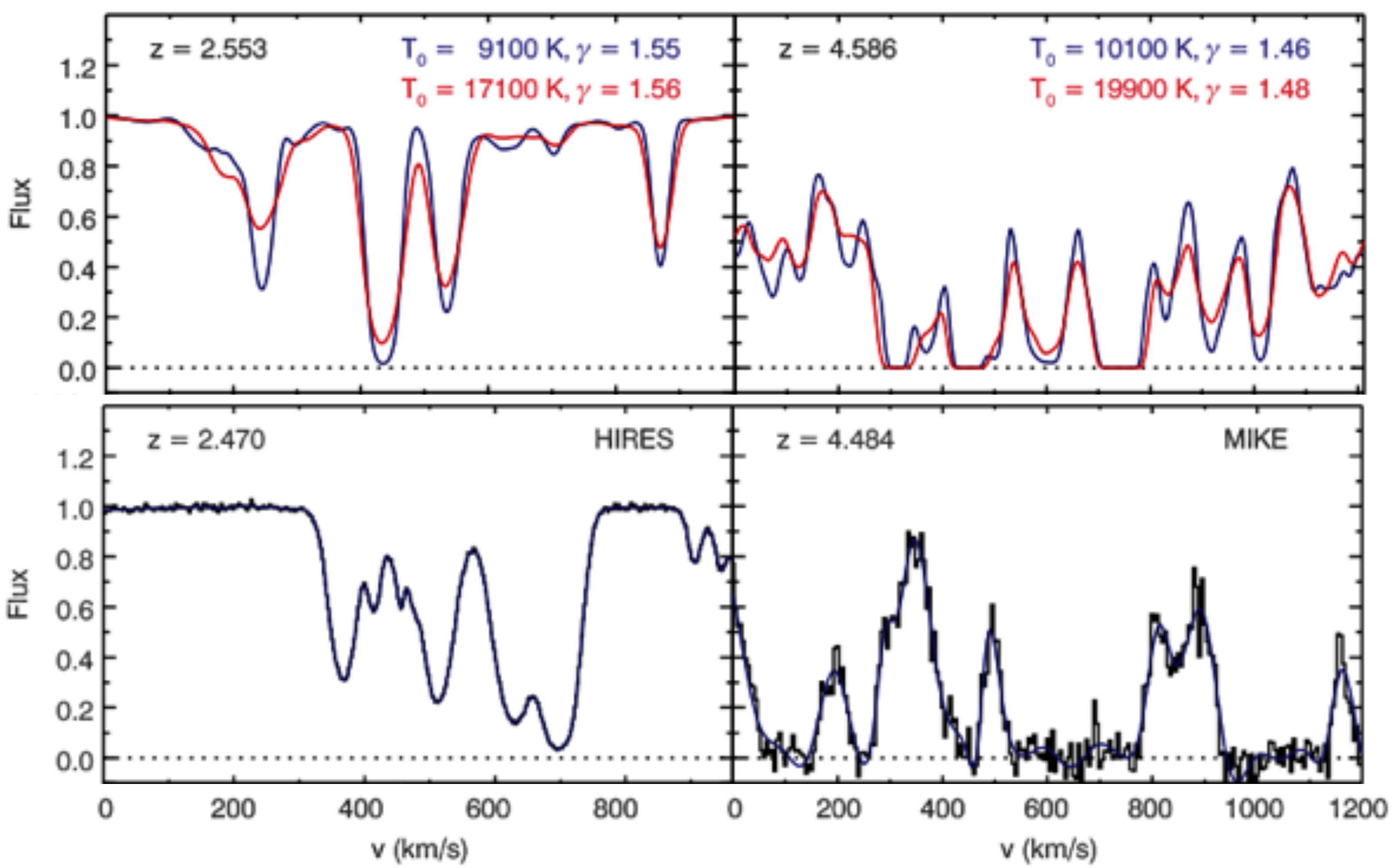


A substantial volume of helium in the Universe was already doubly ionized at early times, in conflict with current models of He II reionization driven by luminous QSOs ➪ He II reionization must have begun at z≫4!

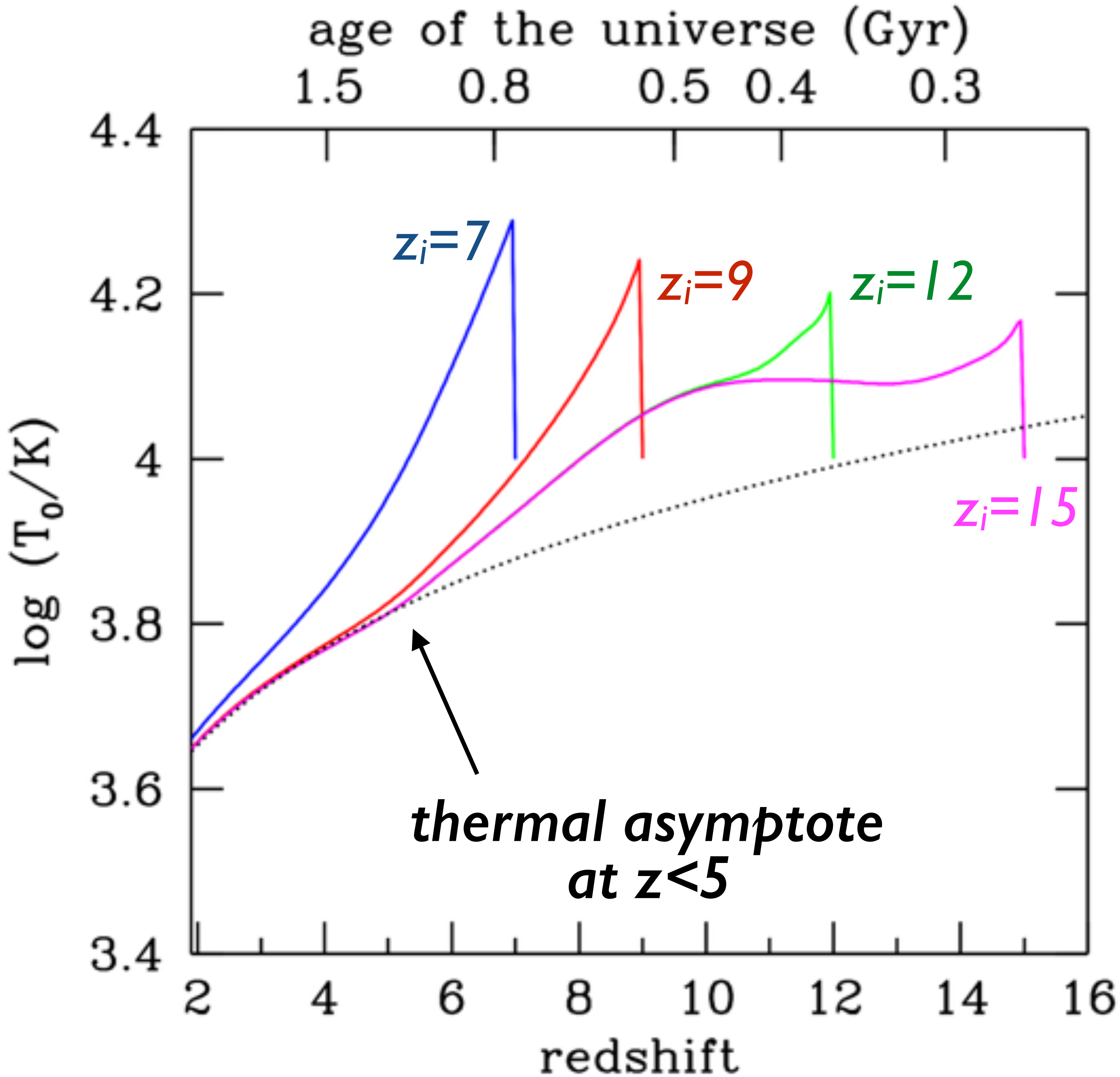
Thermodynamics of the IGM



Becker et al. 2011



A power-law temperature-density relation, $T = T_0(1 + \delta)^{\gamma - 1}$, arises in the low density IGM as a consequence of the interplay between photoheating and adiabatic cooling.

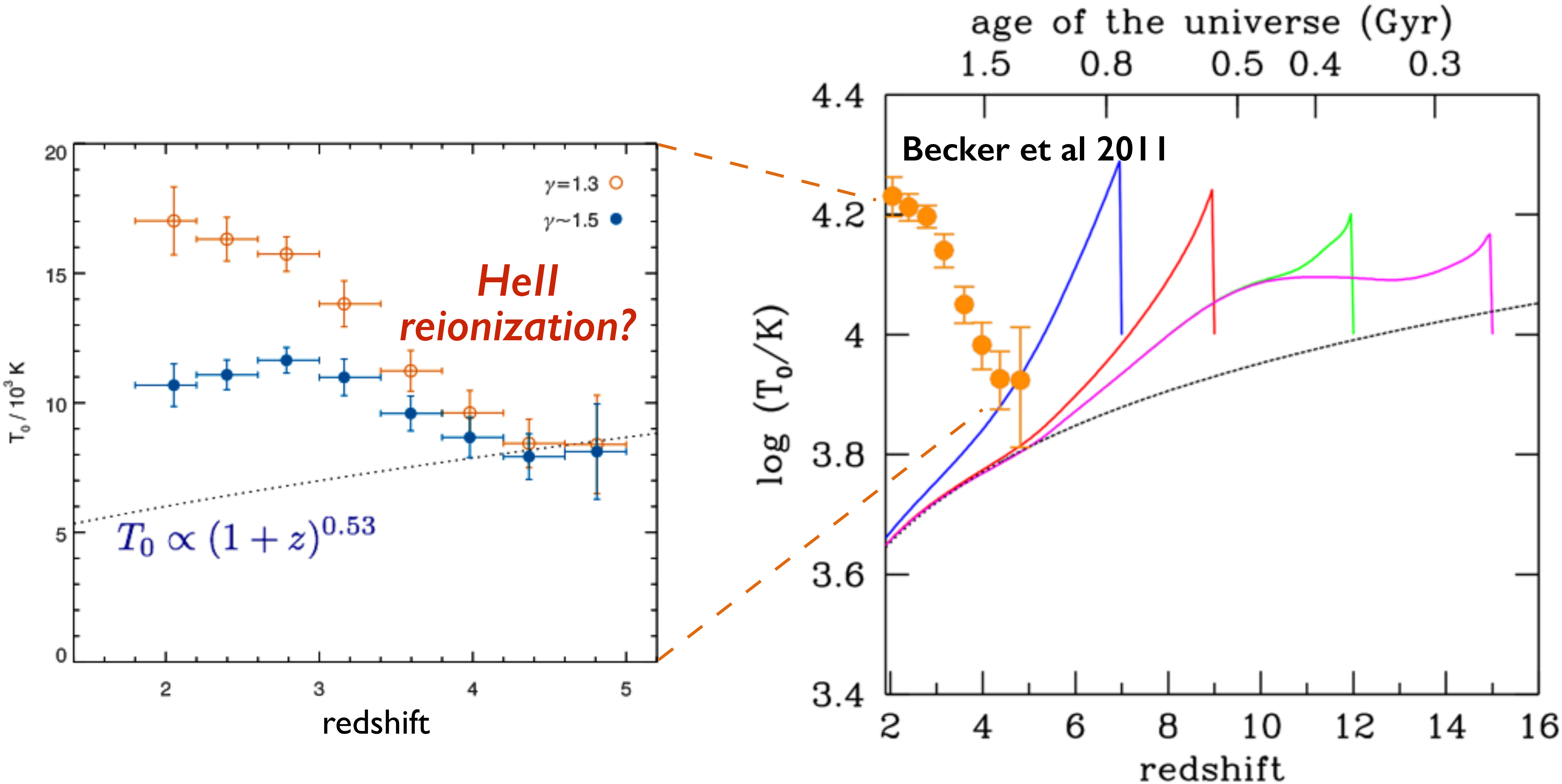


H-photoheating only: ***wide range of ionization histories result in the about the same IGM temperature by z~5***

Temperature evolution for gas at the mean density

$$\frac{dT_0}{dt} = -2HT_0 + \frac{T_0}{\mu}\frac{d\mu}{dt} + \frac{2\mu m_p}{3k_B\bar{\rho}_b}(\mathcal{H} - \Lambda)$$

WHAT'S WRONG WITH THE FOREST?



A Wager

On the matter of when was the Universe fully reionized, there are two interesting cases: late, i.e. @ z_{ion}~6.3 as perhaps implied by observations of the SDSS quasars, or early, i.e. @ z_{ion}>8.

Nick Gnedin holds to the first case; Piero Madau claims the second case.

On this day, June 5th 2002, P. Madau bets N. Gnedin that future observations will imply an early epoch of reionization; N. Gnedin bets that $z_{ion} = 6.2 \pm 0.3$.

It is mutually agreed that A. Ferrara shall adjudicate in the matter when the data become available.

If the Italian is found to be right, N. Gnedin will furnish the former with a bottle of champagne of his choice. If the Russian is found to be right, P. Madau will furnish the former a bottle of champagne of his choice.

Signed: *Piero Madau & Nick Gnedin*

Galaxies or AGNs: Anyone Willing to Bet Before JWST?