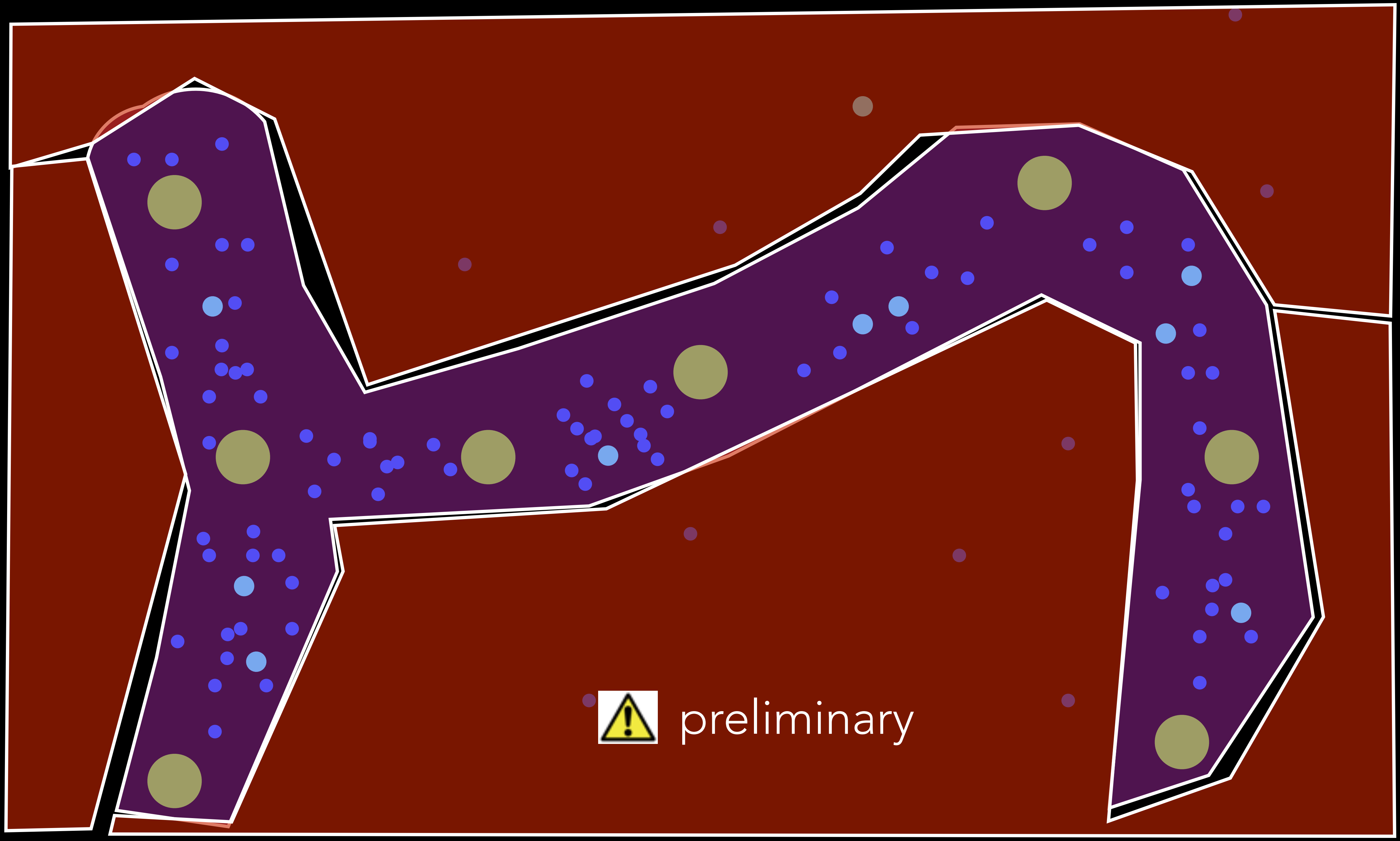
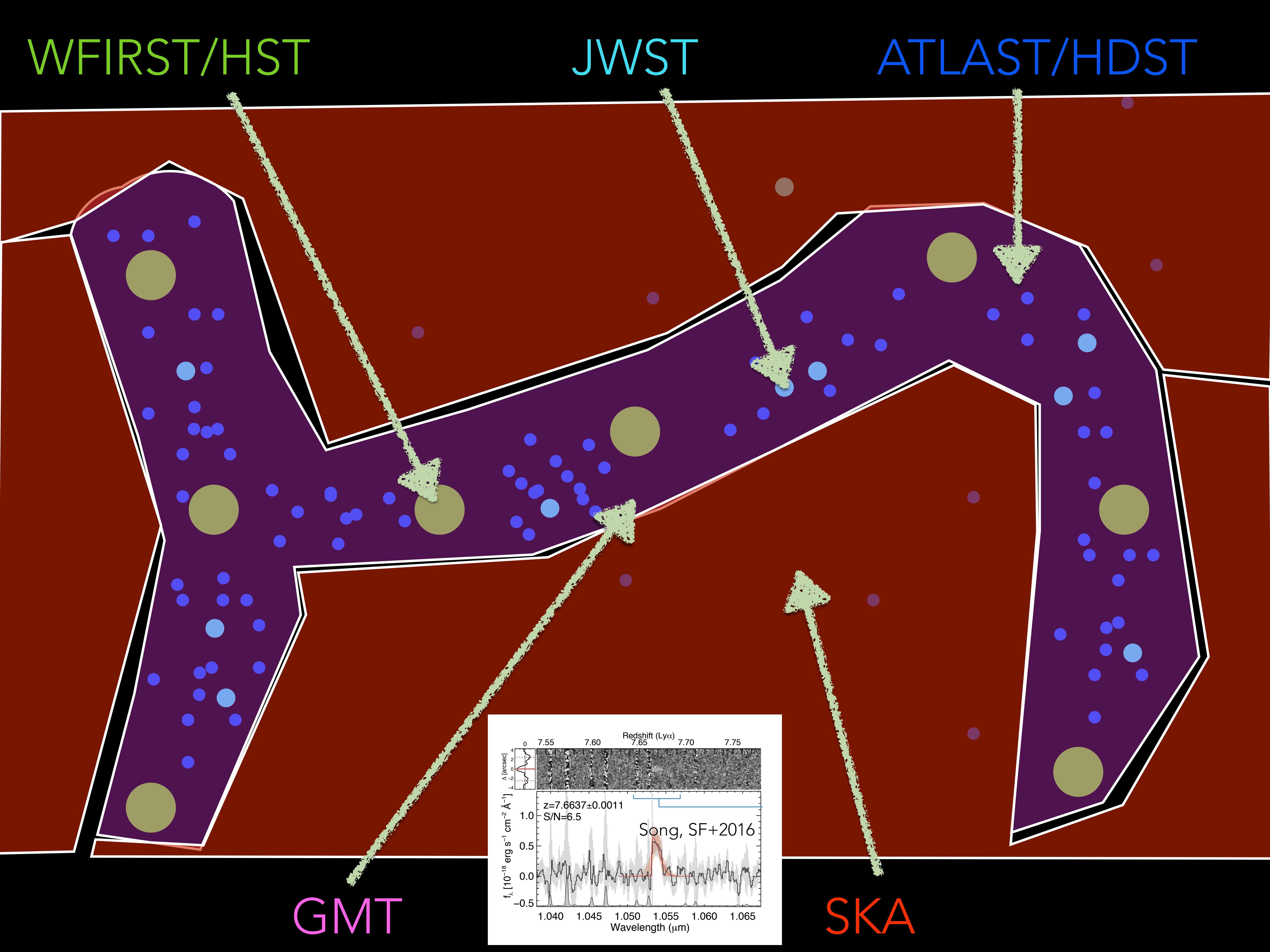
A PHYSICALLY MOTIVATED ASSESSMENT OF THE IONIZING EMISSIVITY FROM GALAXIES IN THE EPOCH OF REIONIZATION



STEVEN FINKELSTEIN **THE UNIVERSITY OF TEXAS AT AUSTIN**

with Jan-Pieter Paardekooper, Peter Behroozi, Rachael Livermore & Kristian Finlator


WFIRST/HST
JWST
ATLAST/HDST
GMT
SKA
Redshift (Lyα)
7.55
7.60
7.65
7.70
7.75
z=7.6637±0.0011
S/N=6.5
Song, SF+2016
1.040
1.045
1.050
1.055
1.060
1.065
Wavelength (μm)

In reality, reionization is of course more complicated.
Let's start with what we can see: galaxies.

CALCULATING THE CONTRIBUTION OF GALAXIES TO THE REIONIZING BUDGET

- Step 1: Integrate the UV LF to obtain the specific UV luminosity density: ρ_{UV} [erg/s/Hz/Mpc^3]
  - Assumption: Need to assume a minimum value of M_{UV} (especially when $\alpha < 2$).
  - Common values in the literature: -17, -15, -13, -10.
    - We see galaxies down to -17, so its likely fainter. We often assume M_{lim}=-13, though this bears watching from the theoretical side (e.g., Jaacks+12, O'Shea+15; talks by S. Mutch, M. Norman).
- Step 2: Assume a Lyman continuum photon production efficiency, ξ_{ion}., to convert from UV luminosity density to ionizing emissivity. For 0.2 solar metallicity, log (ξ_{ion})~25.3.
- Step 3: Choose a reionization model.
  - Assumptions: Madau (1999) model, which tells you the number of ionizing photons per volume (the ionizing emissivity) needed to keep the IGM ionized at a given redshift.
  - Assumptions: clumping factor of the IGM (C) and escape fraction of ionizing photons from galaxies (f_{esc}). Typically assumed values are: C~3-5, f_{esc}~20-50%.

CALCULATING THE CONTRIBUTION OF GALAXIES TO THE REIONIZING BUDGET

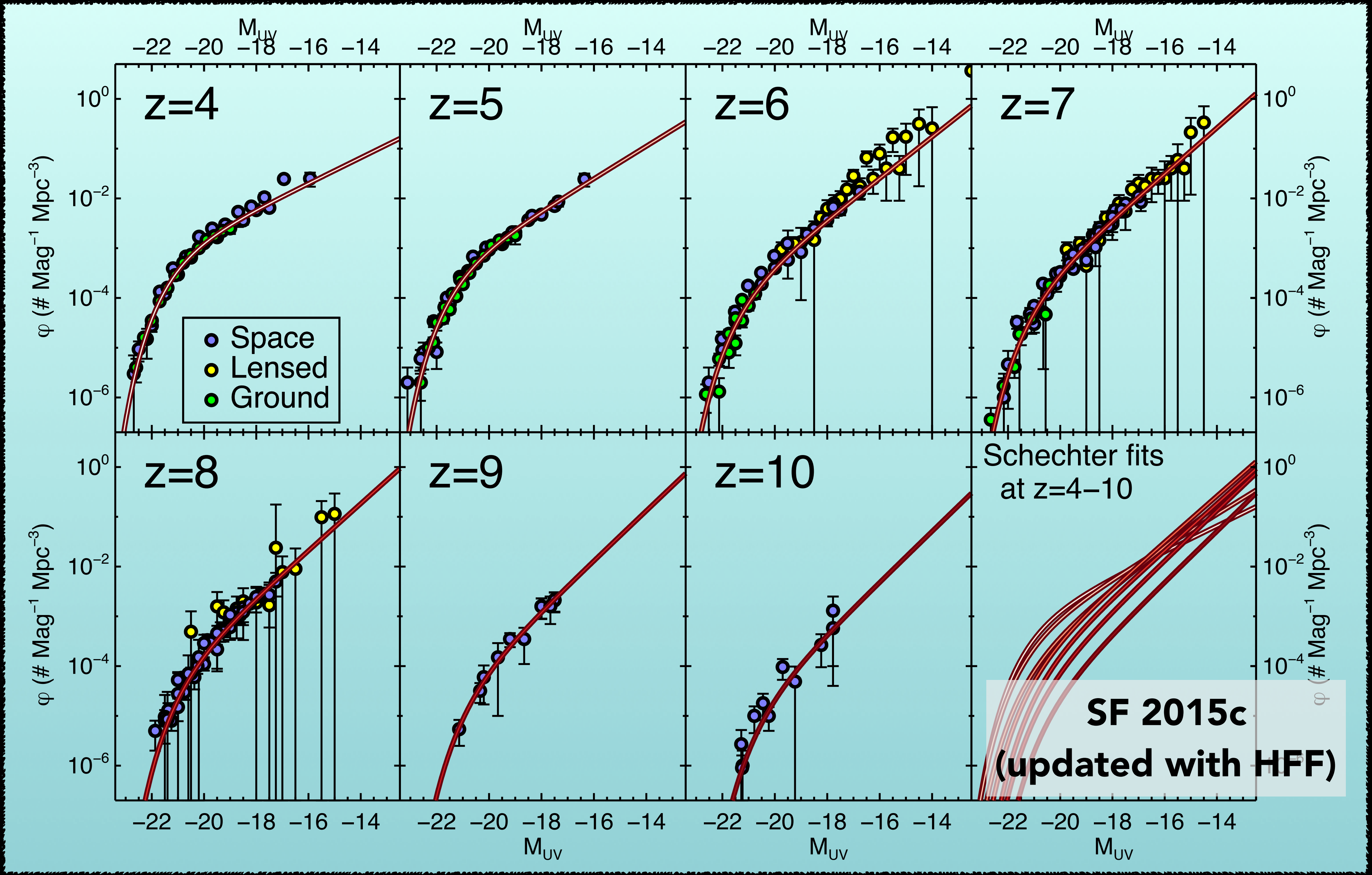
- Step 1: Integrate the UV l… the specific UV lumi… ity: ρ_{UV} [erg/s/Hz/Mpc^3]
  - Assumption: Ne… e a minimum value of M_{UV} (especi… $\alpha < 2$).
  - Common val… the lit… -17, -15, -13, -10.
    - We se… xies down to - … likely fainter. We often assum… =-13, though this be… atching from the t… al side (e.g., Jaacks+12, O'S… 5; talks by S. Mutch… Norman).
- Step 2: Assum… yman continuum photon p… efficiency, ξ_{ion}, to … rt from UV luminosity de… o ionizing emissivity. For 0.2 s… llicity, log (ξ_{ion})…
- Step 3: Choose … ization model.
  - Assumptions: … (1999) model, which tells you the n… ng photons per volume (the ioniz… sivity) needed to keep the IGM io… given redshift.
  - Assumptions: clumping … IGM (C) and … on of ionizing photons from galaxies (f_{esc}). Typically assu… -50%.

We have learned a lot over the past few years via observations and modeling.

We can move beyond these simple assumptions!!

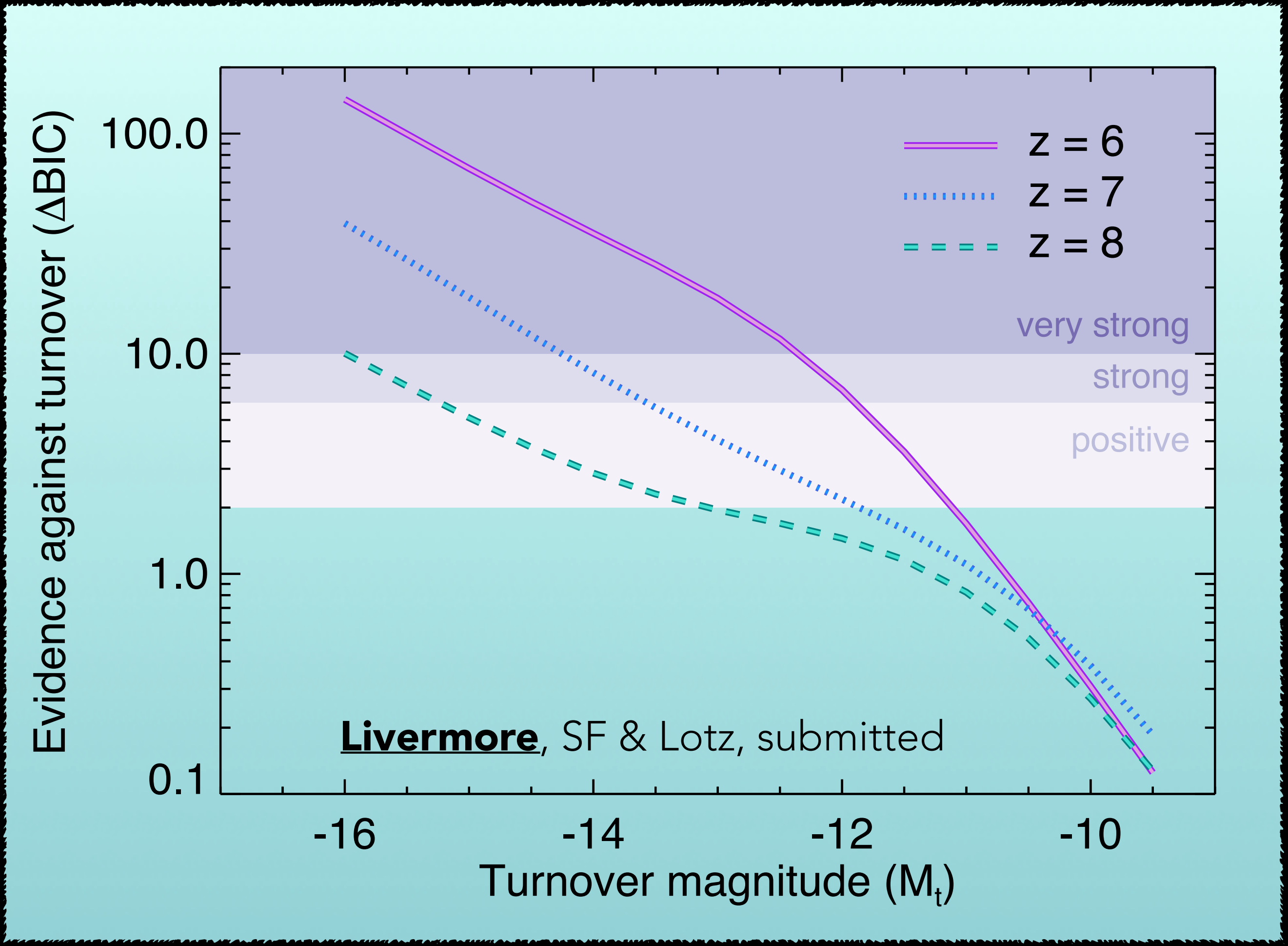
PIECE #1: THE LUMINOSITY FUNCTION

- Rather than rely on the luminosity functions from a specific group, e.g., "Santa Cruz" (Bouwens, Oesch), "Edinburgh" (McLure, Bowler, McLeod) or "Texas" (Finkelstein, Livermore), we fit the data from all recent studies simultaneously.
  - This allows us to better-constrain the luminosity function by including space and ground-based data, as well as to marginalize over different techniques.



PIECE #1: THE LUMINOSITY FUNCTION

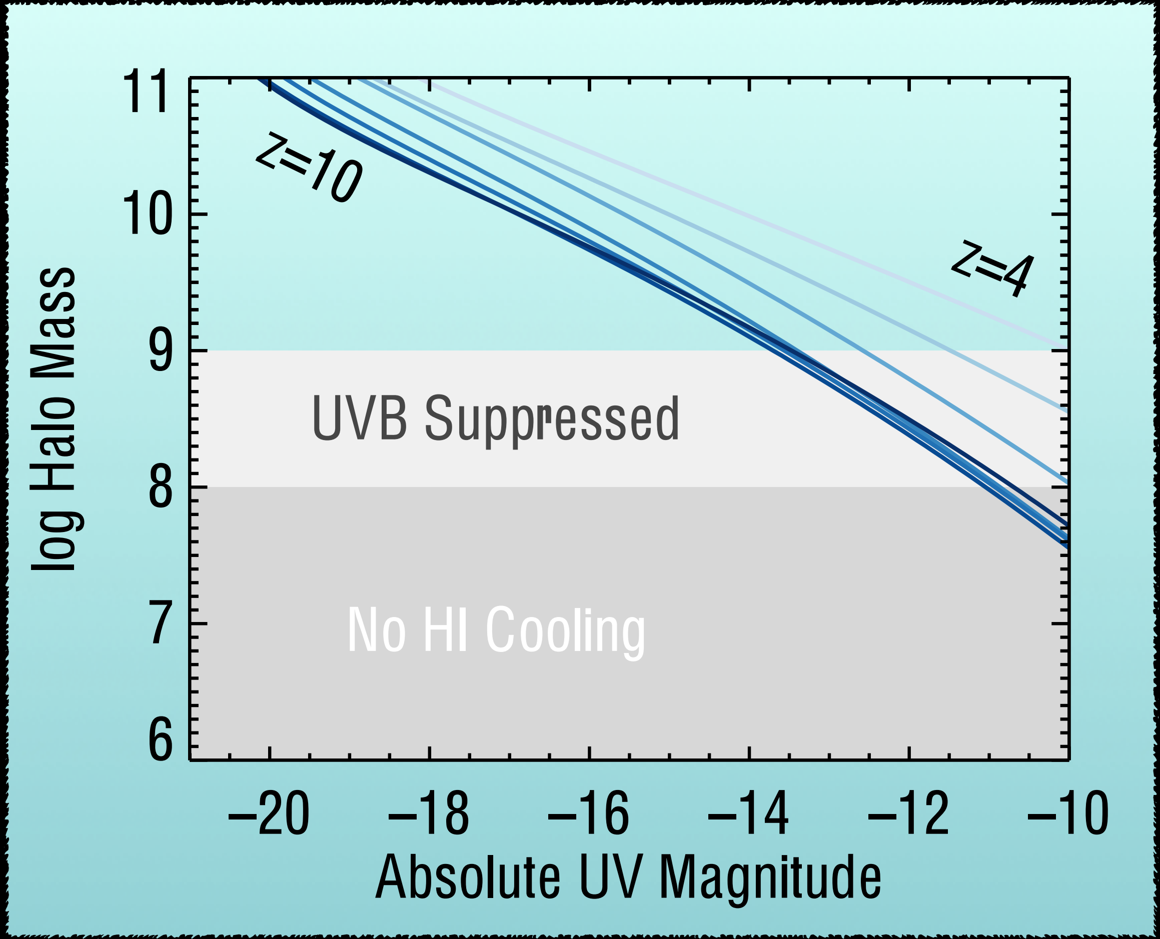
- We can obtain ρ_{UV} by integrating the luminosity function to some limit.
  - We now have evidence from the Frontier Fields that at z=6, the luminosity function continues unbroken (with $\alpha \sim -2$) to at least M_{UV}=-13.

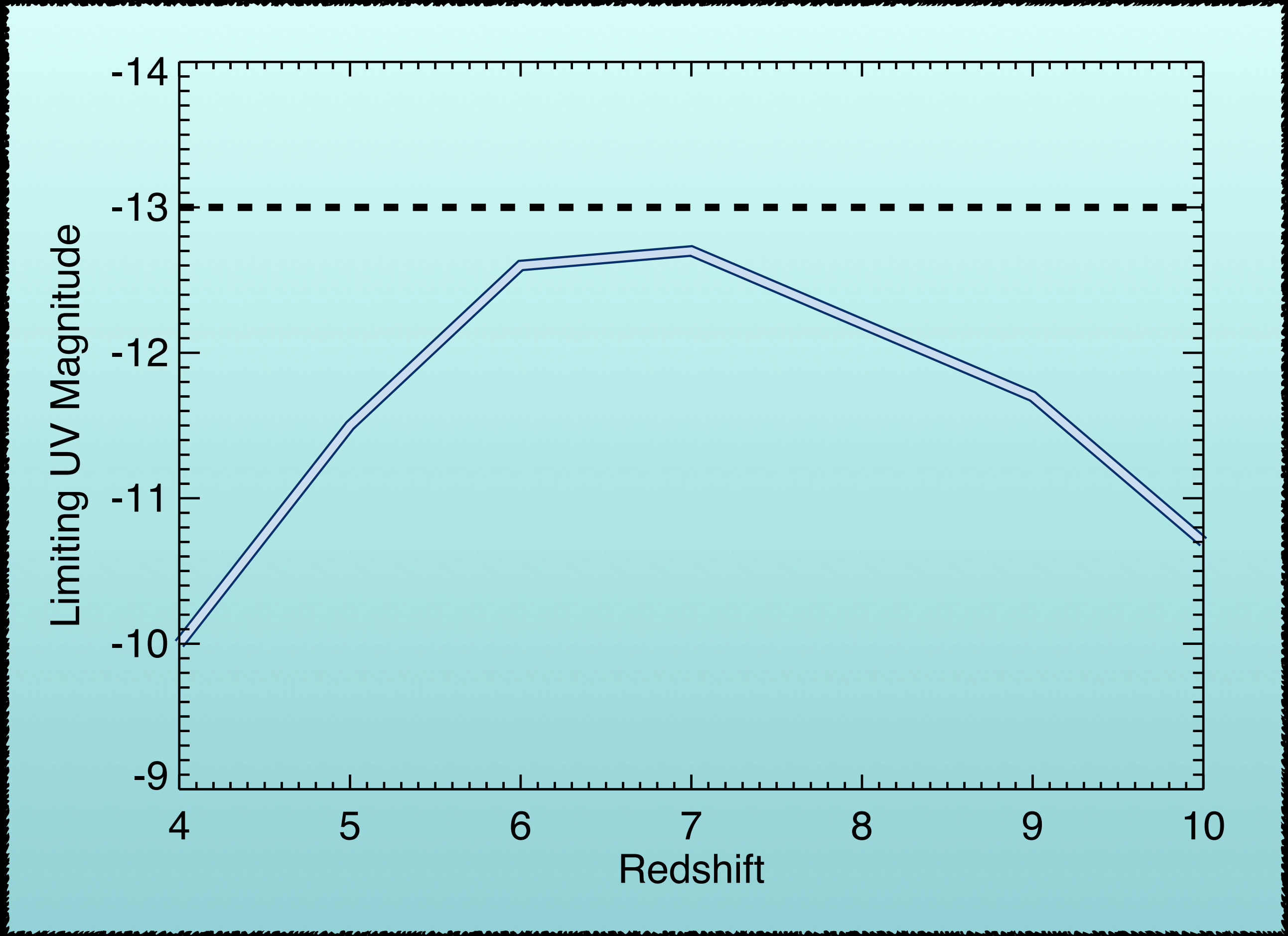


- So, previous studies which integrated to -13 weren't doing too poorly. But, can we go fainter?
  - Theoretically, we expect stars to form in halos only with log $(M/M_\odot) > 9$ after the onset of reionization due to the extragalactic ultraviolet background (EUVB).
  - Before reionization, stars likely form in halos down to the atomic cooling limit of log $(M/M_\odot) = 8$ (or possibly even 7; Wise et al. 2014; M. Norman talk).

PIECE #1(PART B): THE LUMINOSITY FUNCTION CUTOFF

- To understand where these cutoff halo masses lie on our luminosity function, we perform abundance matching.
  - Method from Behroozi+2013, accounts for subhalos, and uses analytic halo mass functions, averaging over the observed redshift ranges.





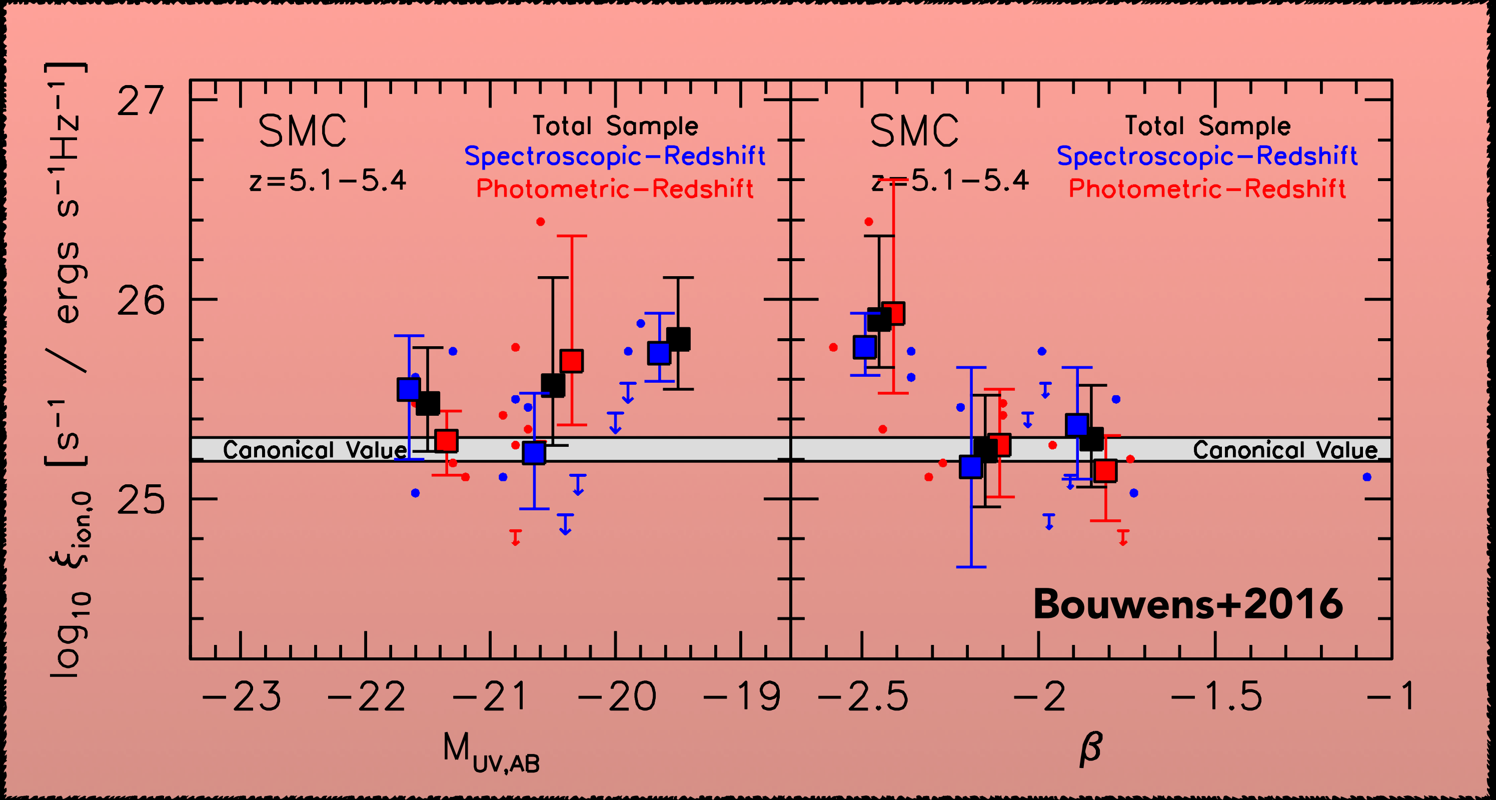
PIECE 2: THE STELLAR POPULATION

- Previously, we needed to use an educated guess here. If one assumed a "normal" stellar population, but with a lower metallicity (~20% Solar), one found a production rate of Lyman continuum photons per unit UV luminosity density of: $\log(\xi_{ion})$=25.3.

- This was recently empirically verified by Bouwens+2016 for sub-L* galaxies at z=4-5 (see also Stark+2015).

  - However, they found that $\log(\xi_{ion})$ increased for the faintest, bluest galaxies, to 25.5-25.9.

  - For this analysis, we assume $\log(\xi_{ion})$=25.34 for galaxies with M_{UV} < -20, and $\log(\xi_{ion})$=25.8 for M_{UV} > -20.

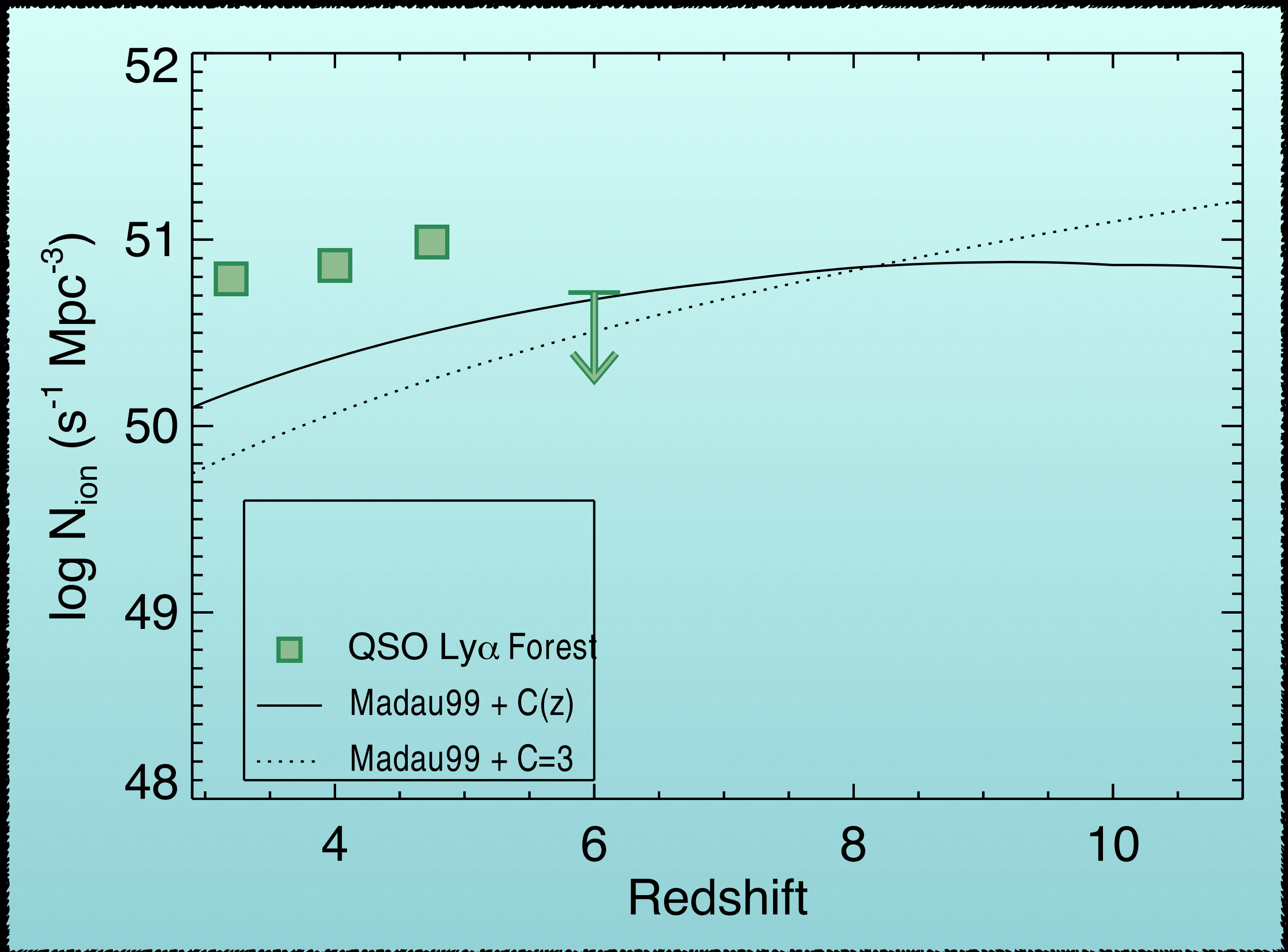


PIECE 3: THE REIONIZATION MODEL

- Adapting the model from Eqn 26 of Madau (1999) into our cosmology, we have:

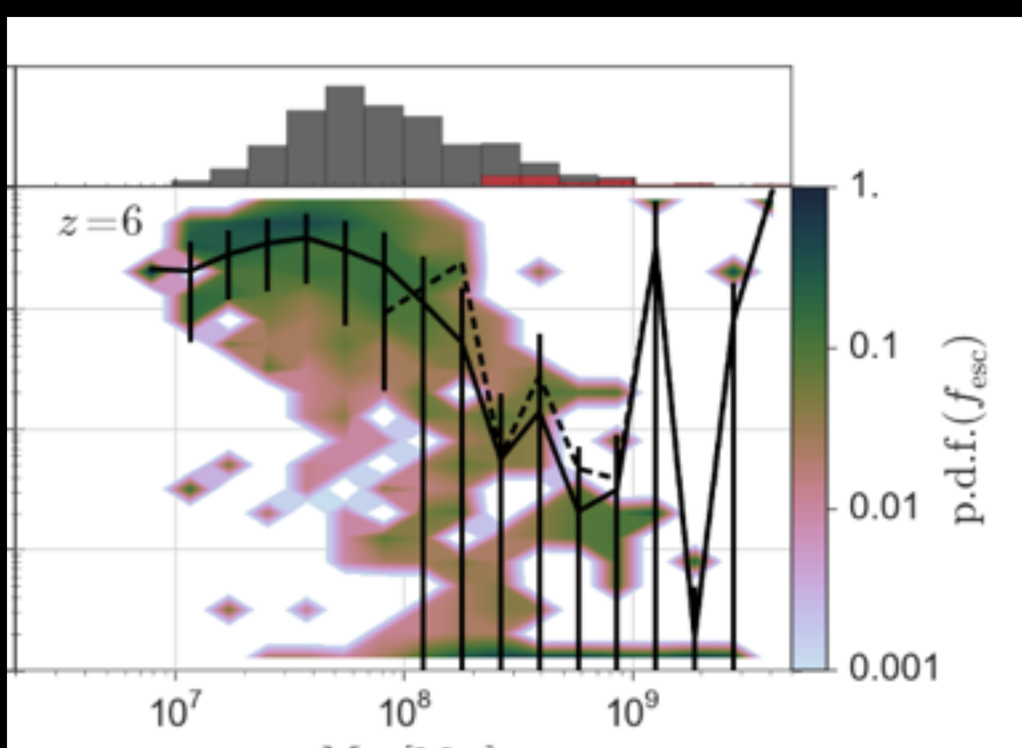
$$\dot{\mathrm{N}}_{ion,crit} = 10^{50.03}\ \mathrm{C}\left(\frac{1+z}{7}\right)^3\left(\frac{\Omega_b\ h_{70}}{0.0461}\right)^2$$

- This is dependent on the clumping factor of the IGM. Our fiducial results use the recent redshift-dependent results from Pawlik, Schaye & Dalla Vecchio 2015, of C=[4.5, 3.1, 1.8] at z=[6, 8, 10].

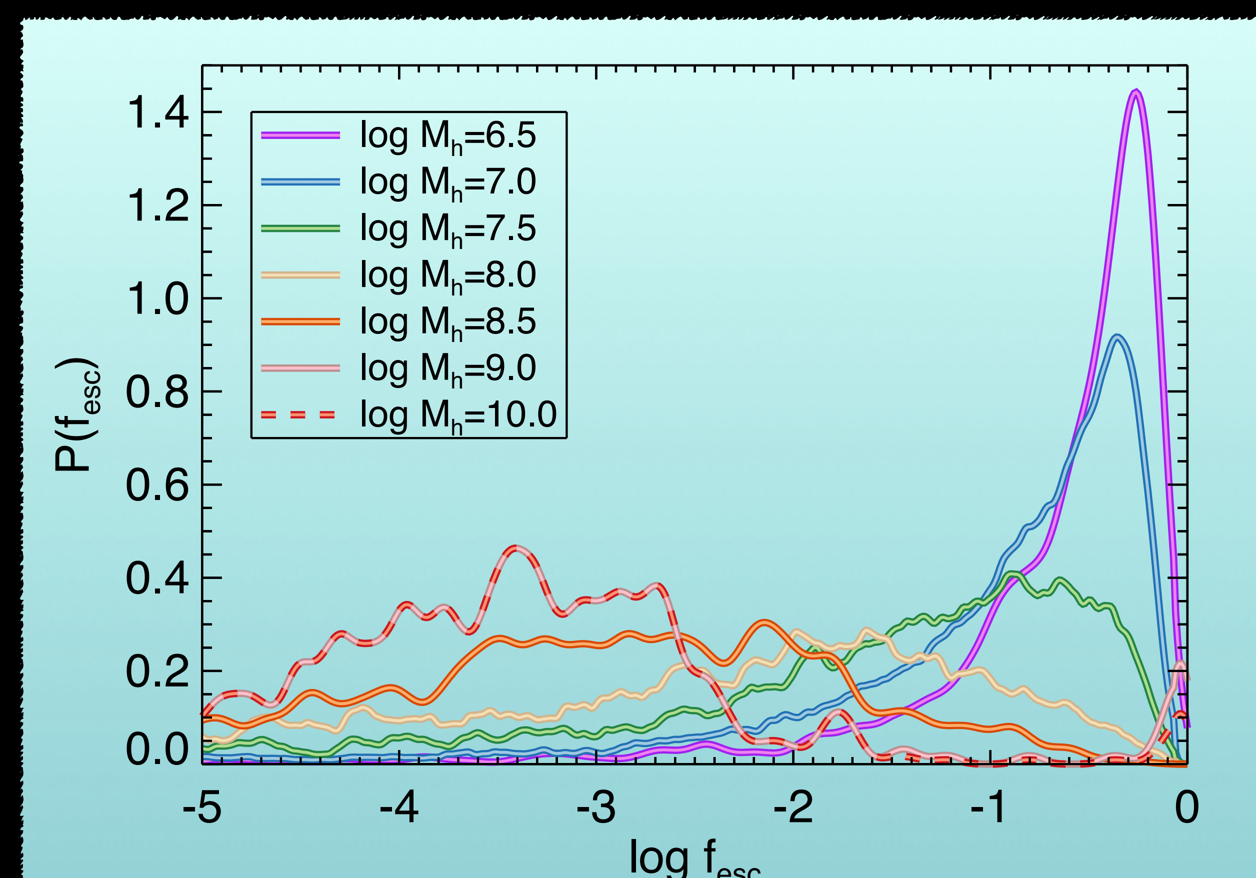


PIECE 3 (PART B): THE REIONIZATION MODEL ESCAPE FRACTION

- This is the tricky part. Nearly *all* observations at $z < 4$ result in non-detections, with typical limits on f_{esc} of less than a few percent (Siana+10), though there are isolated cases of some galaxies have f_{esc}~20-50% (Nestor+11; Vanzella+2016).
  - Here, we adopt the simulations of Pardekooper+2016. They performed zoom-in, high-resolution radiative transfer simulations of ~70,000 galaxies extracted from the First Billion Years (FiBY) simulations (Khochfar+).



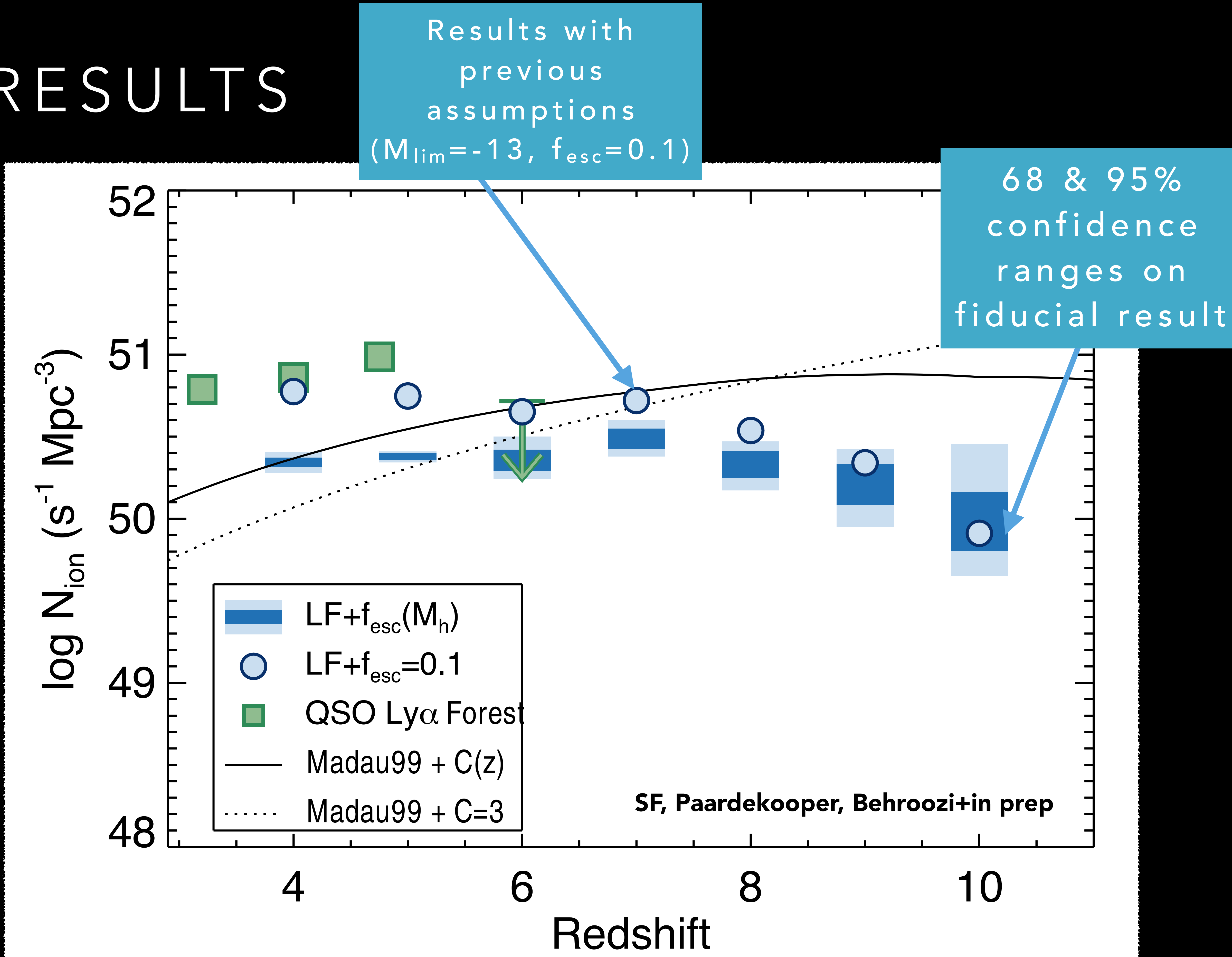
Paardekooper+2015



COMPLETING THE PICTURE

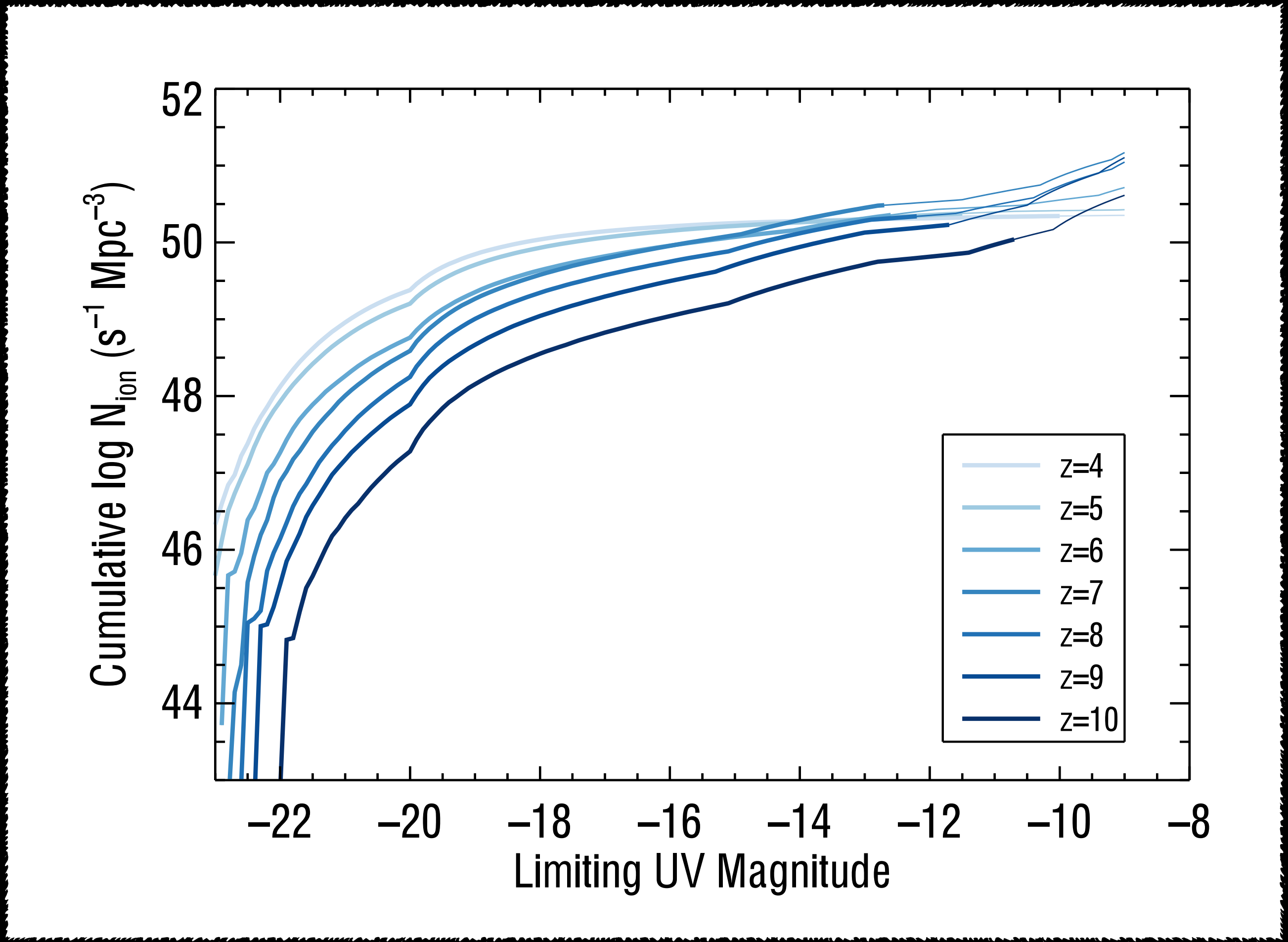
- We now have all of the pieces in place.
- We can calculate the ionizing emissivity from galaxies as a function of redshift by:
  - Integrating the luminosity function to the fiducial magnitude limit (a function of redshift).
  - Using the appropriate value of ξ_{ion} for a given UV magnitude.
  - Using the appropriate value of f_{esc} for a given halo mass.
- To marginalize over all uncertainties, we do this via a Monte Carlo simulation. In each simulation, we:
  - Randomly draw a luminosity function from our MCMC chain results.
  - Create a "population" of mock galaxies drawn from the given Schechter function distribution.
  - Assign an escape fraction to each galaxy based on the assumed halo mass for its UV magnitude. The escape fractions are randomly drawn from the f_{esc} PDFs.
  - Calculate the total UV luminosity density (ρ_{UV}), total number of ionizing photons created ($N_{ion,tot}$), and total ionizing emissivity (N_{ion}).

RESULTS



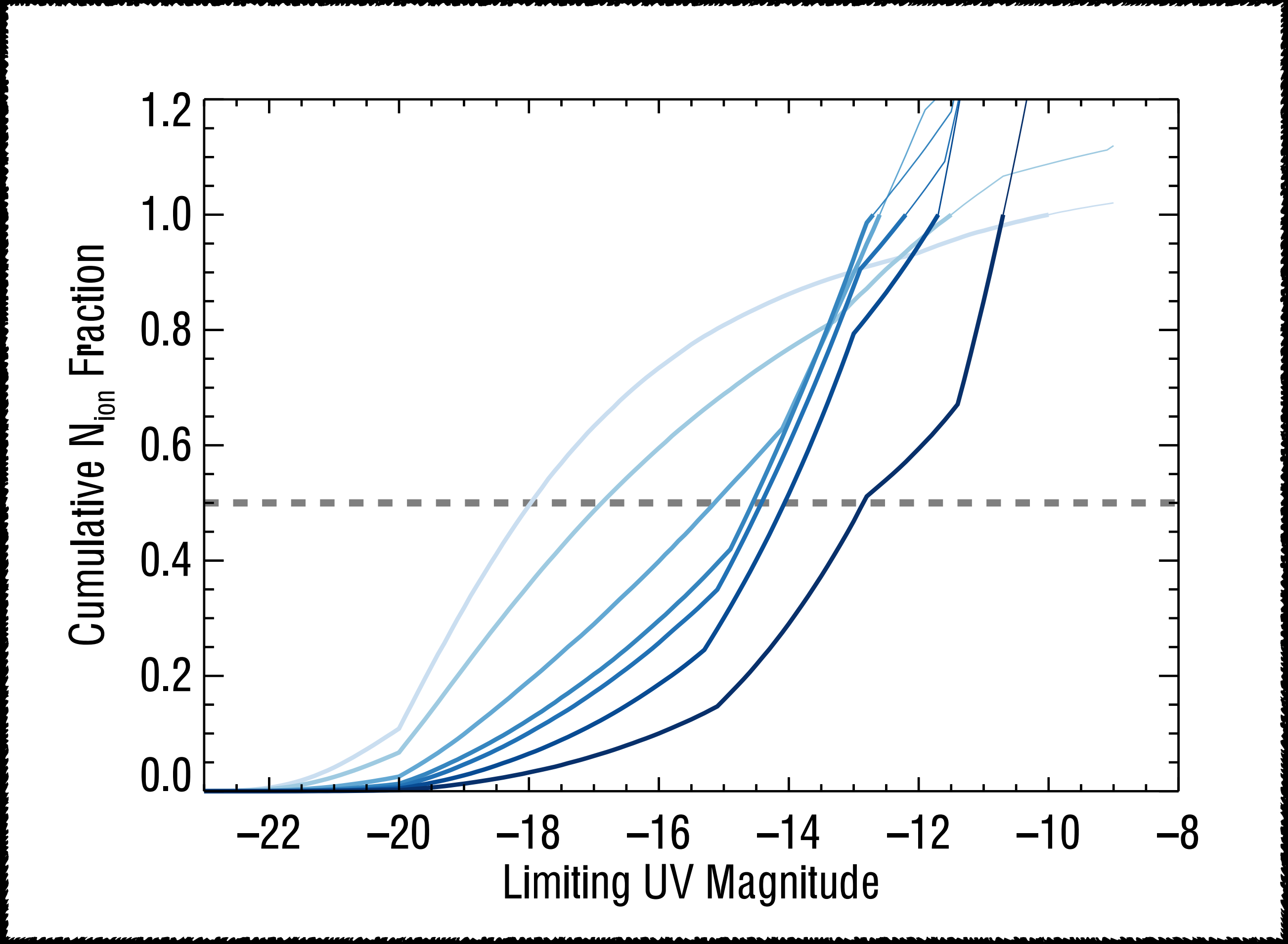
Results with previous assumptions (M_{lim}=-13, f_{esc}=0.1)
68 & 95% confidence ranges on fiducial result
log N_{ion} (s^{-1} Mpc^{-3})
Redshift
52
51
50
49
48
4
6
8
10
LF+f_{esc}(M_h)
LF+f_{esc}=0.1
QSO Lyα Forest
Madau99 + C(z)
Madau99 + C=3
SF, Paardekooper, Behroozi+in prep

WHERE ARE THE PHOTONS COMING FROM?

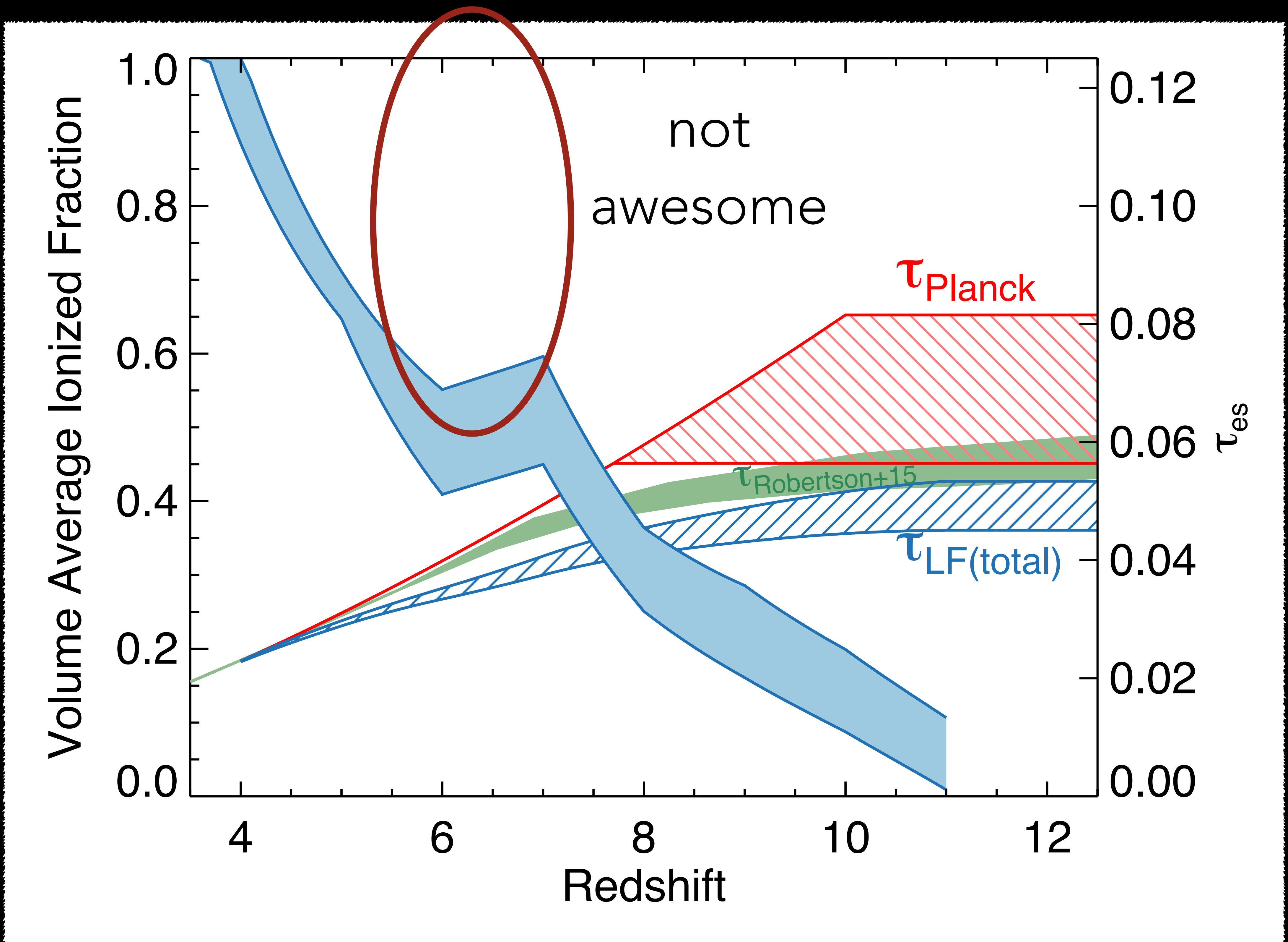


GLOBALLY AVERAGED ESCAPE FRACTION ~2% AT ALL REDSHIFTS

At z > 6, more than half of the ionizing photons come from systems with M > -15

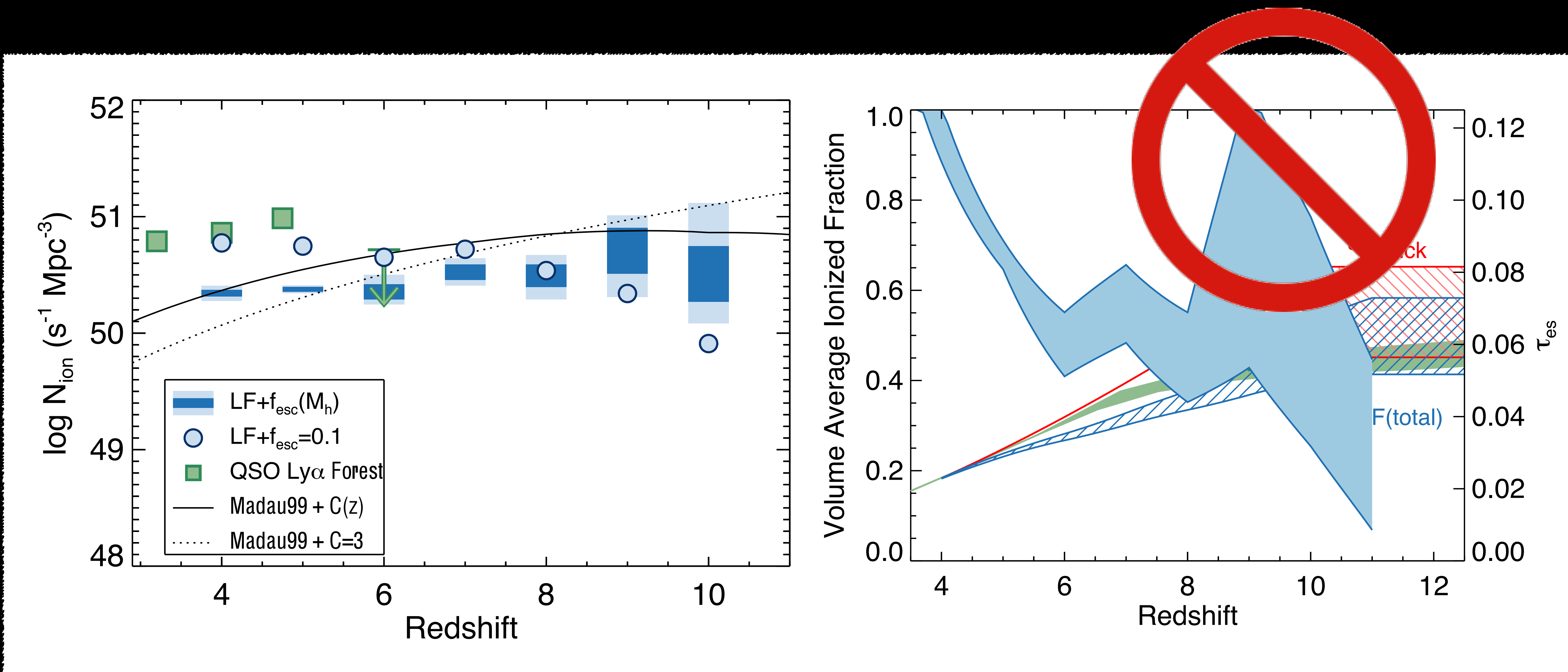


REIONIZING THE UNIVERSE



OPTIONS: 1) CHANGING THE HALO FILTERING MASS

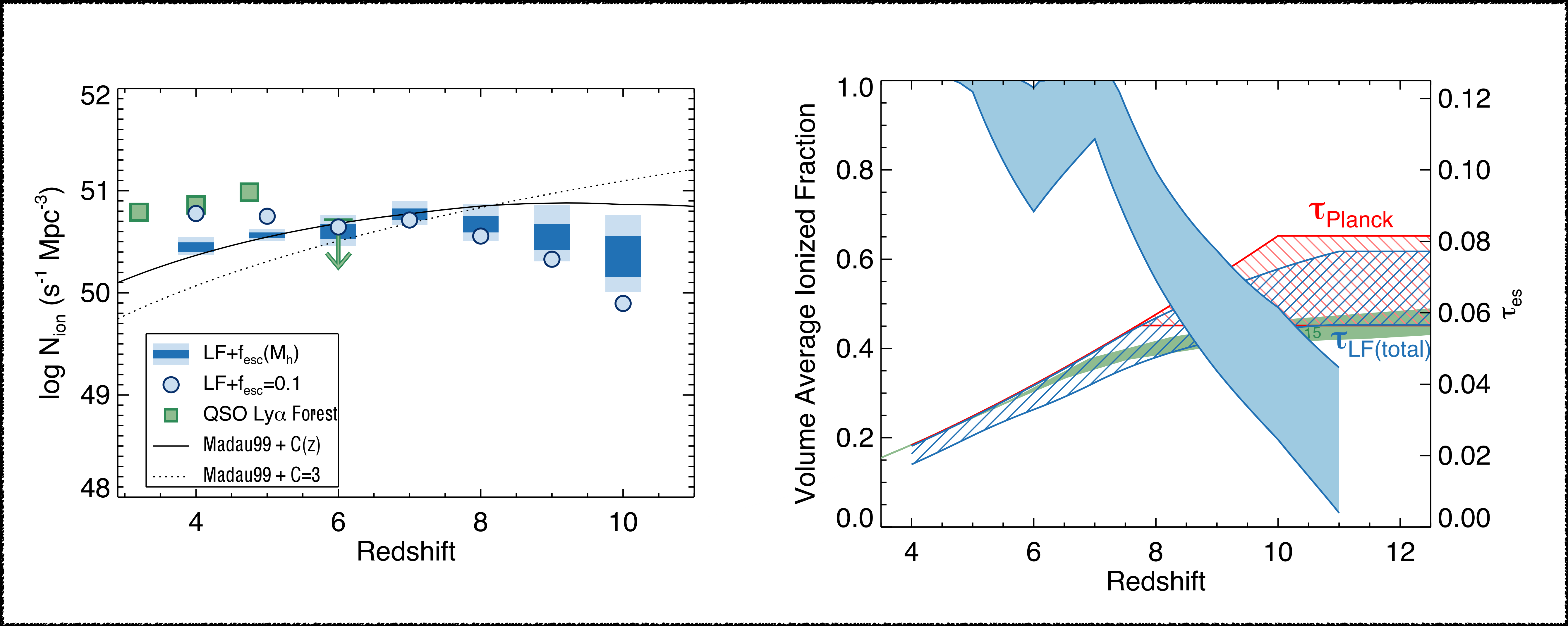
- Before reionization: $M_{h,limit}$=7



OPTIONS: 2) CHANGING THE LYMAN CONTINUUM PRODUCTION EFFICIENCY

- Making it even higher for fainter galaxies: $\log(\xi_{ion})$=26.3 for M_{UV} > -16

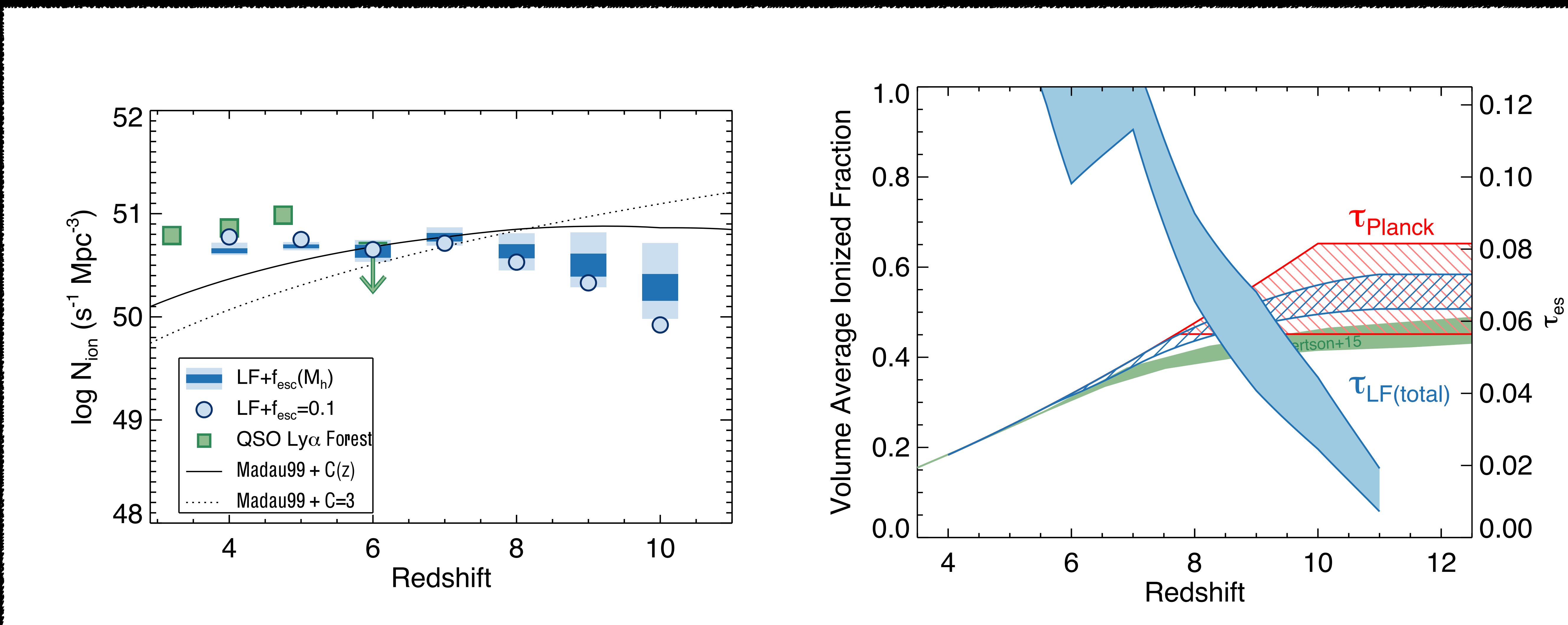
MAYBE? THOUGH IMPLIES ~FULL REIONIZATION AT Z=7



OPTIONS: 3) CHANGING ESCAPE FRACTION

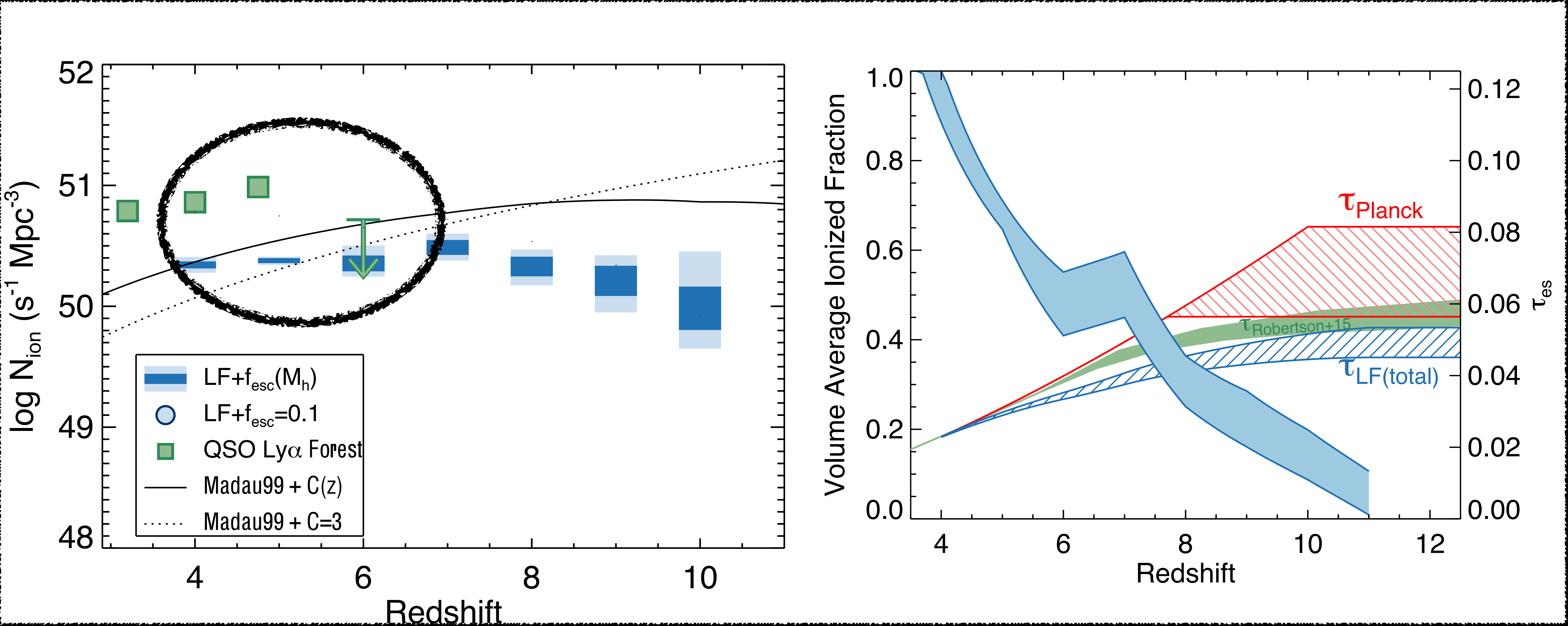
- Simple: Multiply f_{esc} by two.

MAYBE? BUT AGAIN, REIONIZATION FINISHES POSSIBLY TOO EARLY. MAYBE TAU IS TOO HIGH?



OPTIONS: 4) *GULP* AGNS?

- We're missing a factor of ~2 in ionizing emissivity at z~6, and this gets more discrepant compared to the Lya forest at z=5.
- A quasar contribution which decreases with increasing redshift, but is not negligible, could reconcile these tensions.



TAKE AWAY POINTS

- We now have the observational and theoretical insight to do more realistic modeling of the contribution of galaxies to reionization.
  - We now use realistic values for the limiting magnitude, the ionizing emissivity, and the escape fraction.
    - Some/all are dependent on redshift and/or halo mass.
  - We find a global ionizing escape fraction of ~2% over the entire population.
  - This ***cannot*** on its own complete reionization by z=6.
    - Knobs can be turned to rectify this, though some (limiting halo mass) reionize too much volume too early.
  - **Solutions: Higher ionizing photon production, higher f_{esc}, or AGNs.**