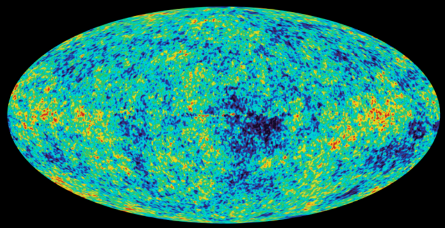
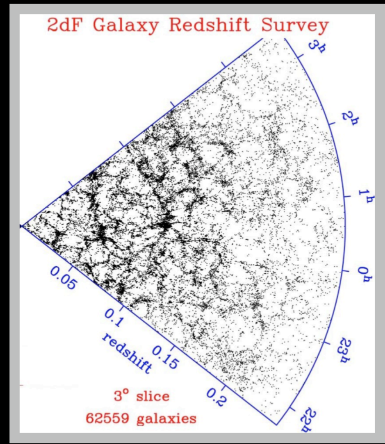
THE UNIVERSITY OF MELBOURNE

# Ly$\alpha$ Absorption and the Photon Budget for Reionization

Stuart Wyithe

# Reionization: Basic Questions



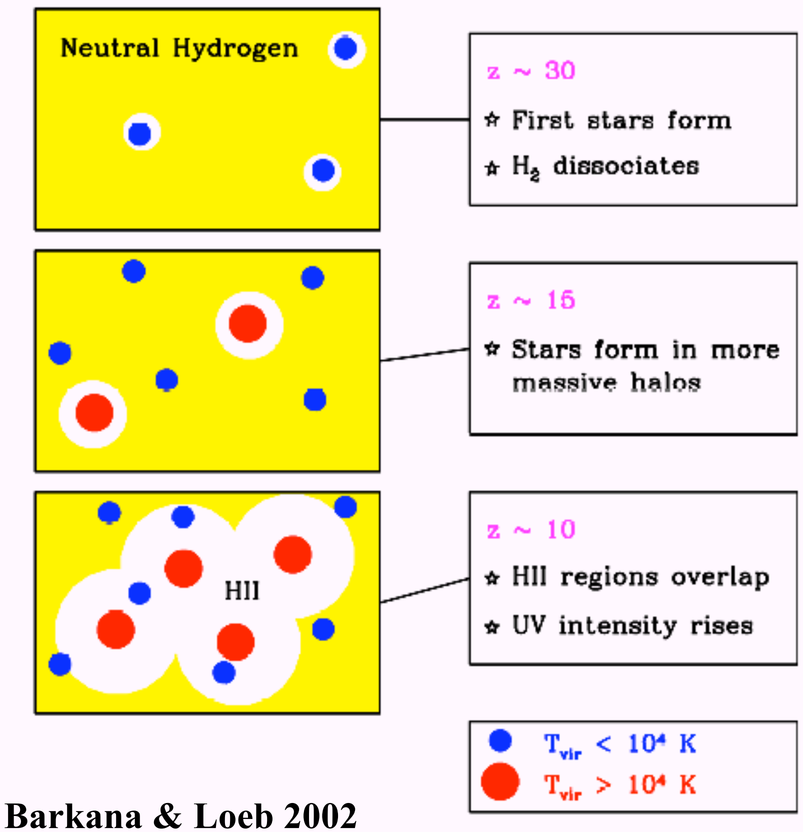



**Neutral Gas** → **Ionised Gas**

- What were the sources? (stars or quasars)
- When did it occur? ($6<z<15$)
- What was the topology? (smooth or patchy)
- Where did it start? (outside-in or inside-out)
- Was it regulated by feedback? (radiative or chemical)

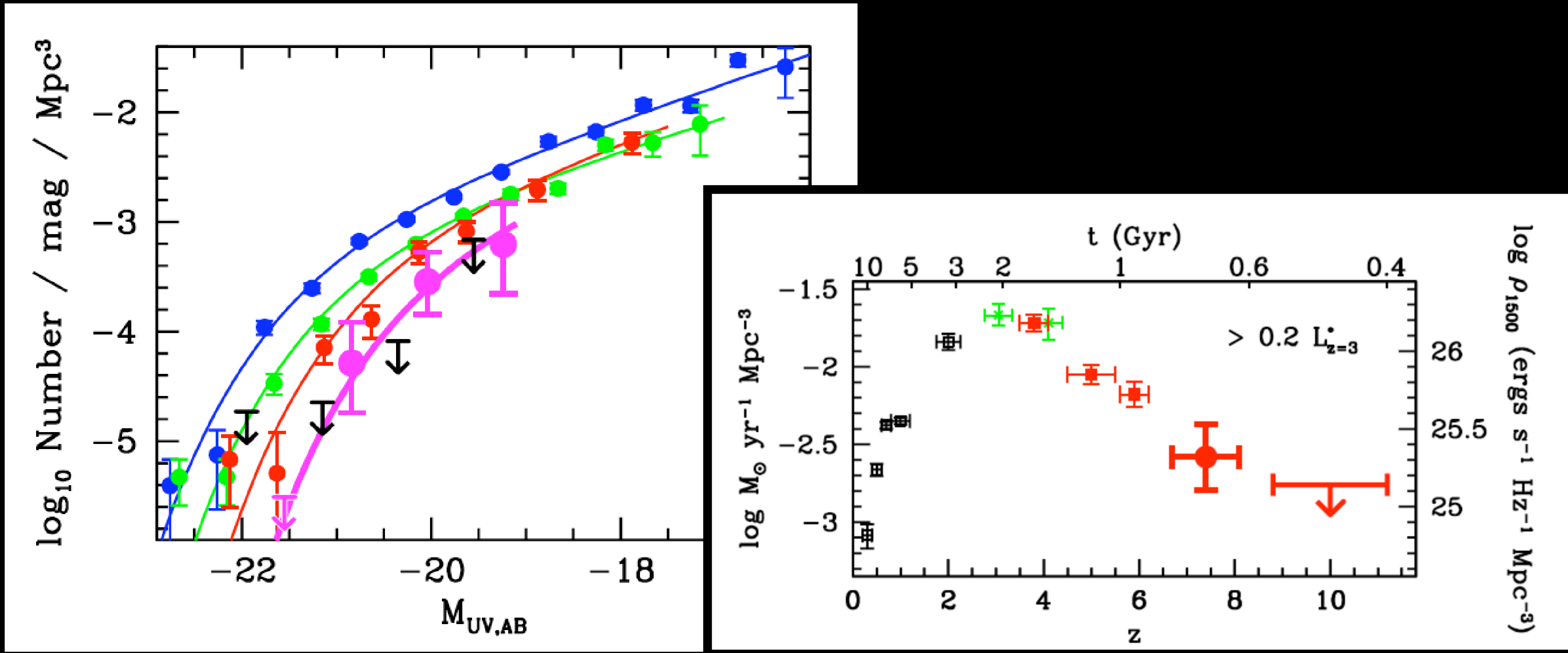
# Things We (think we) Know

- $\Lambda$CDM cosmology plus hierarchical structure formation
- The first sources appeared in halos above the Jeans mass [$H_2$ cooling in $3\sigma$ peaks ($10^6 M_\odot$) at z=30]
- Photo-ionization provided the ionization mechanism, as evidenced by the Ly$\alpha$ forest
- Stars rather than quasars provided the ionizing photons, at 6<z<20




Barkana & Loeb 2002

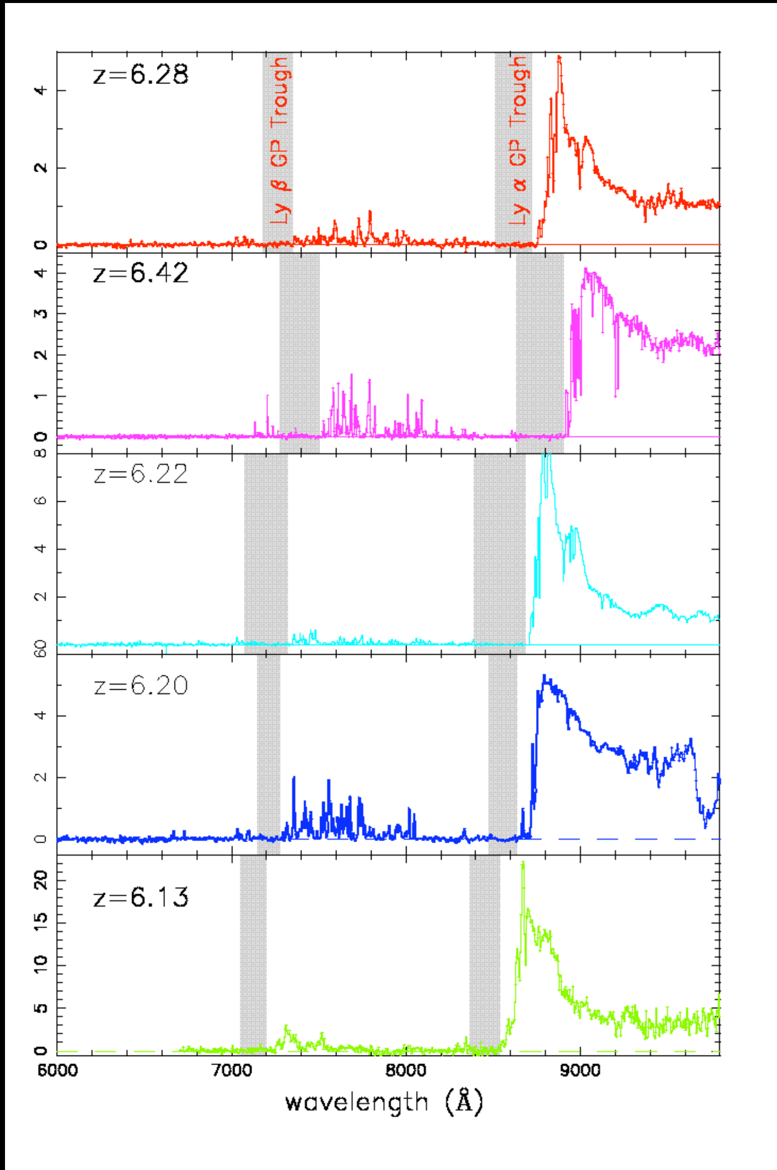
# Galaxies at the End of Reionization




Bouwens et al. (2008)

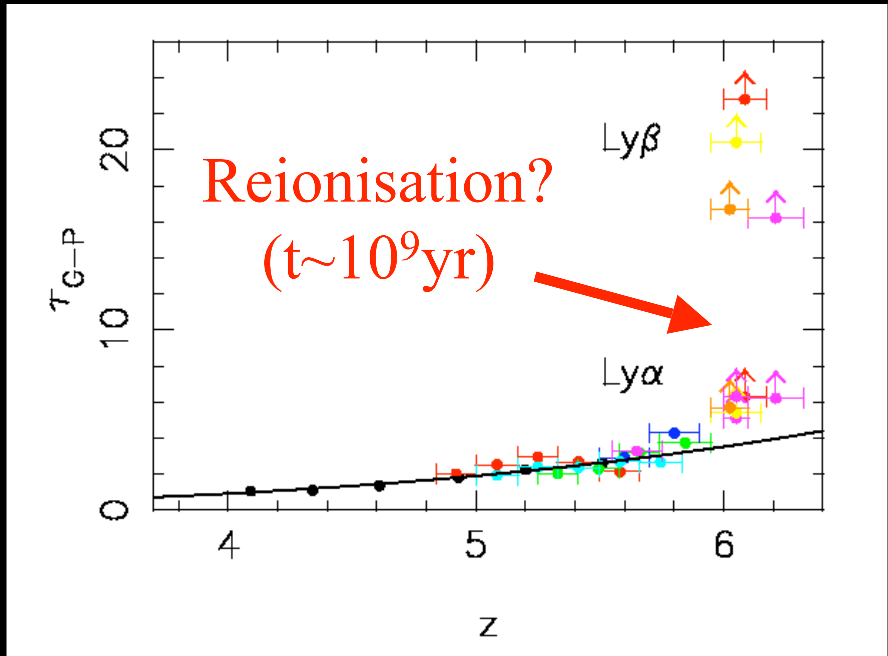
- Star-formation rate at z~6 consistent with maintaining reionization at z~6
- THIS TALK: A declining star-formation rate towards high-z does not account for reionization

# Quasar Absorption Spectra as a Probe of the High-z IGM




- Quasar spectra measure an increase in IGM opacity towards large redshift

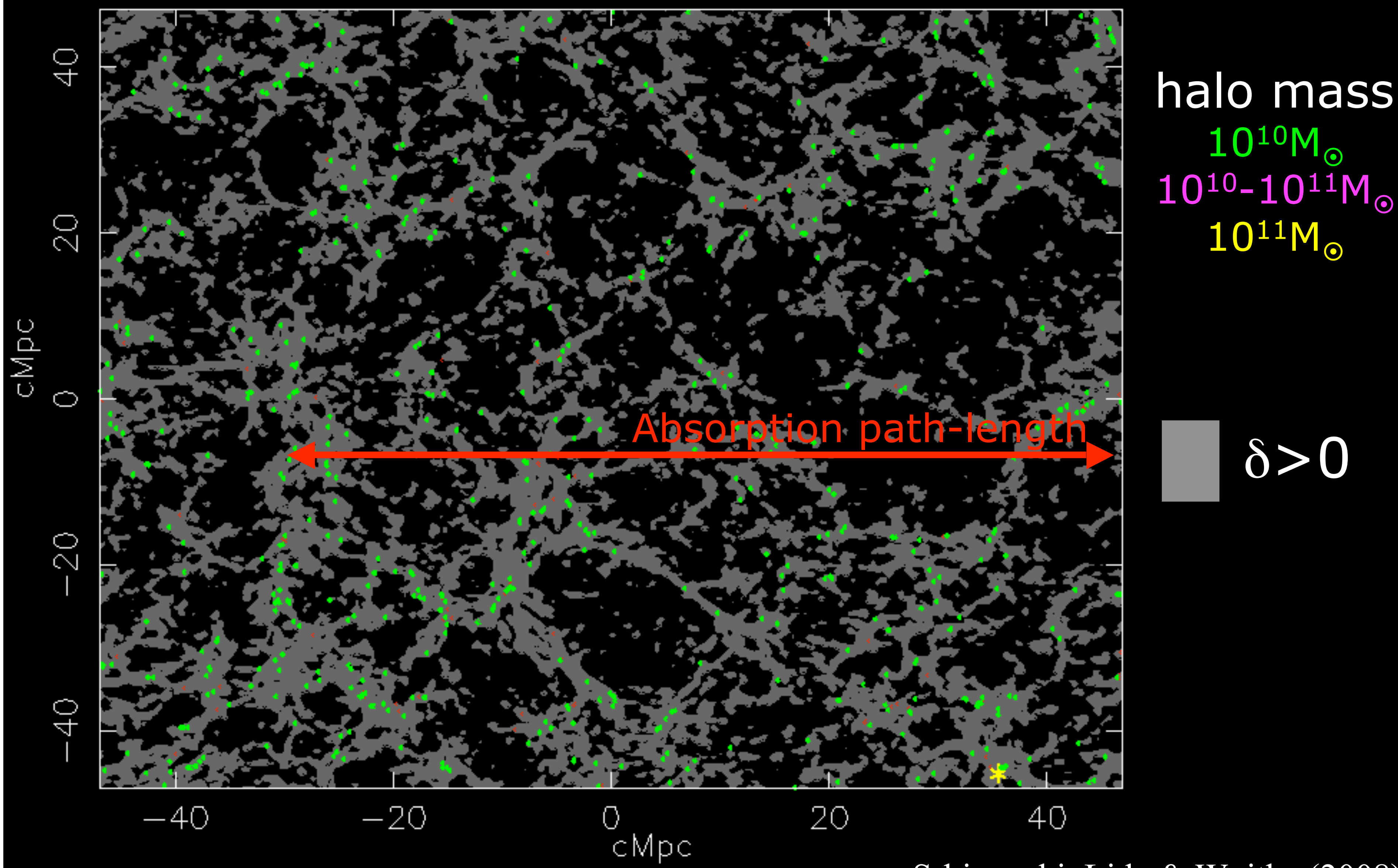
Fan et al. (2001,2004,2006)



# Constraining the Photon Budget for Reionization From Quasar Spectra

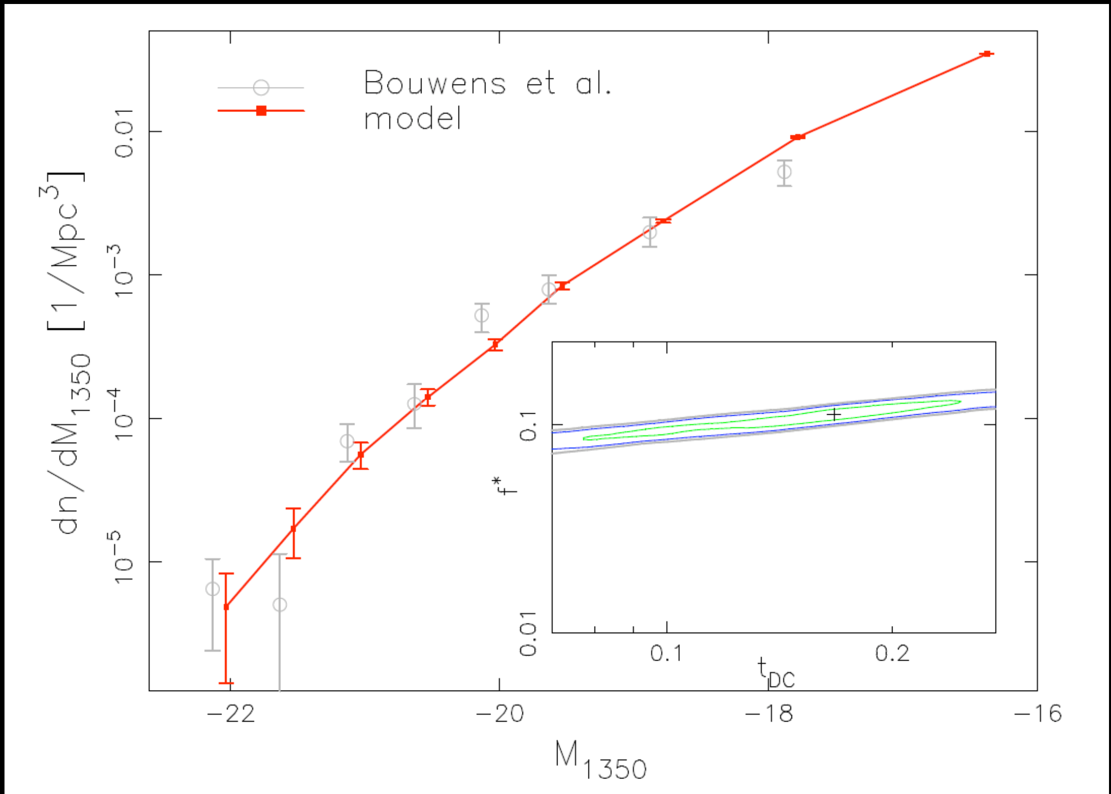
- The ionization rate and mean-free-path may be inferred from the observed optical depth via a simulation.
- Together, these yield the emissivity of the galaxy population.
- If the emissivity is compared with the observed star-formation rate, the escape fraction of ionizing photons can be obtained.
- The integral of emissivity over time must be sufficient to reionize the universe (reionization history).
- An advantage of measuring the emissivity via the IBG rather than a LF is that it is not subject to a flux limit.

# N-body Simulation of Ionizing BG




Srbinovski, Lidz & Wyithe (2008)

# Modeling of Luminosity Function and Transmission




$$\mathrm{SFR} = 0.17 \left(\frac{M}{10^9\ M_\odot}\right)\left(\frac{t_s}{10^8\ yr}\right)^{-1} \times \left(\frac{f^*}{0.1}\right)\left(\frac{\Omega_B/\Omega_M}{0.17}\right)\ M_\odot\ yr^{-1},$$

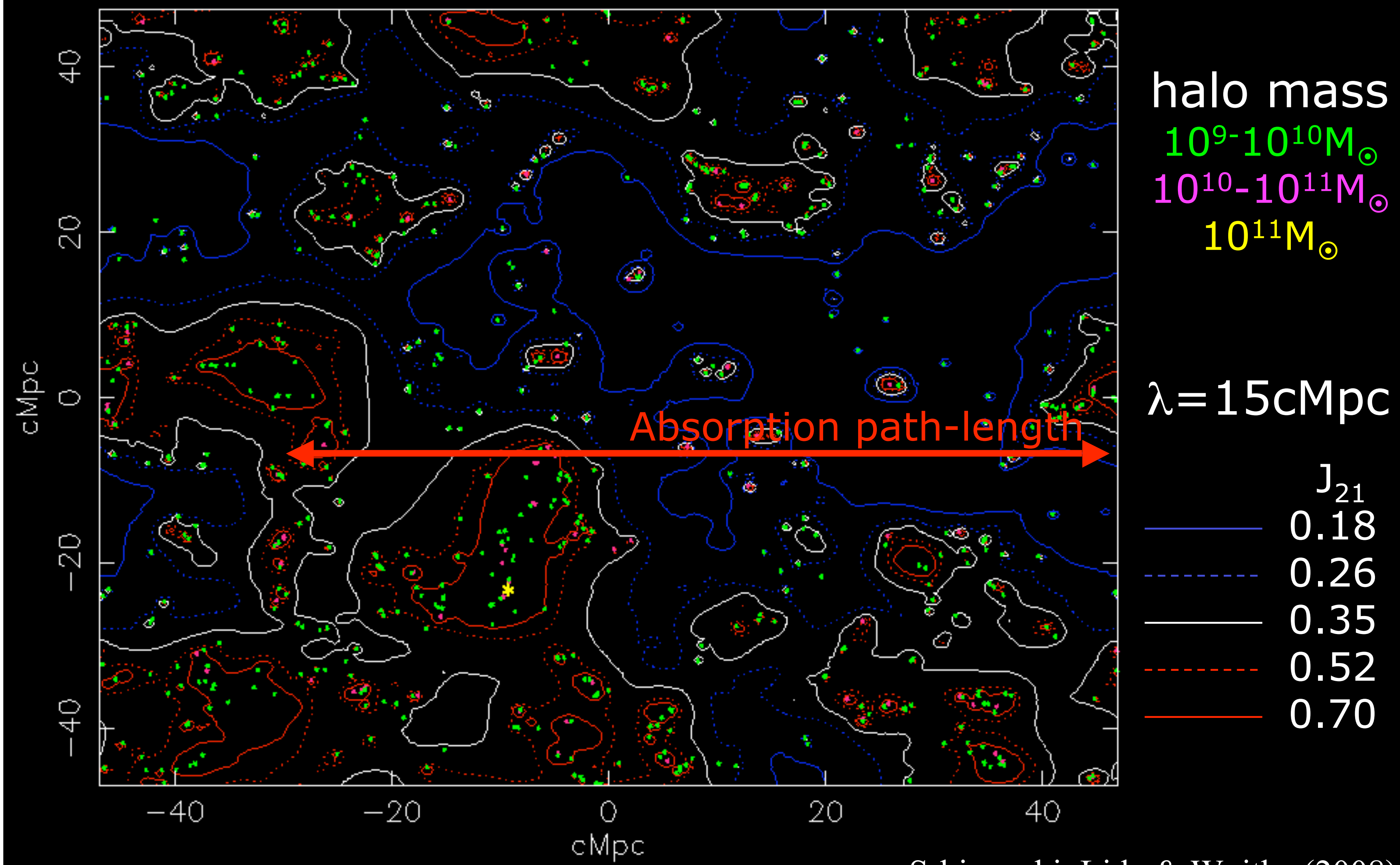
$$f_{1350} = 7 \times 10^{27} (\dot{M}_*/[\mathrm{M}_\odot/\mathrm{yr}])\ \mathrm{erg\ s^{-1}\ Hz^{-1}}$$

$$N(> f_{1350}) = \epsilon_{\mathrm{DC}} \int_{M_{\mathrm{UV}}}^{\infty} \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M},$$

Srbinovsky & Wyithe (2008)

- Halo population identified from an N-body simulation (Zahn et al. 2007; Lidz et al. 2007; McQuinn et al. 2007)

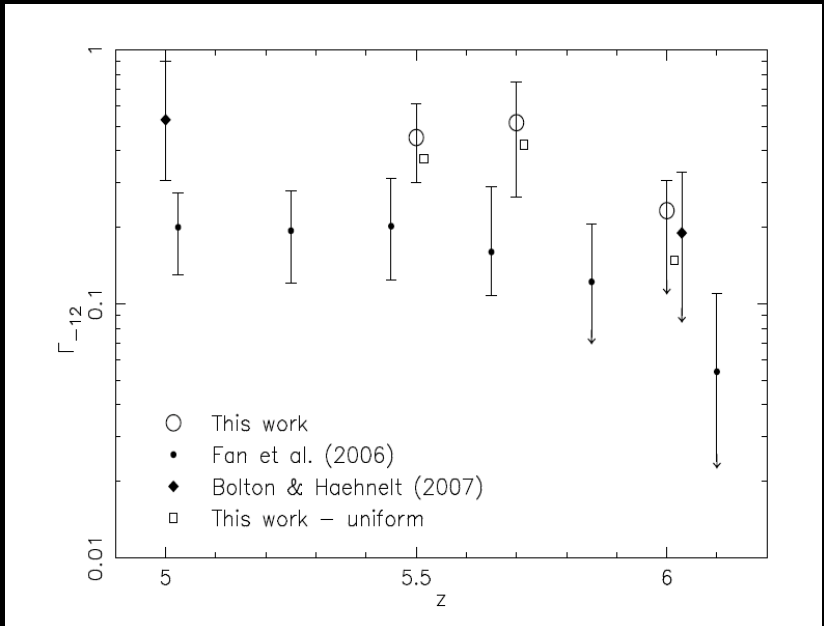
# N-body Simulation of Ionizing BG




Srbinovski, Lidz & Wyithe (2008)

# Ionization Rate from Ly$\alpha$ Transmission

- Ionization rate constrained to match effective Ly$\alpha$ optical depth (Fan et al. 2006).

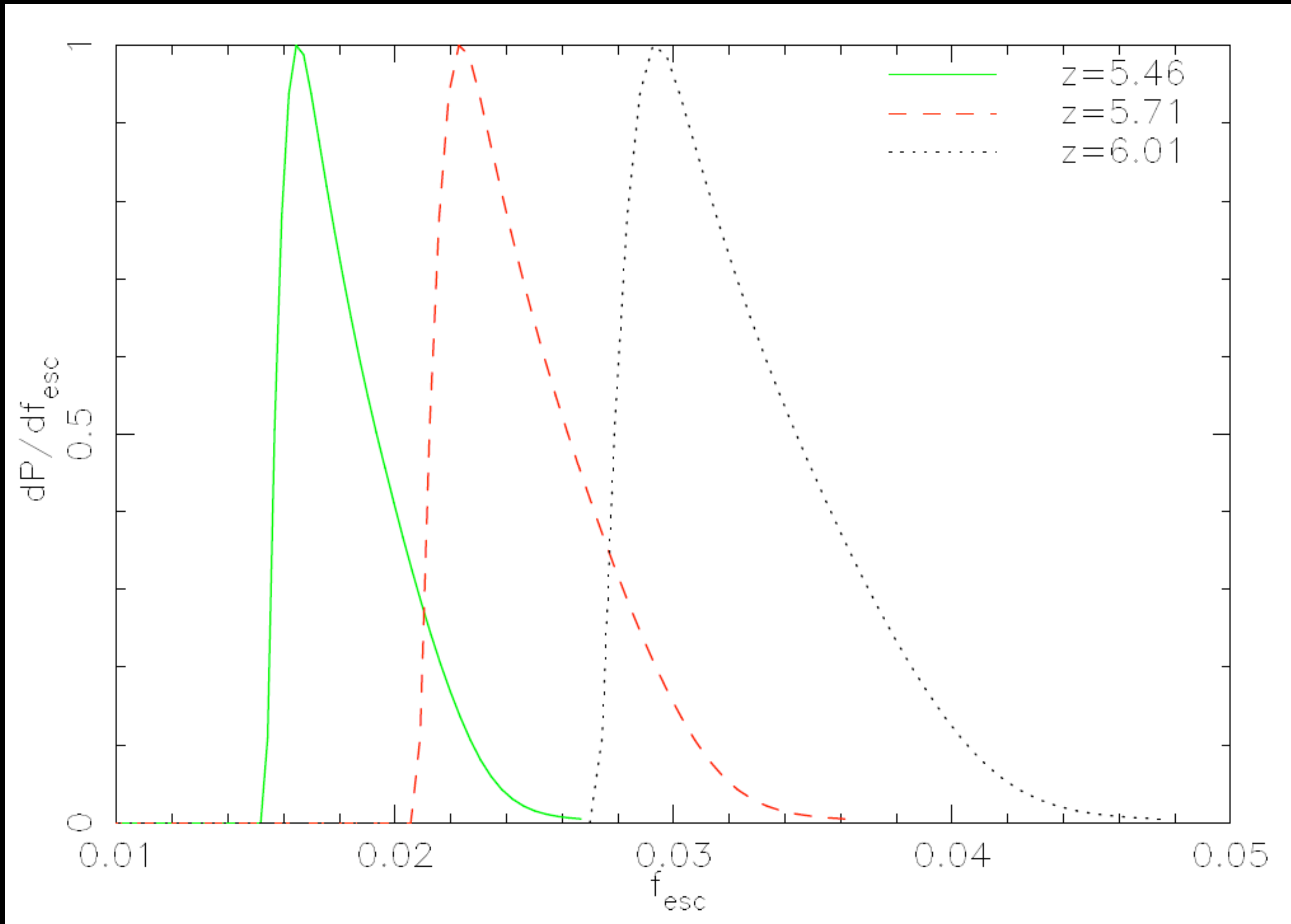



- Ionization rate is dependent on:
  - the global star formation rate (and IMF),
  - the mean-free-path for ionizing photons,
  - and the escape fraction of ionizing photons from galaxies.

- The star-formation rate and mean-free-path can be constrained, leaving the escape fraction to be measured.

Srbinovsky & Wyithe (2008)

# Escape Fraction of Galaxies

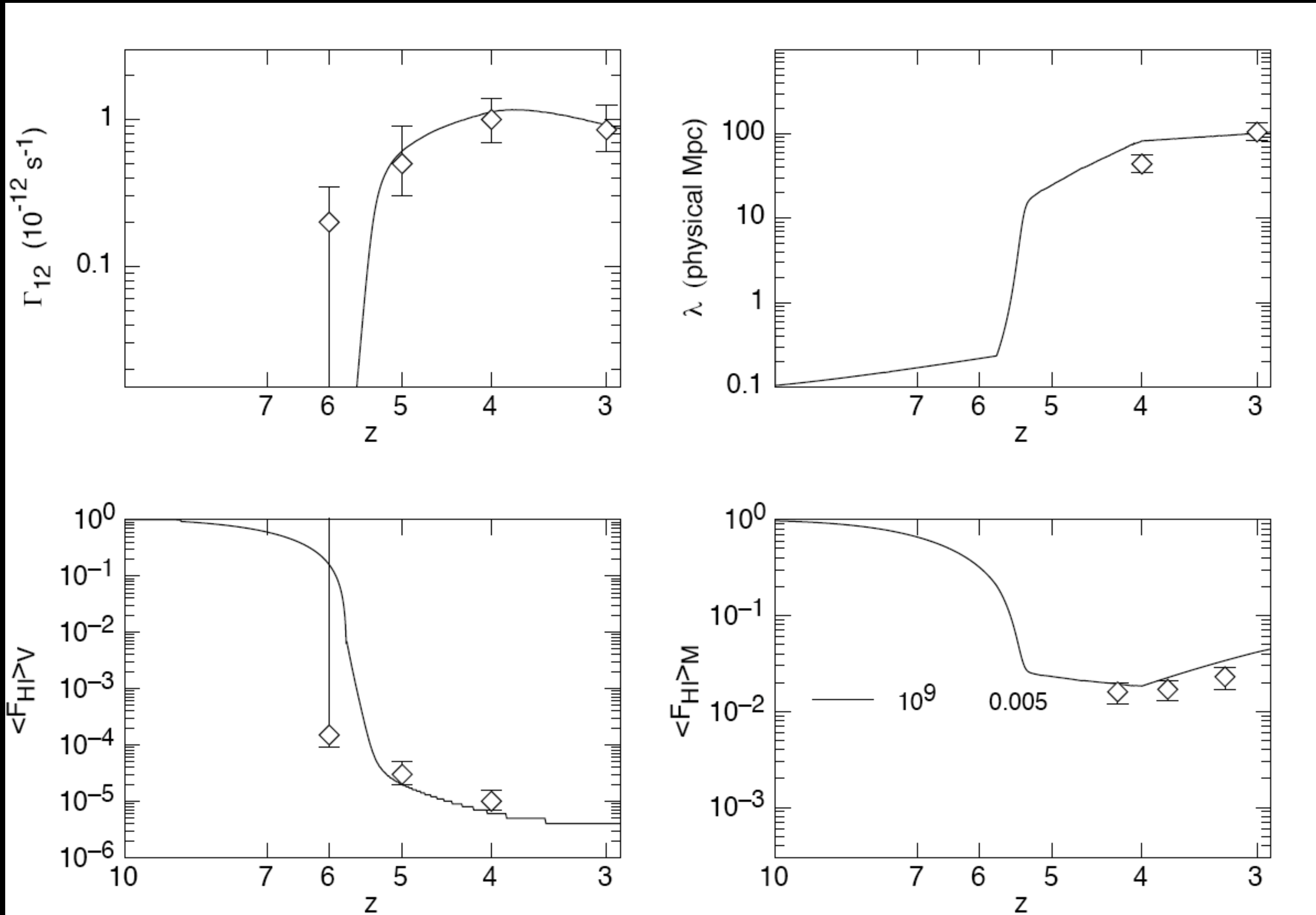



- Sources in all halos resolved in simulation ($M>10^9 M_{solar}$).

$$\frac{dP}{df_{\rm esc}} = \frac{dP}{df^\star}\left|\frac{df^\star}{df_{\rm esc}}\right| = \frac{dP}{df^\star}\frac{\mathcal{C}}{{f_{\rm esc}}^2}.$$

Srbinovsky & Wyithe (2008)

# Escape Fraction for Ionizing Photons and the Reionization History




- Ionization rate is not consistent with reionization at z~6

Srbinovsky & Wyithe (2008)

# The Marginal Photon Budget for Reionization

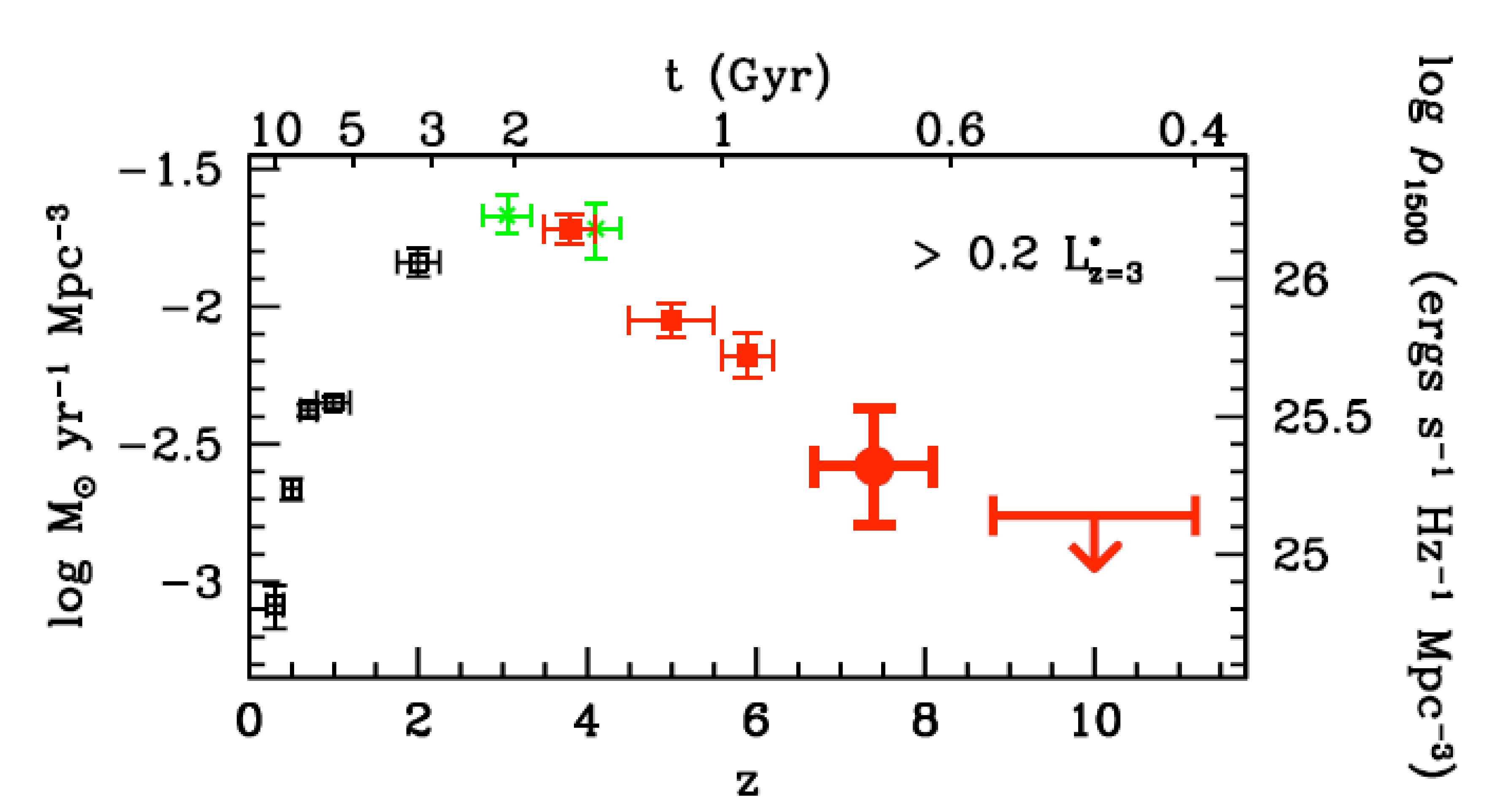
• The emissivity is measured via the IGM opacity

• This emissivity can be associated with galaxies above a minimum mass threshold via a starformation efficiency (constrained through the LF), and an escape fraction (constrained through the ionization rate).

• Given a minimum mass threshold, star-formation efficiency and escape fraction, the emissivity can be integrated through the reionization era.

• The ionization rate at z~6 is not consistent with reionization at z>6 unless emissivity *increases* towards higher redshift. -> Not consistent existing observations.

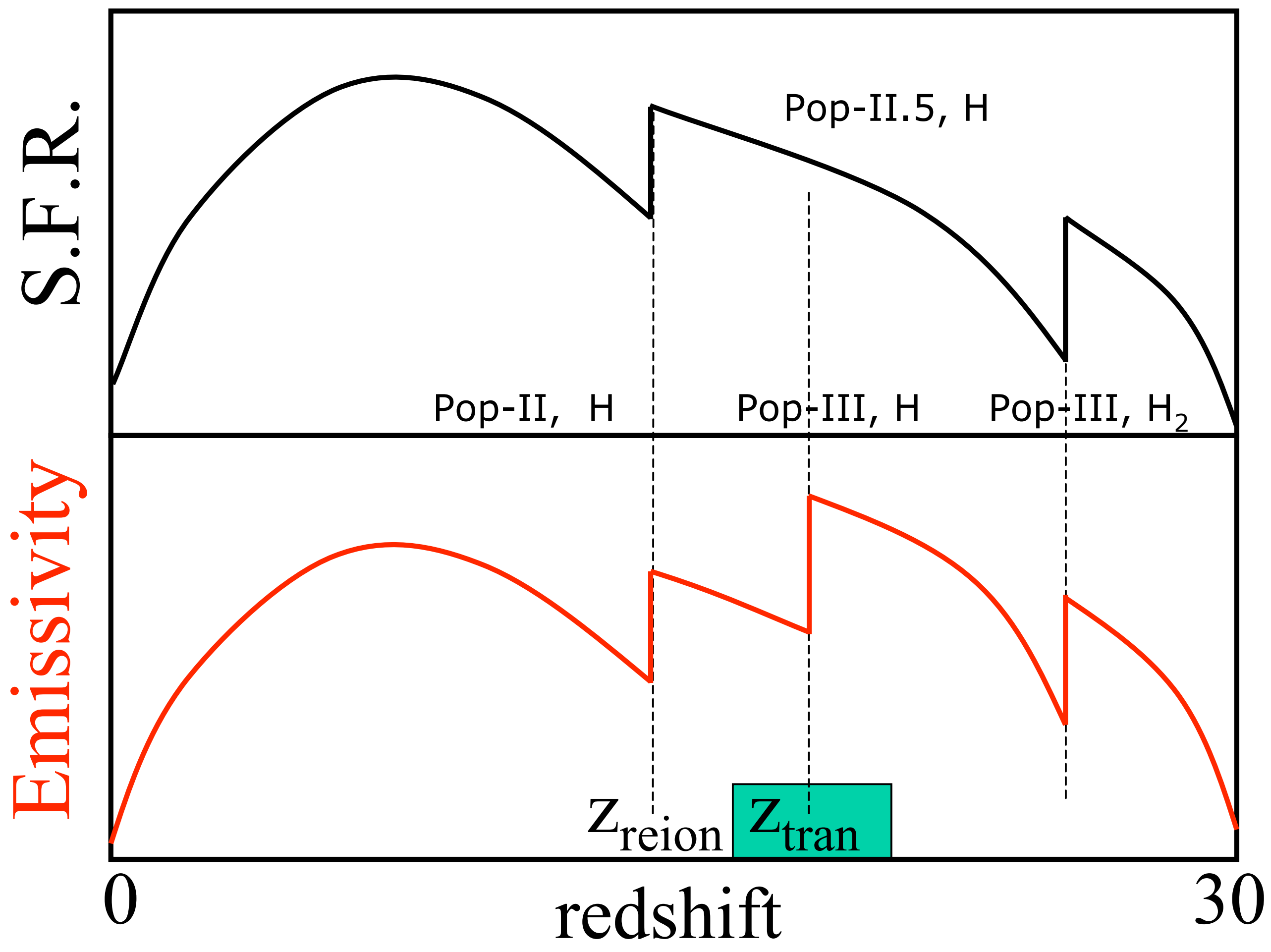
# The Marginal Photon Budget for Reionization



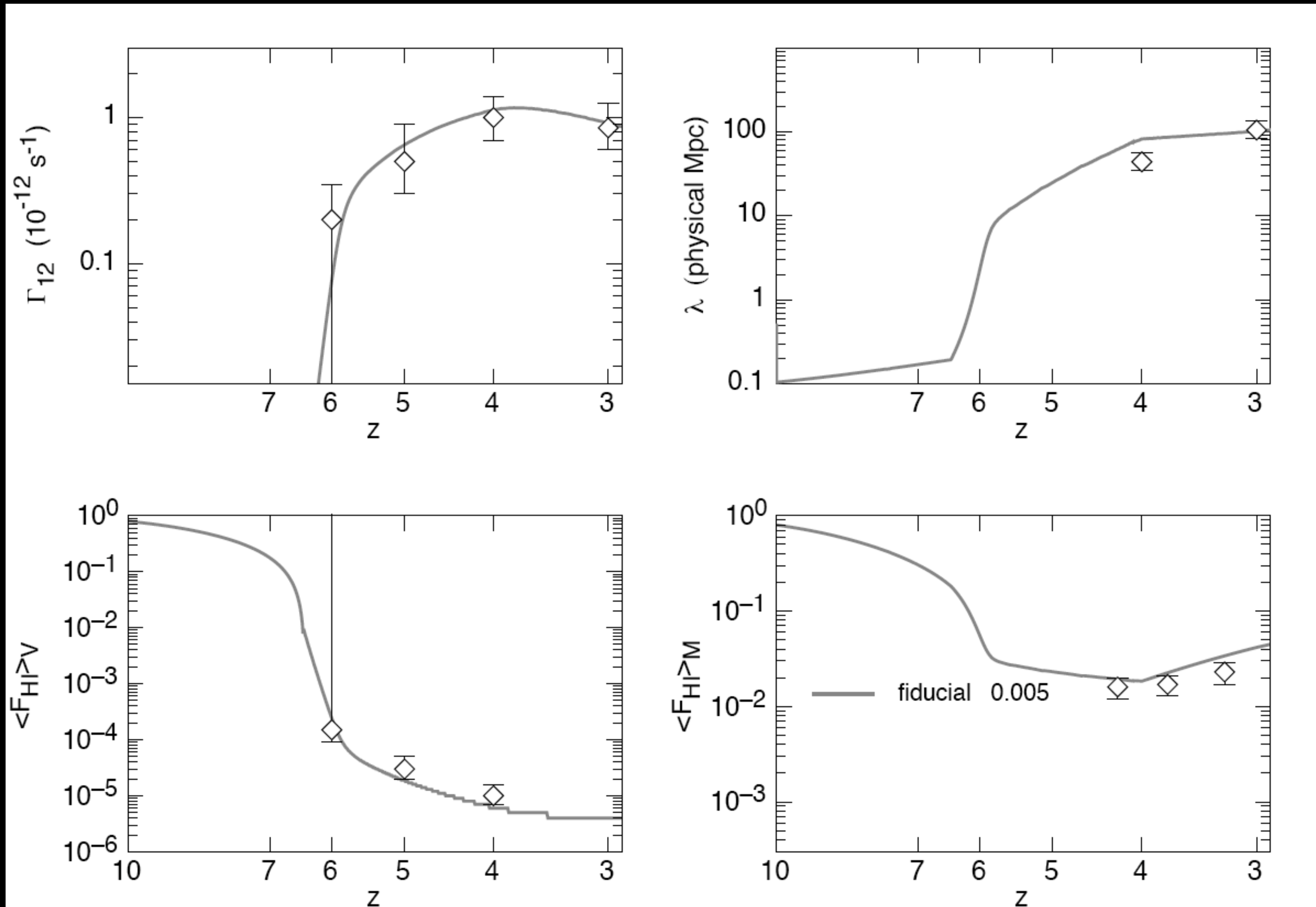

Bouwens et al. (2008)

# Ionizing Photons from Stars

(Barkana & Loeb 2000; Mackey et al. 2000)



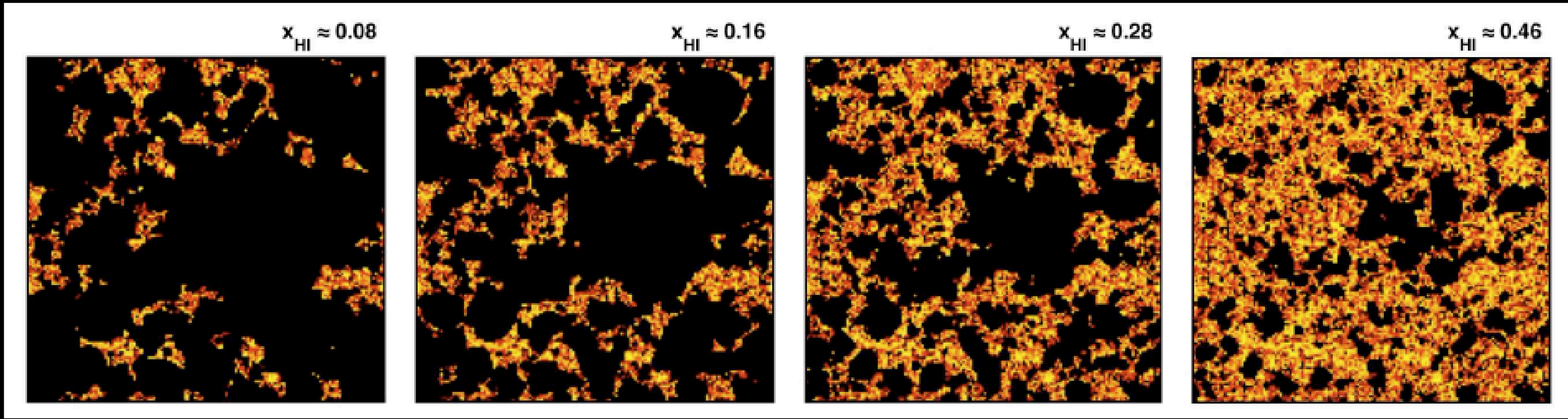
# Escape Fraction for Ionizing Photons and the Reionization History




- Ionization rate increased by low mass galaxy formation?

Srbinovsky & Wyithe (2008)

# Redshifted 21cm Emission




- The warm IGM is visible in 21cm line emission, and at $z>6$ could be detected at frequencies $<200$MHz.
- Redshifting of line emission produces a continuum => 21cm tomography.
- The evolution of neutral hydrogen traces the appearance and evolution of early galaxies. The 21cm emission is effected by all sources of ionizing radiation, and will be complementary to searches for high-z galaxies as well as spectroscopy of high redshift sources.

# Conclusions

• The rate of production of ionizing photons at the completion of reionization is encoded in the Ly$\alpha$ absorption towards high-z quasars.

• The implied emissivity would need to increase at $z>6$ in order to have reionized the universe by that time.

• Searches for high redshift galaxies beyond $z \sim 6$ should see an increase in the ionizing photon emissivity.

• Some options include sources with harder spectra (e.g. Pop-III) and suppression of low-mass galaxy formation late in the reionization.