The galaxies that reionised the Universe have already been seen

Tom Theuns
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Sharma, Frenk, Schaye, Crain, Bower, Schaller, Furlong

Quick reminder of what came before:

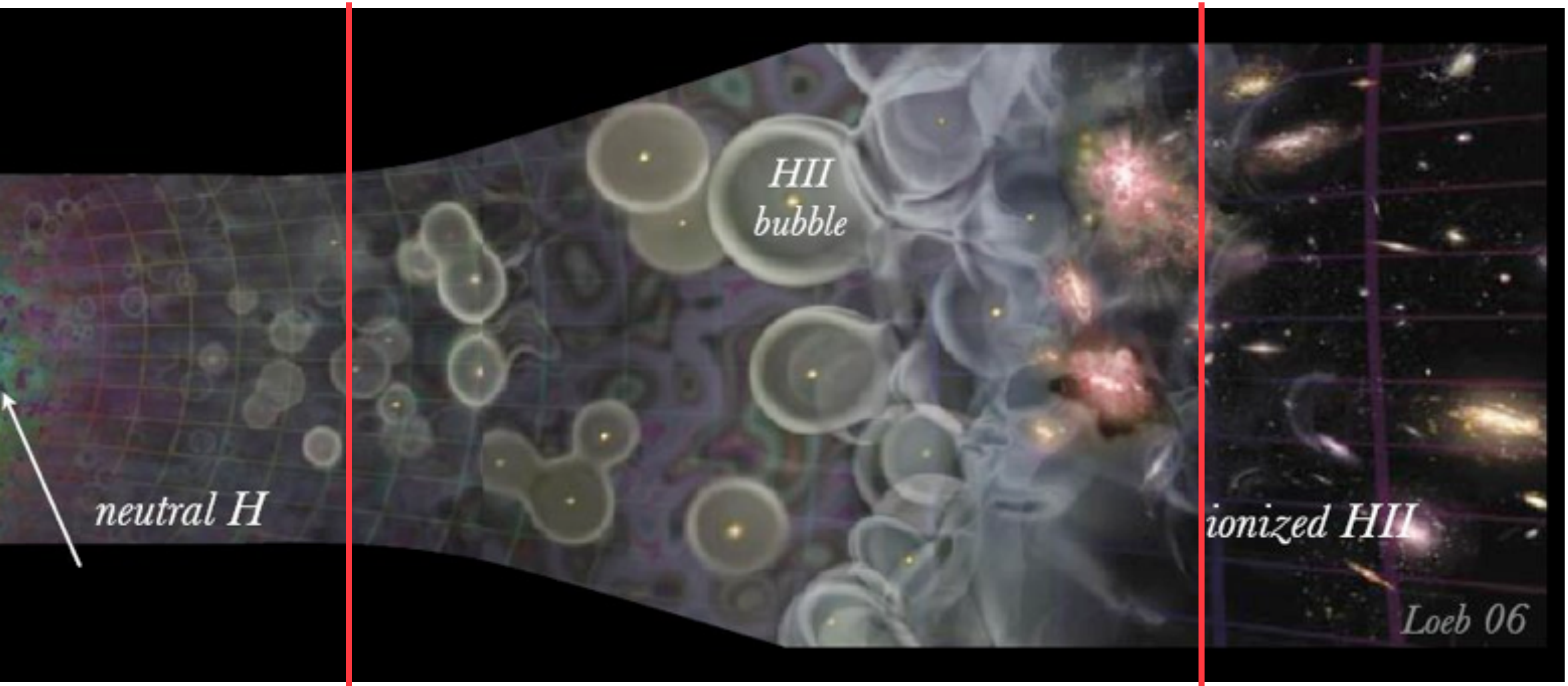
- Robertson: $Q_{II}(z)$, nebular emission lines at high z
- Ellis: Planck v WMAP, physics from JWST spectra
- Zackrisson: use nebular lines to get f_{esc}
- Windhorst: f_{esc} = tanh(log(1+z))
- Bunker: reionization by faint galaxies

My take-away message:

- escape fraction high in observed HST galaxies
- these dominate the emissivity

IGM neutral

IGM highly ionised
(with neutral DLAs)

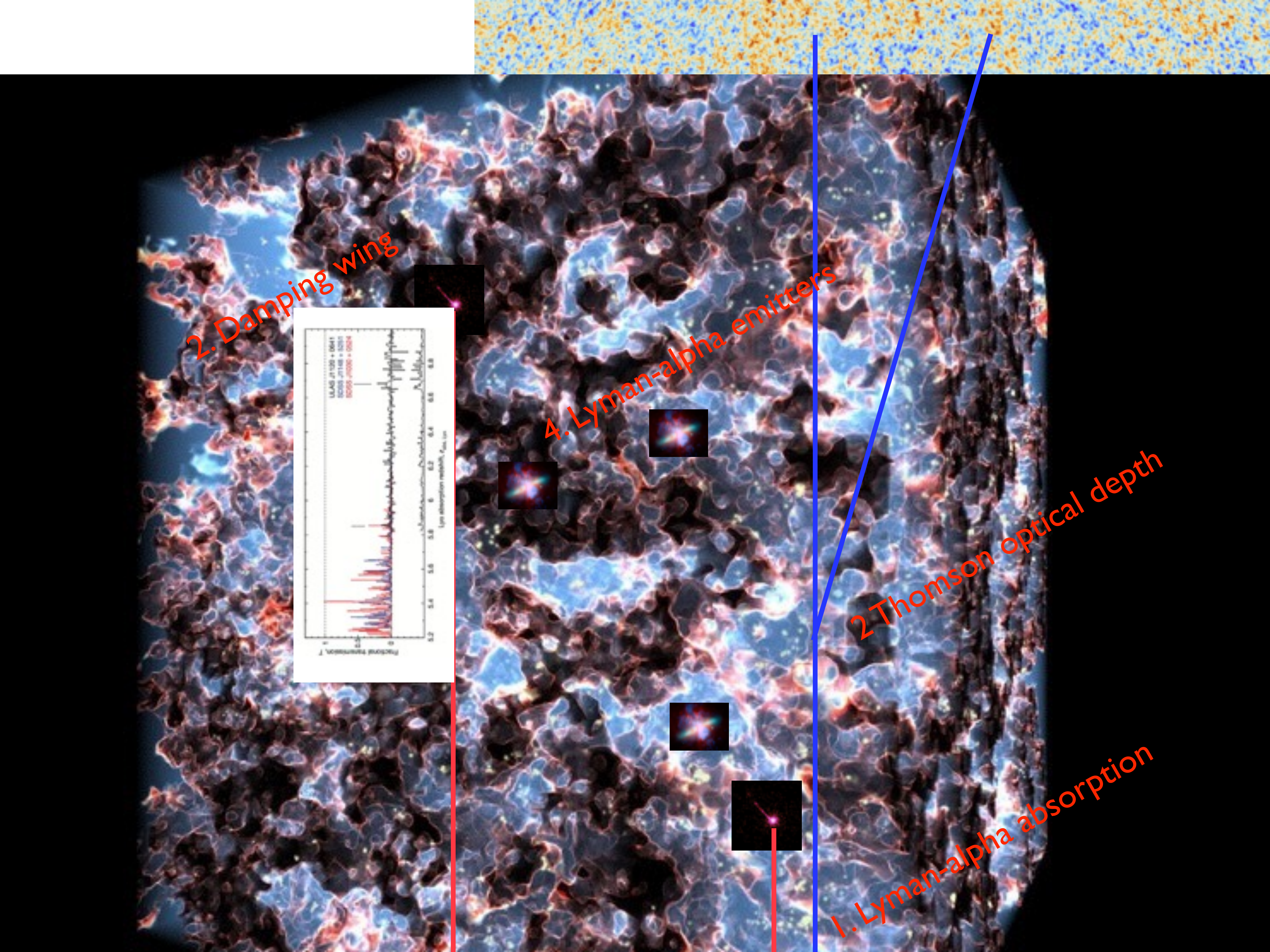


z > 12

epoch of reionisation

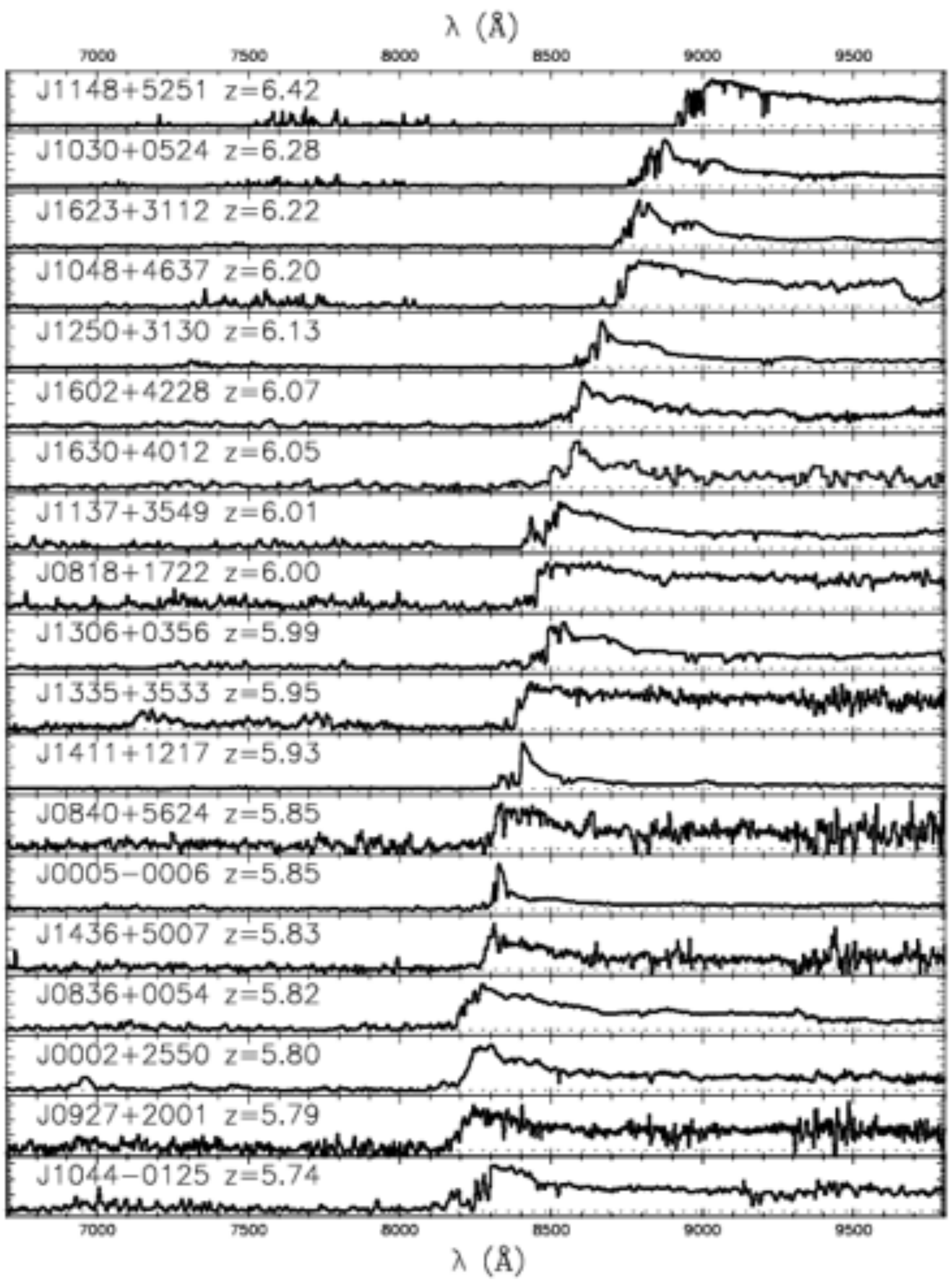
z<5

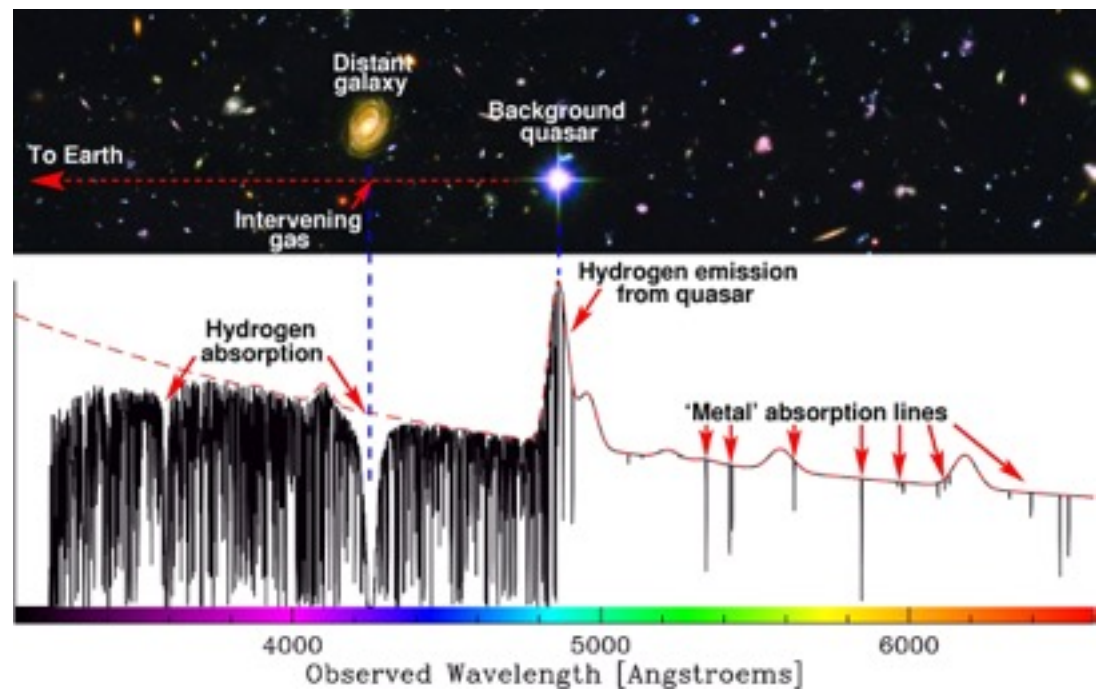
Abel, Wise, Kaehler


2. Damping wing
4. Lyman-alpha emitters
2 Thomson optical depth
1. Lyman-alpha absorption

Observational constraints:

1: Lya optical depth

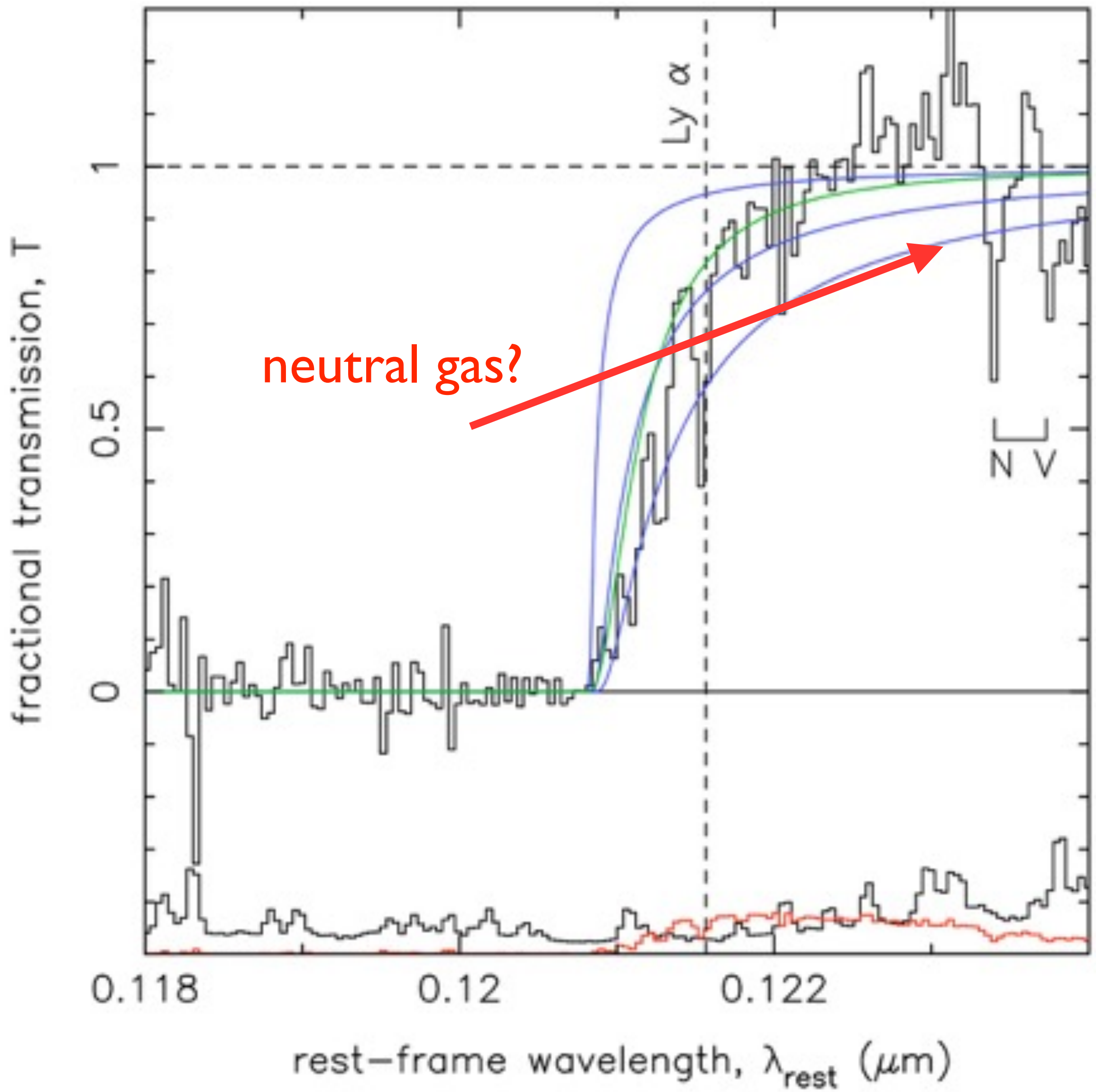




Fan+01, 06

2: Damping wings

Miralda-Escude '98



Mortlock +11

3: Thomson optical depth

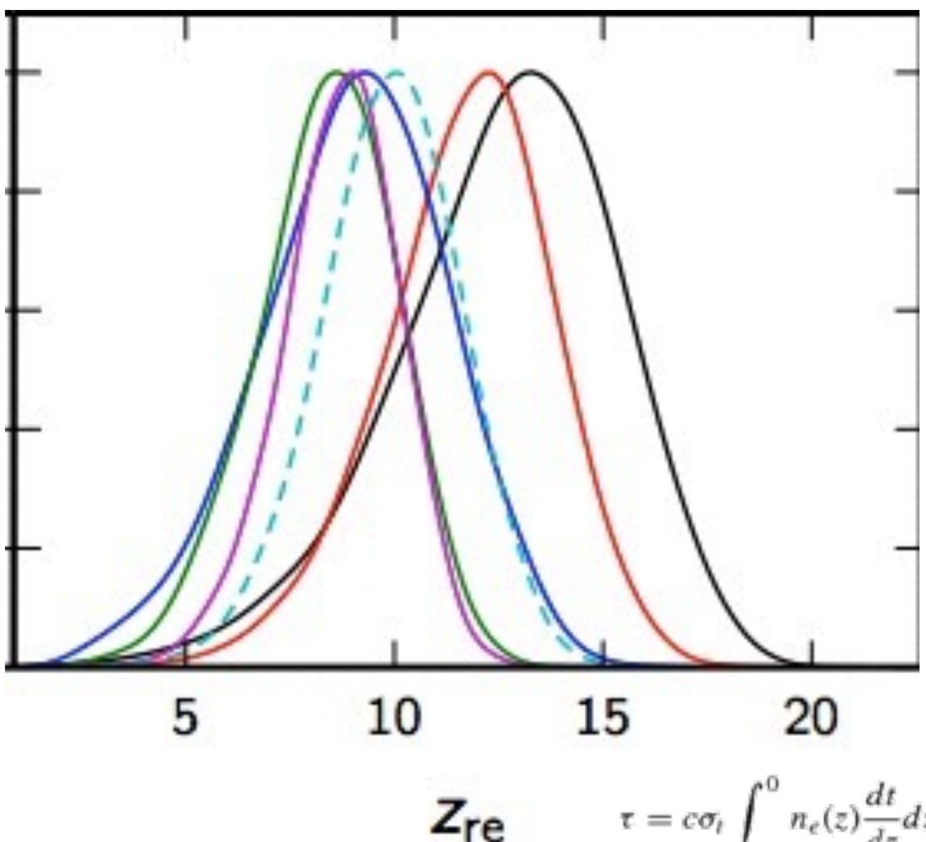
$$\tau = 0.078^{+0.019}_{-0.019},\ z_{\rm re} = 9.9^{+1.8}_{-1.6},\ \textit{Planck}\ \text{TT+lowP}; \tag{17a}$$

$$\tau = 0.070^{+0.024}_{-0.024},\ z_{\rm re} = 9.0^{+2.5}_{-2.1},\ \textit{Planck}\ \text{TT+lensing}; \tag{17b}$$

$$\tau = 0.066^{+0.016}_{-0.016},\ z_{\rm re} = 8.8^{+1.7}_{-1.4},\ \textit{Planck}\ \text{TT+lowP+lensing}; \tag{17c}$$

$$\tau = 0.067^{+0.016}_{-0.016},\ z_{\rm re} = 8.9^{+1.7}_{-1.4},\ \textit{Planck}\ \text{TT+lensing+BAO}; \tag{17d}$$

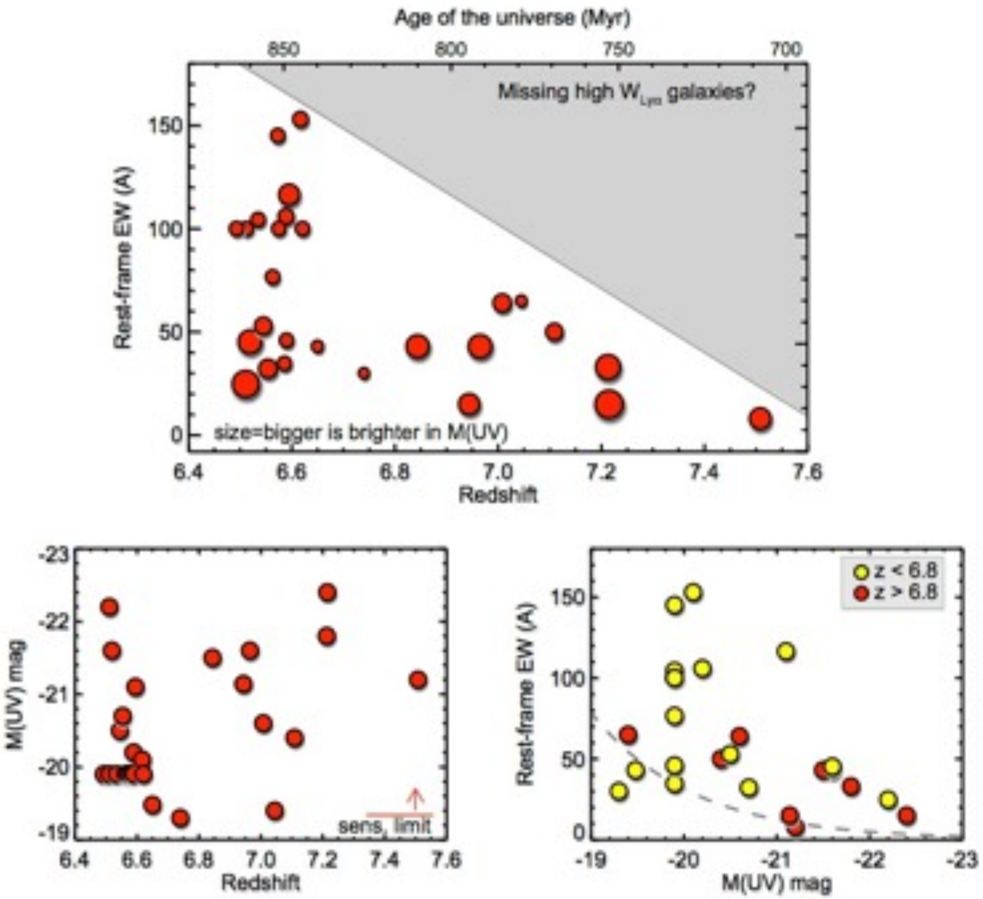
$$\tau = 0.066^{+0.013}_{-0.013},\ z_{\rm re} = 8.8^{+1.3}_{-1.2},\ \textit{Planck}\ \text{TT+lowP+lensing+BAO}. \tag{17e}$$

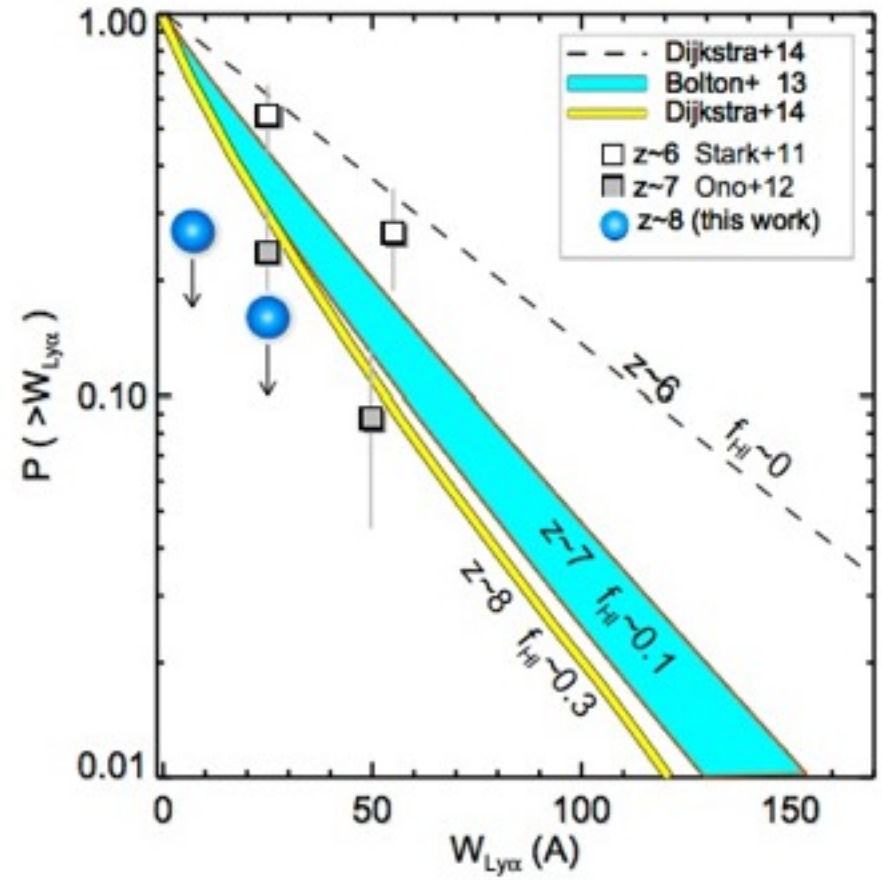


$$\tau = c\sigma_t \int_{z_{\rm rec}}^{0} n_e(z)\frac{dt}{dz}dz, \tag{10}$$

4: Fraction of galaxies detectable in Lya emission

Stark+10, Caruana+12, Tilvi+14

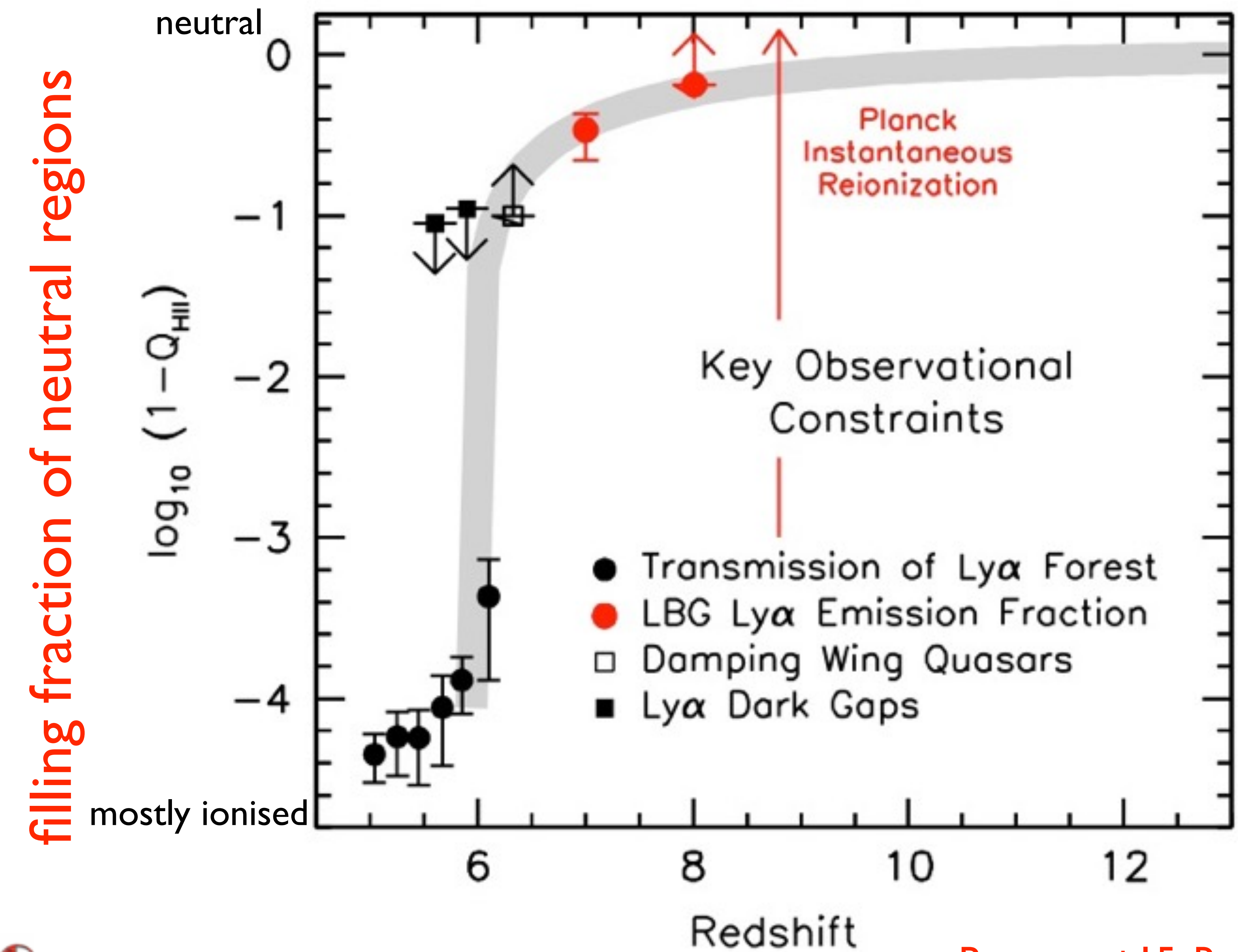




Tilvi +14

Observational constraints: summary

Bouwens+15



Bouwens+15, Robertson+15

Theoretical description

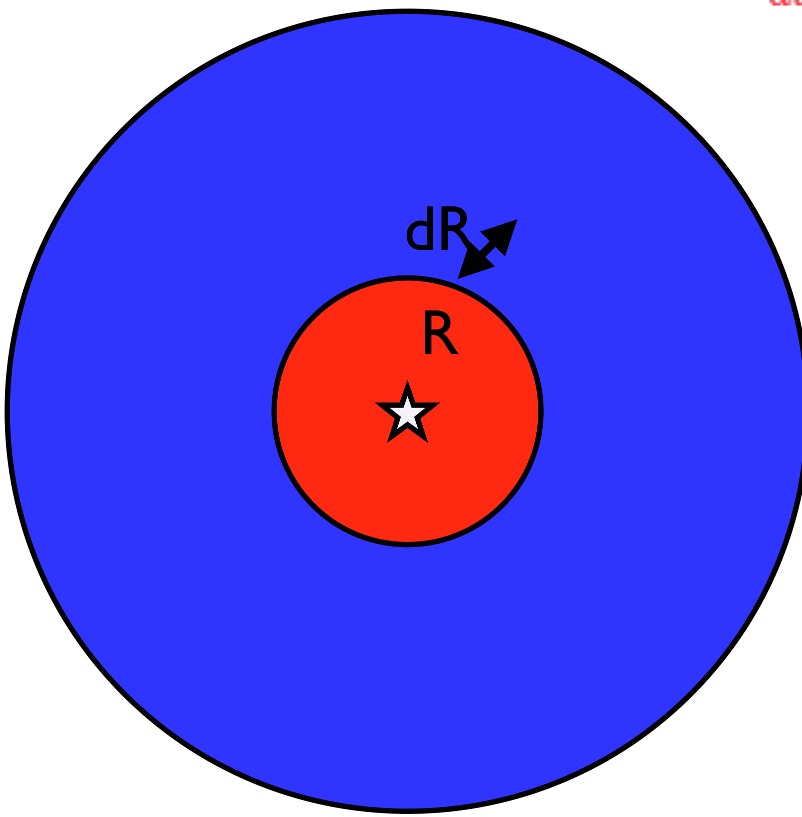
Before reionisation:

Increase in volume of an HII region

$$\dot{N}_\gamma \, dt = 4\pi R^2 \, n_H \, dR + \alpha n_H^2 \, \frac{4\pi}{3} \, dt$$

$$\langle \frac{dn_{\rm H}}{dt} \rangle = -\alpha \langle n_{\rm H}^2 \rangle$$

$$Q \equiv \frac{R^3}{R_0^3}$$



Evolution of volume-filling factor

$$\frac{dQ}{dt} = \frac{\dot{n}_\gamma}{n_{\rm H}} - \alpha \frac{\langle n_{\rm H}^2 \rangle}{n_{\rm H}} Q$$

sources

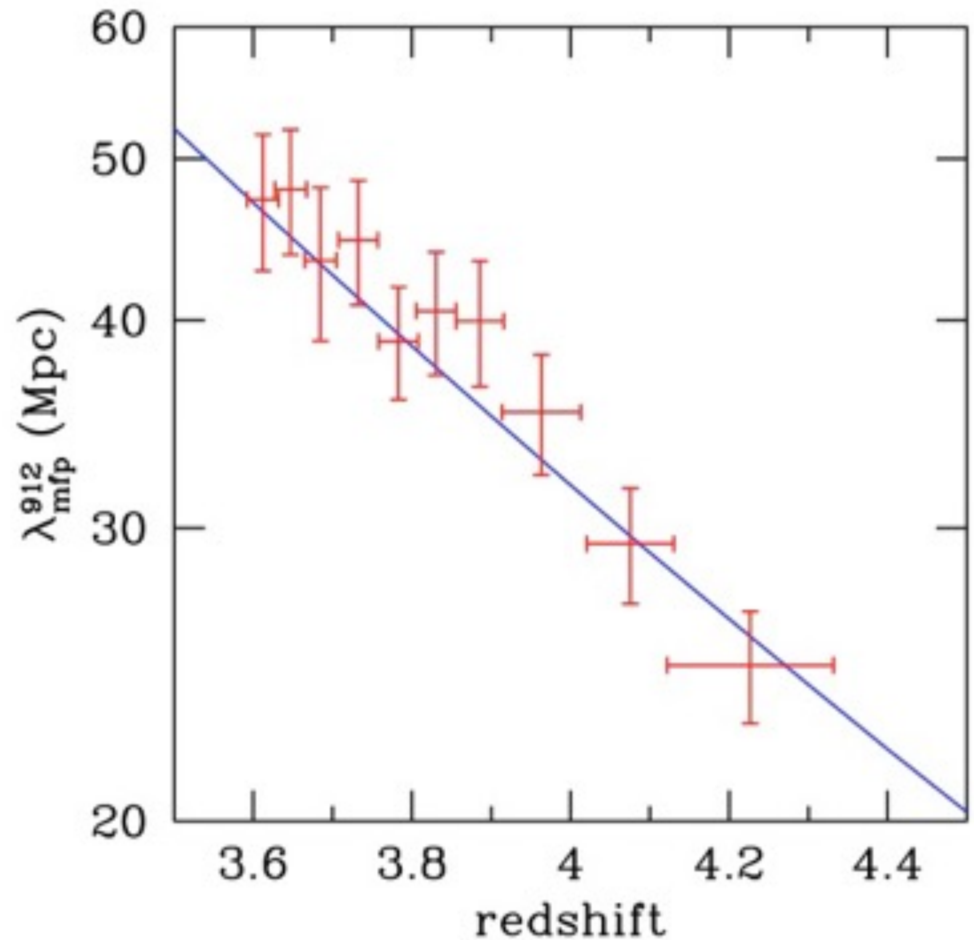
sinks

After reionisation:

$$n_{\rm HI} \approx \frac{\alpha}{\Gamma} n_{\rm H}^2 \propto (1+z)^6$$

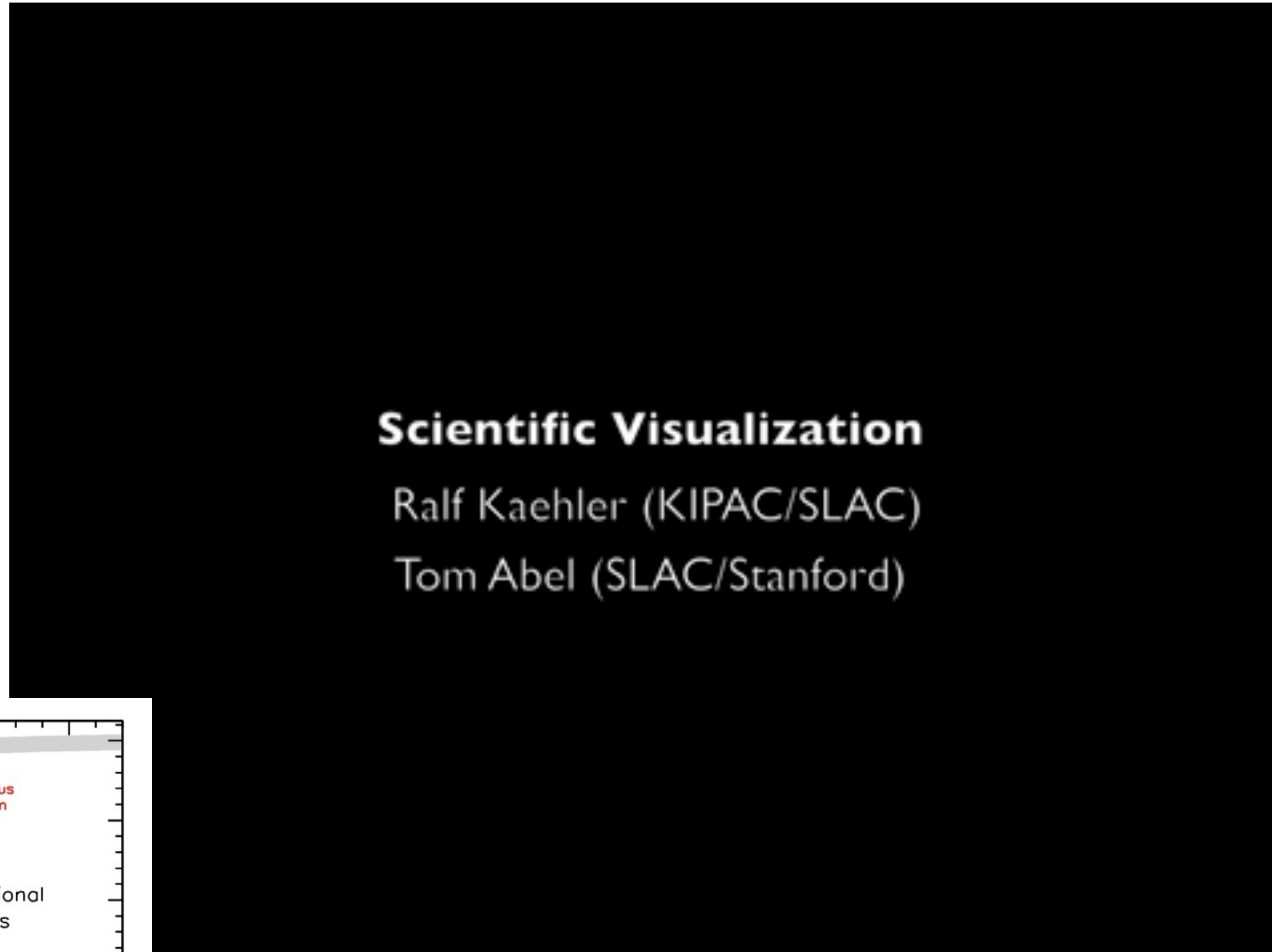
$$\tau_{\rm eff} \propto n_{\rm HI} \propto \frac{1}{\Gamma}$$

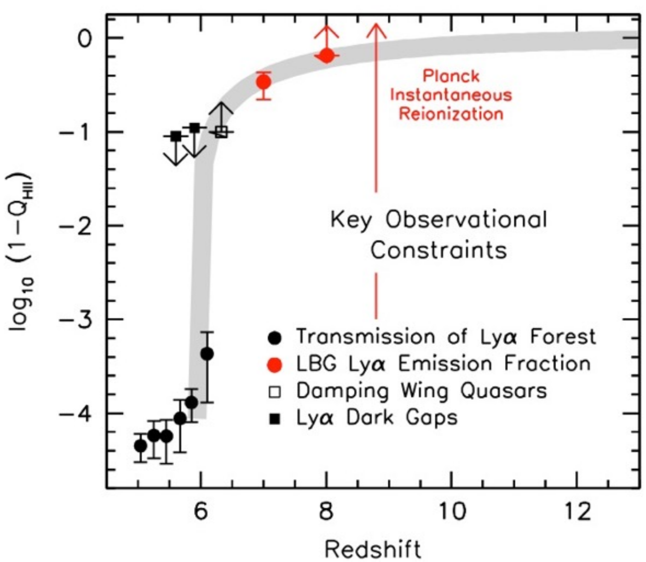
$$\Gamma \approx \dot{n}_\gamma \, (\lambda_{\rm mfp}^{912})^3$$



Haardt & Madau12

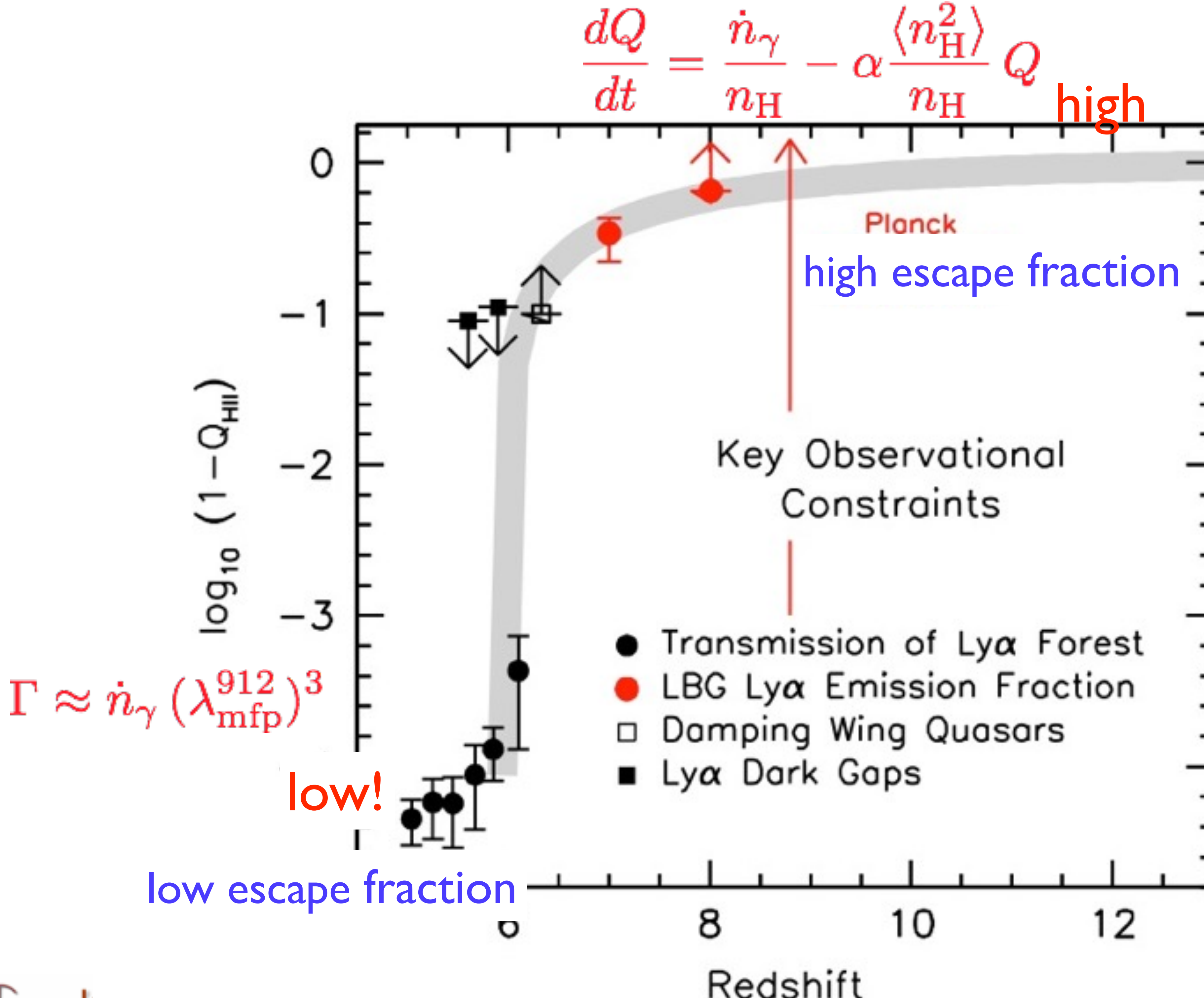
Are galaxies the dominant source of ionising photons?





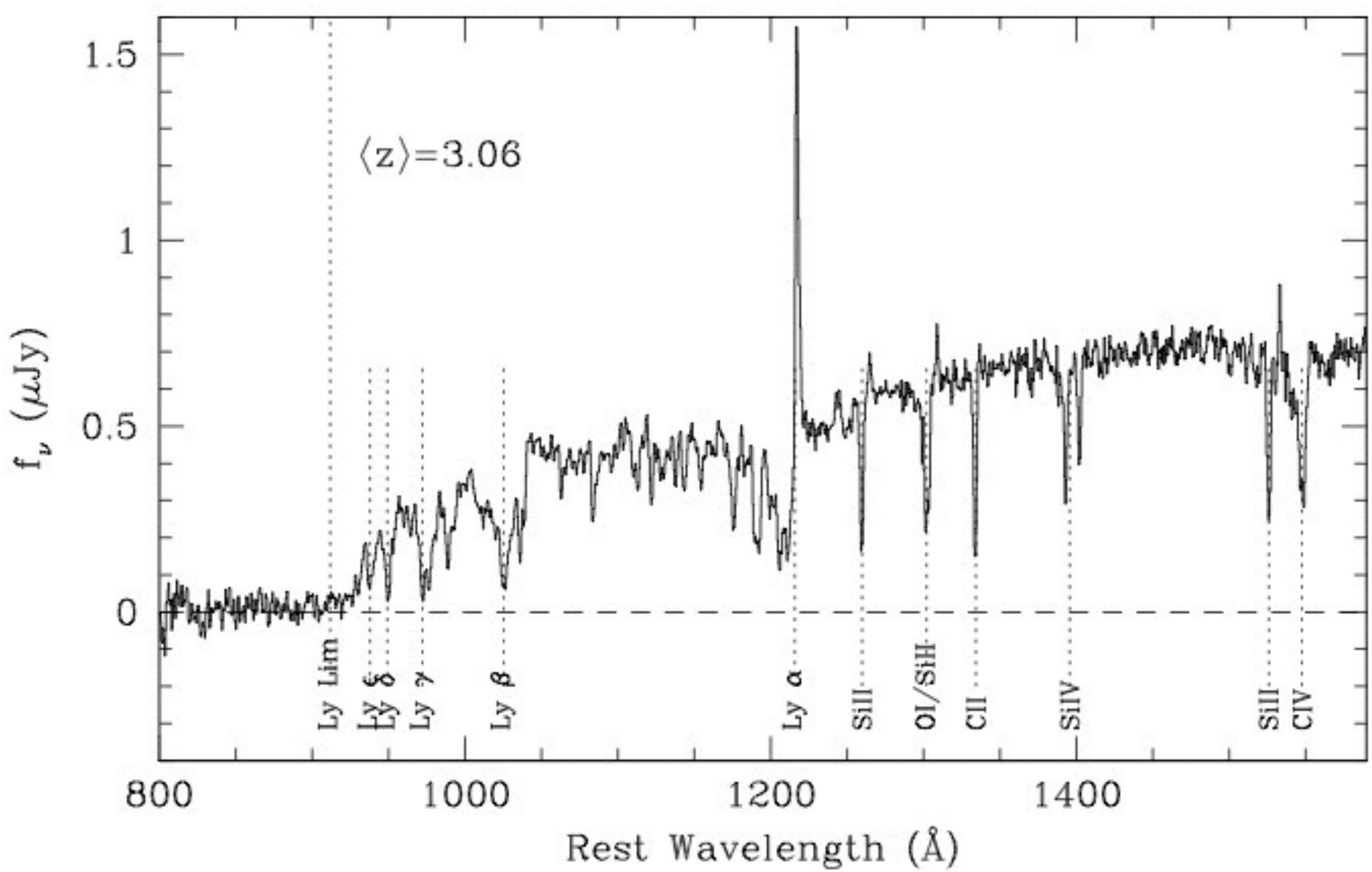
al Cosmology

Abel, Wise, Kaehler



$$\frac{dQ}{dt} = \frac{\dot{n}_\gamma}{n_H} - \alpha \frac{\langle n_H^2 \rangle}{n_H} Q$$
high
Planck
high escape fraction
Key Observational Constraints
Transmission of Lyα Forest
LBG Lyα Emission Fraction
Damping Wing Quasars
Lyα Dark Gaps
$\log_{10}(1-Q_{HII})$
0
−1
−2
−3
$$\Gamma \approx \dot{n}_\gamma \, (\lambda_{mfp}^{912})^3$$
low!
low escape fraction
8
10
12
Redshift

Escape fraction of ionising photons (LBGs at z=3)



relative escape fraction of order 10 %

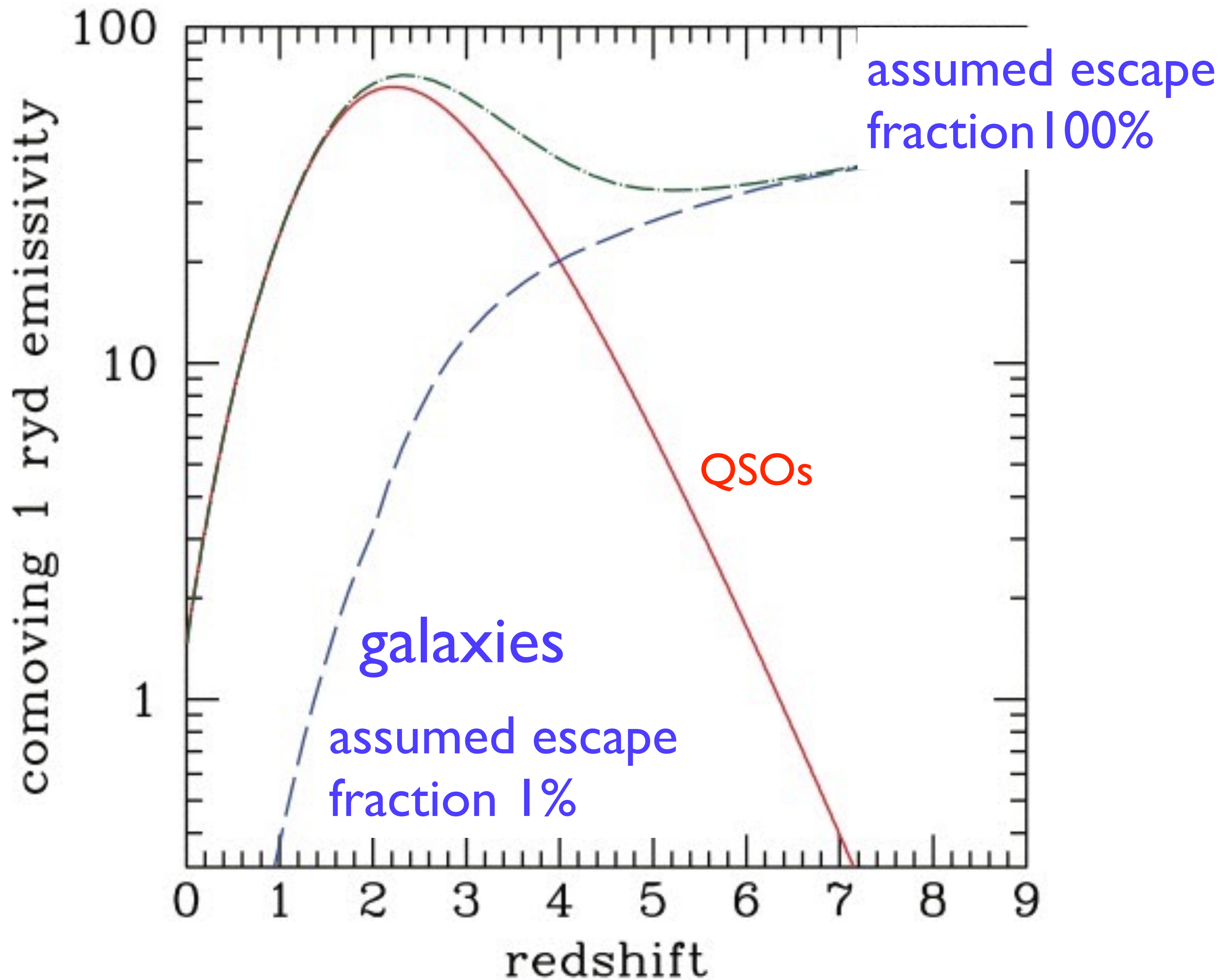
Shapley+06

Absolute escape fractions

Table 1
Compilation of Observed UV to LC Flux Ratios $(f_{1500}/f_{900})_{\rm obs}$ and Escape Fractions of LBGs at $z \sim 3$

Reference	Sample	$(f_{1500}/f_{900})_{\rm obs}$	$(f_{1500}/f_{900})_{\rm int}$[a]	$f_{\rm esc,rel}$	$f_{\rm esc}$
Steidel et al. (2001)	29 LBGs, Average	17.7 ± 3.8	3.0	0.31	
Shapley et al. (2006)	2 LBGs, Direct	12.7 ± 1.8, 7.5 ± 1.0	3.0	0.43, 0.72	
Shapley et al. (2006)	14 LBGs, Average	58 ± 25	3.0	0.094	
This work	7 LBGs, Direct	6.6 (median)	3.0	0.46[b]	0.11[c]
This work	7 LBGs, Direct	6.6 (median)	3.0	0.83[d]	0.20[c]
This work	7 LBGs, Direct	6.6 (median)	1.07	0.16[b]	0.04[c]
This work	7 LBGs, Direct	6.6 (median)	1.07	0.30[d]	0.07[c]

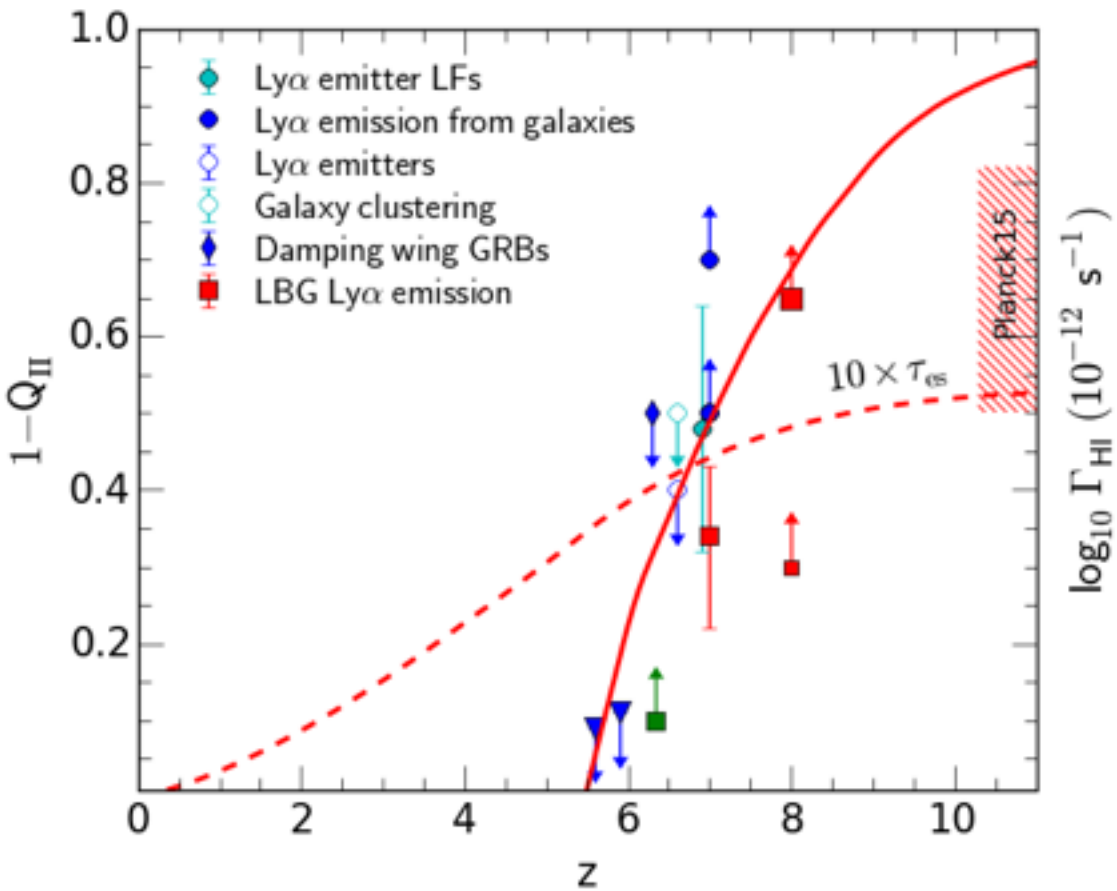
Iwata+09



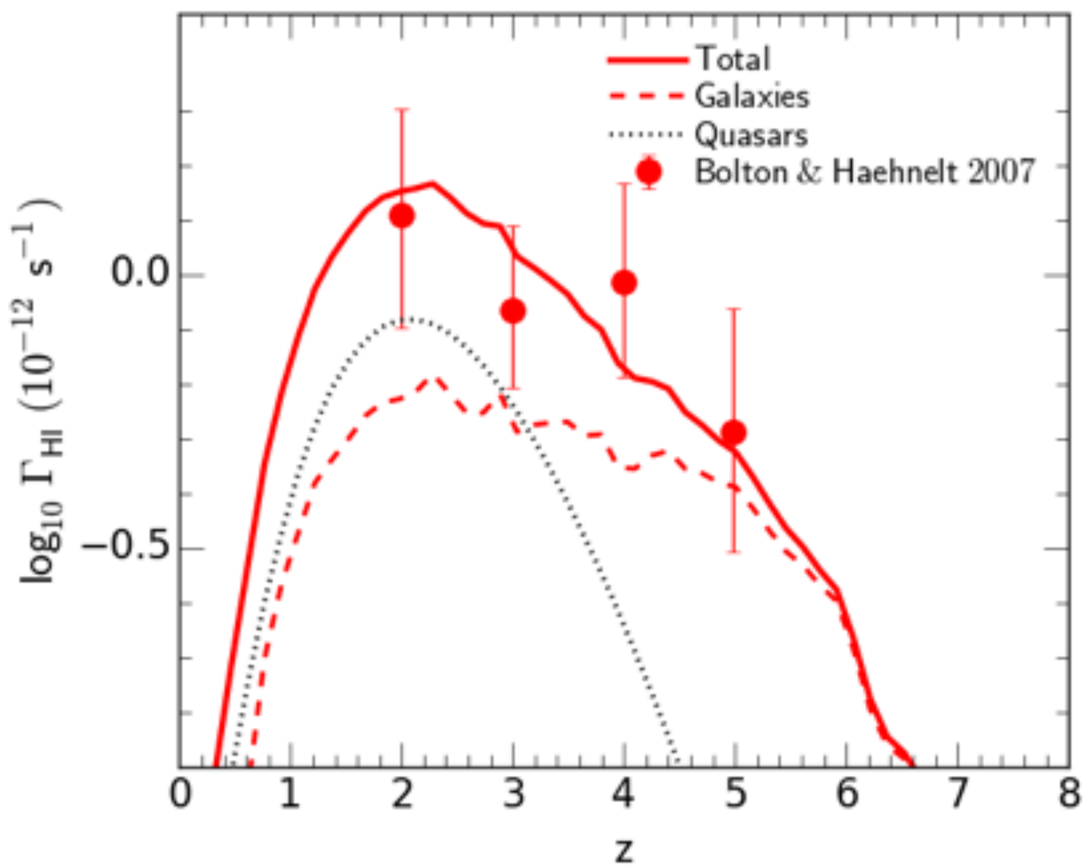
Haardt & Madau 12

Theoretical challenge:

- can we find a local property of galaxies that yields high escape fraction of UV-photons at high-z, and a low escape fraction at low z
- does this yield realistic reionisation redshift as well as a realistic amplitude of the UV-background after reionisation?



Constraints on reionisation



Constraints after reionisation

The EAGLE project: Simulating the evolution and assembly of galaxies and their environments

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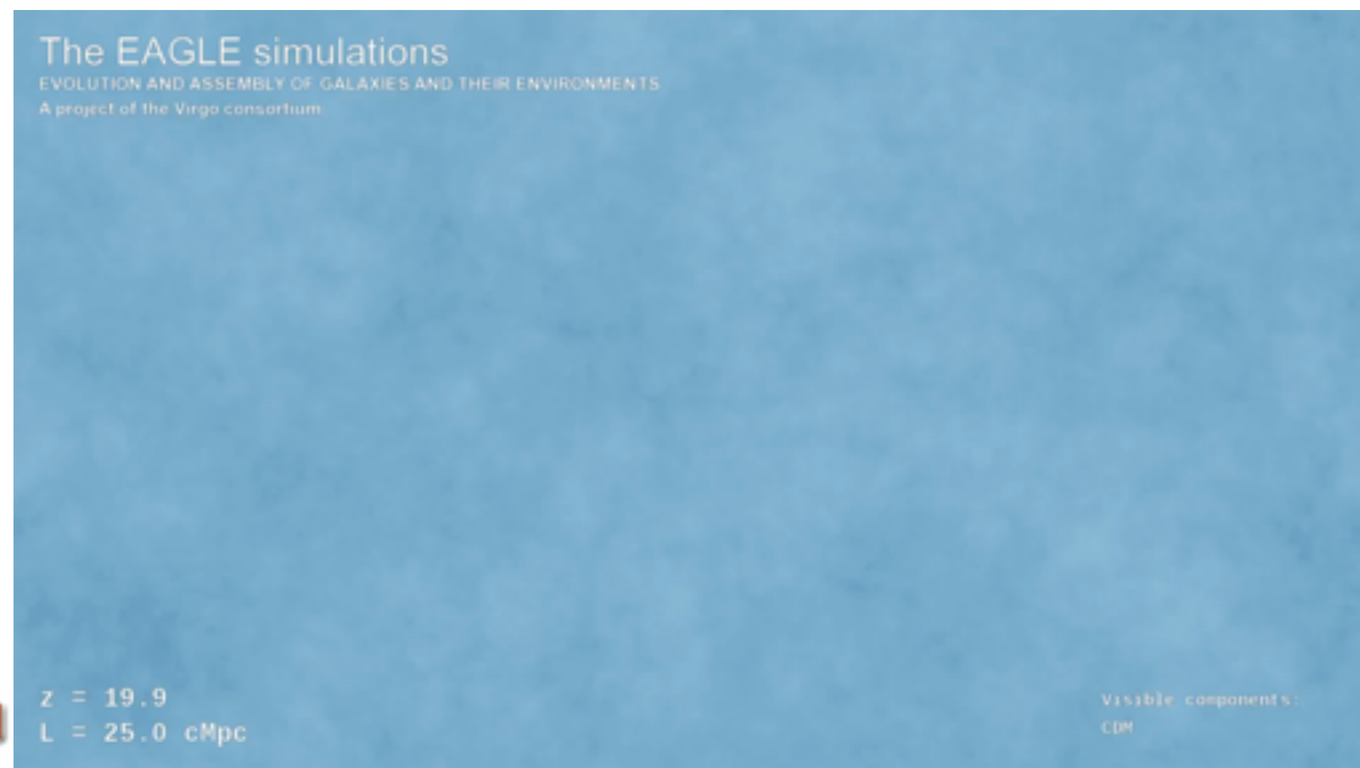
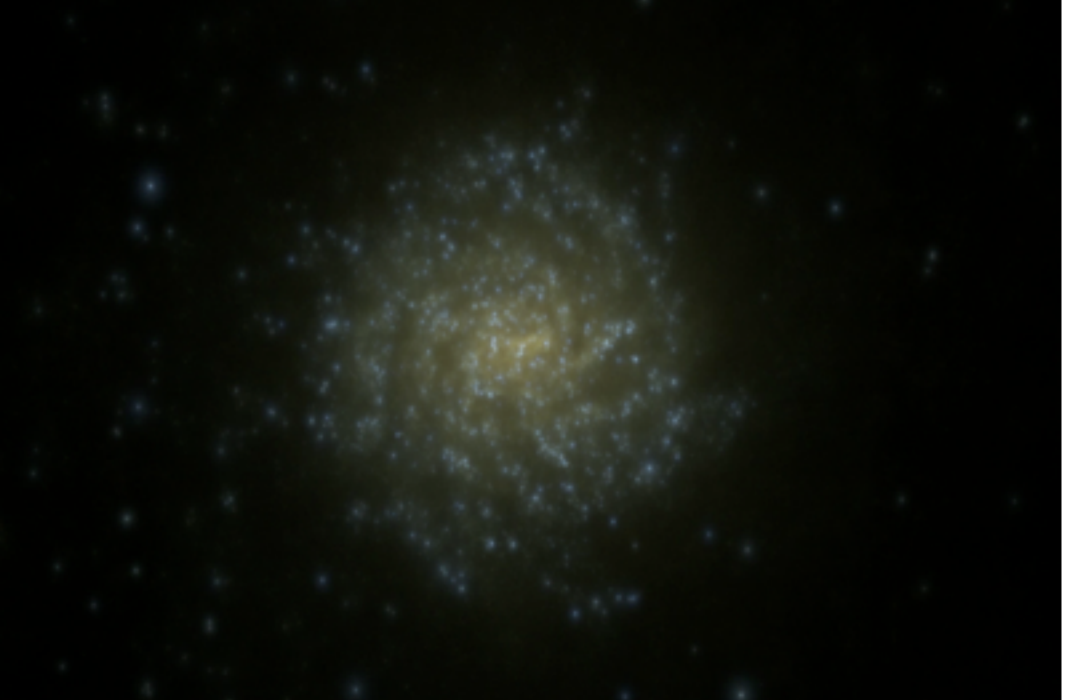
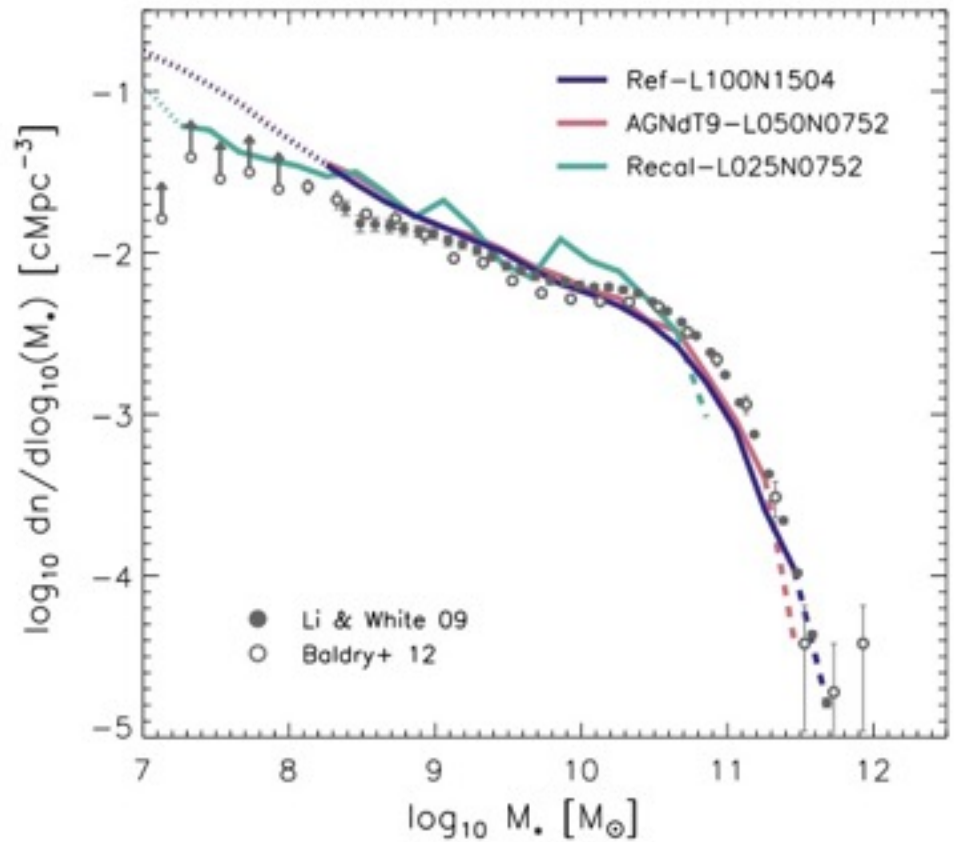
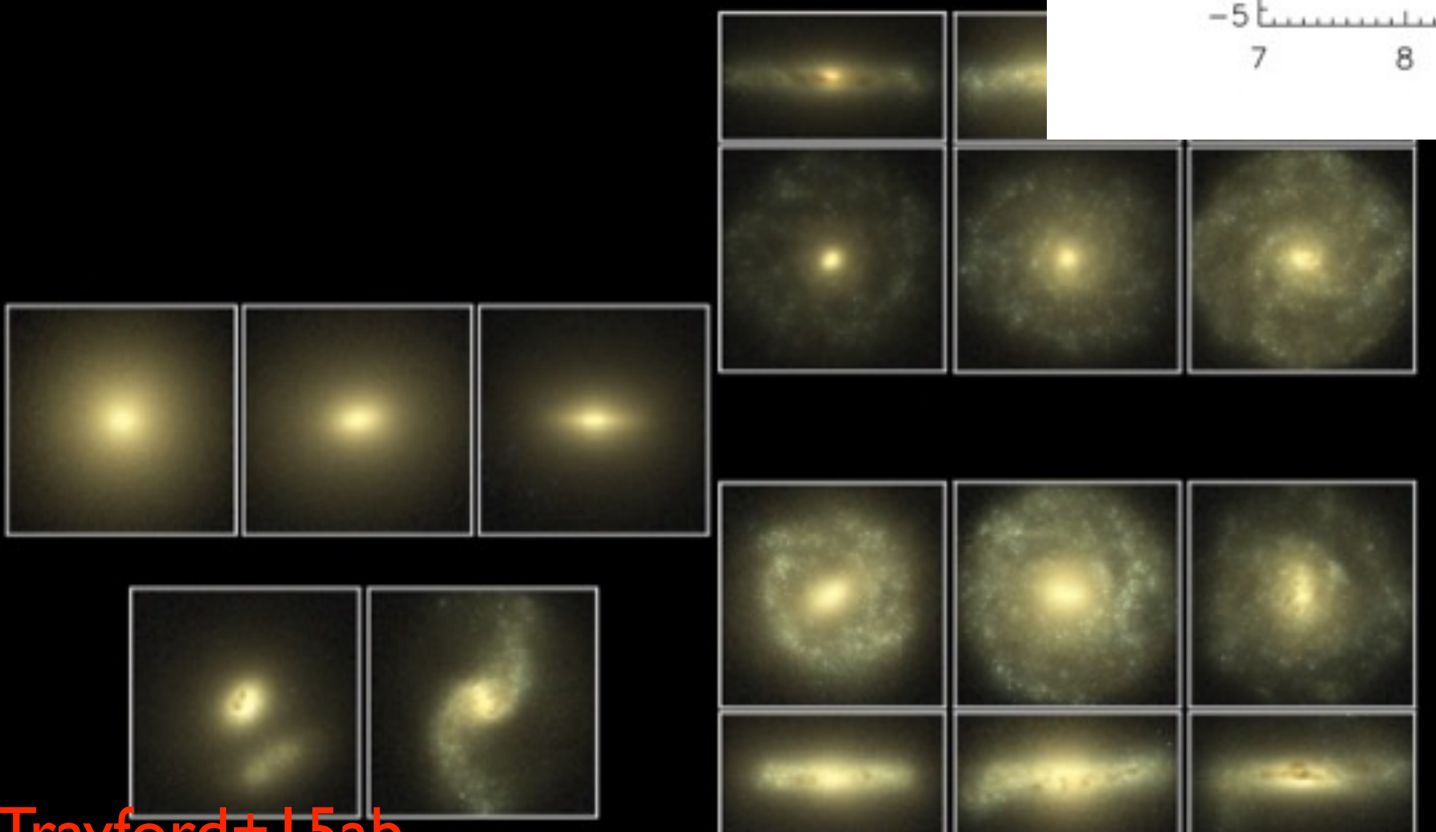
[1] Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, the Netherlands

- 1504^3 Gadget 3 simulation
- $(100\ \mathrm{Mpc})^3$ volume
- baryonic mass $10^6\ M_{sun}$
- Calibrated to stellar MF
- Local physics









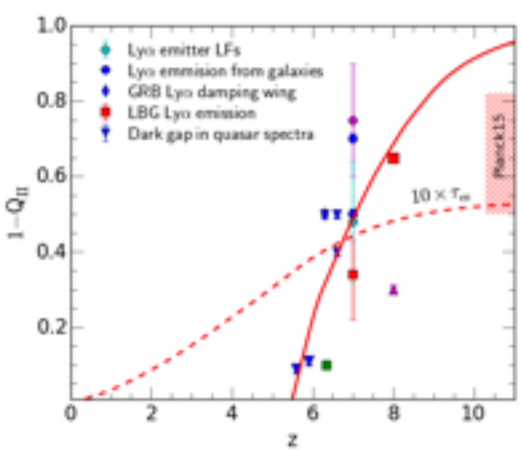
Trayford+15ab

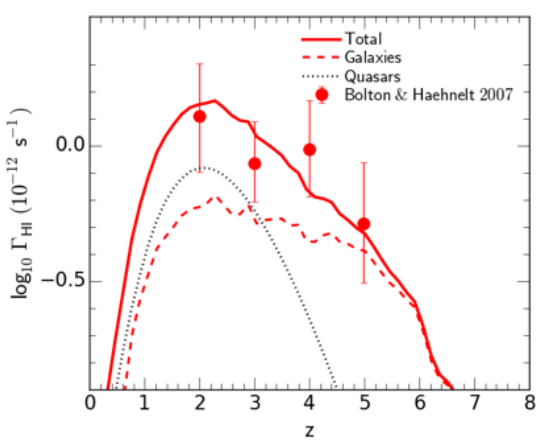
Schaye +14

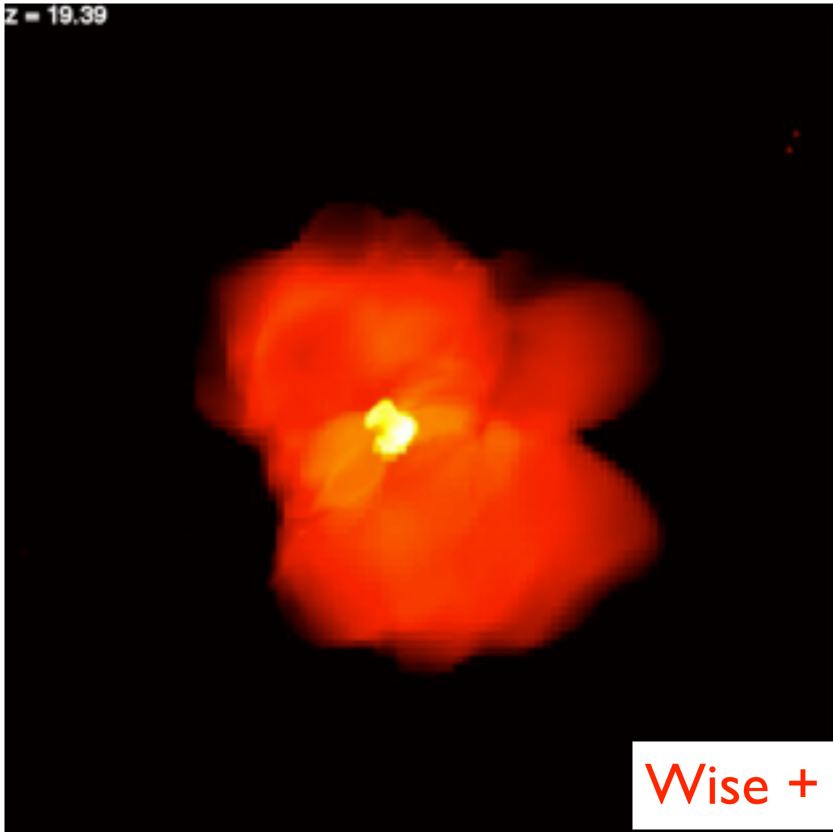
Theoretical challenge:

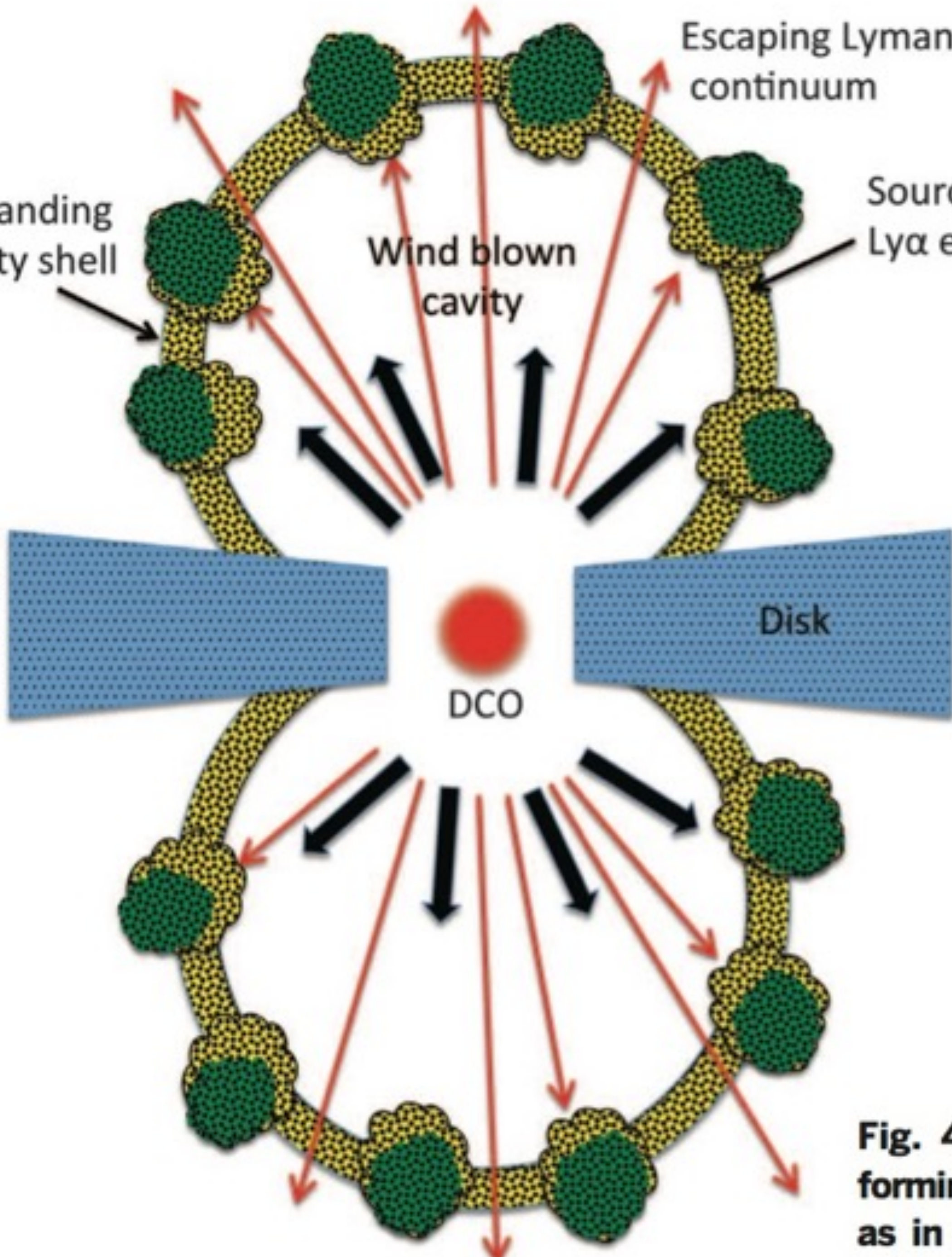
- can we find a local property of galaxies that yields high escape fraction of UV-photons at high-z, and a low escape fraction at low z
- does this yield realistic reionisation redshift, and amplitude of the UV-background?

Assumption: escape fraction depends on star formation surface density









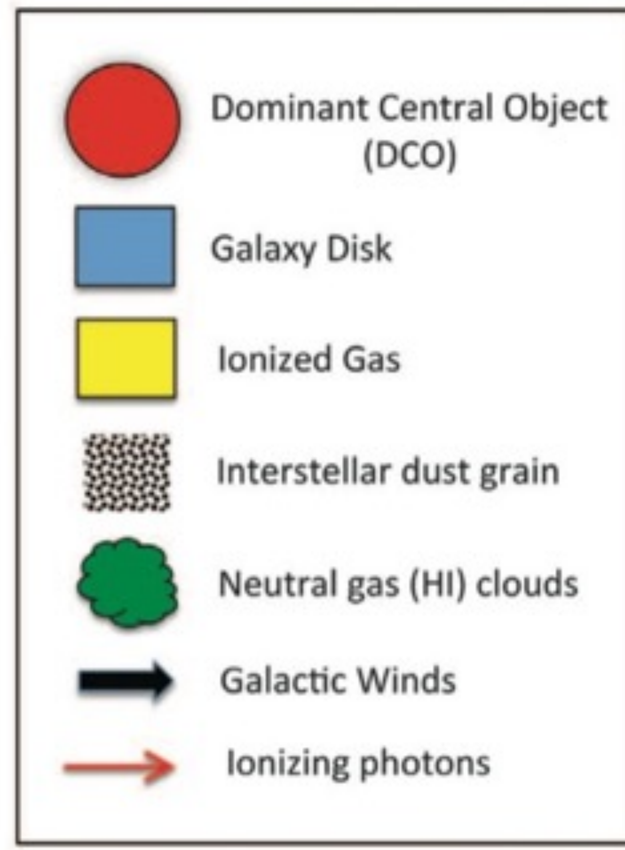
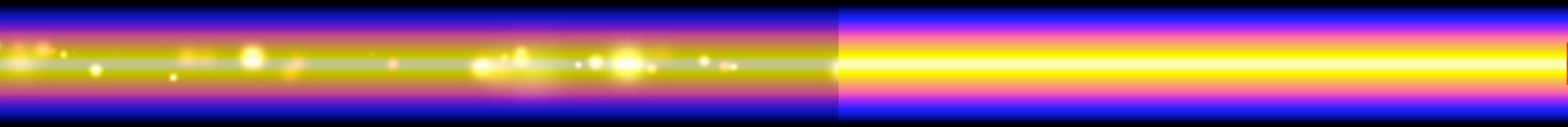


Fig. 4. Schematic diagram of the star-forming region associated with a DCO, such as in J0921+4509. The extreme conditions in the DCO generate a strong galactic wind

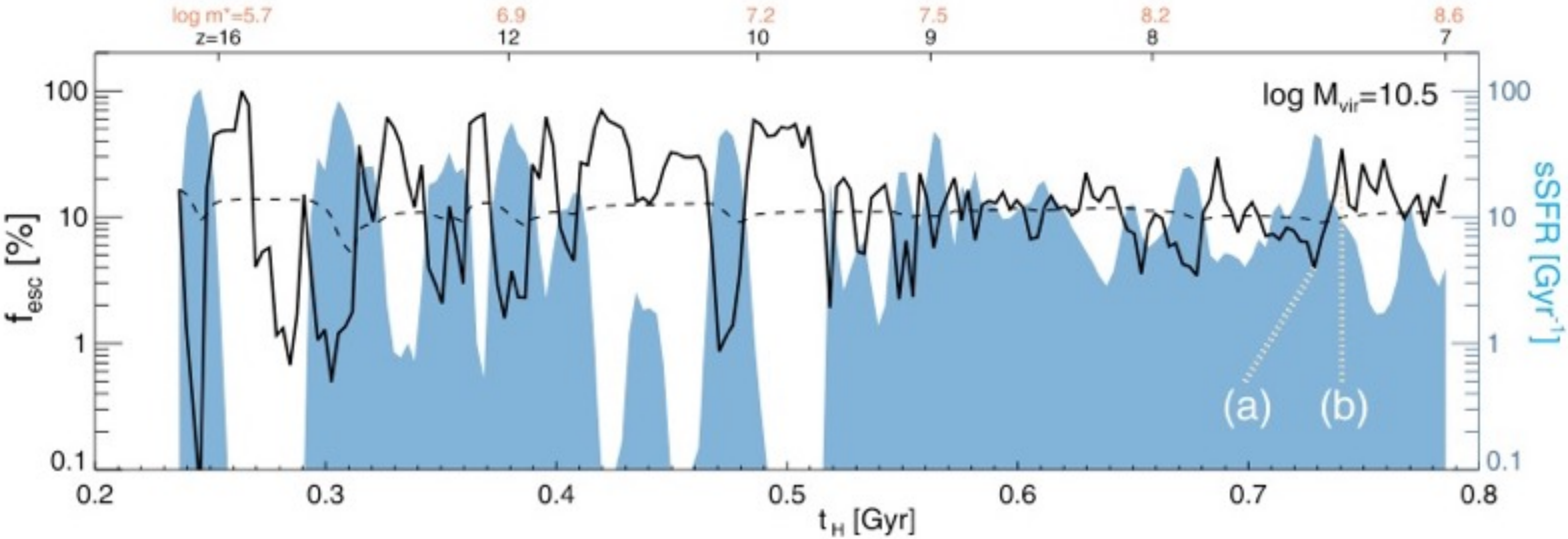
Borthakur+14

Kennicutt

Kennicutt * 10



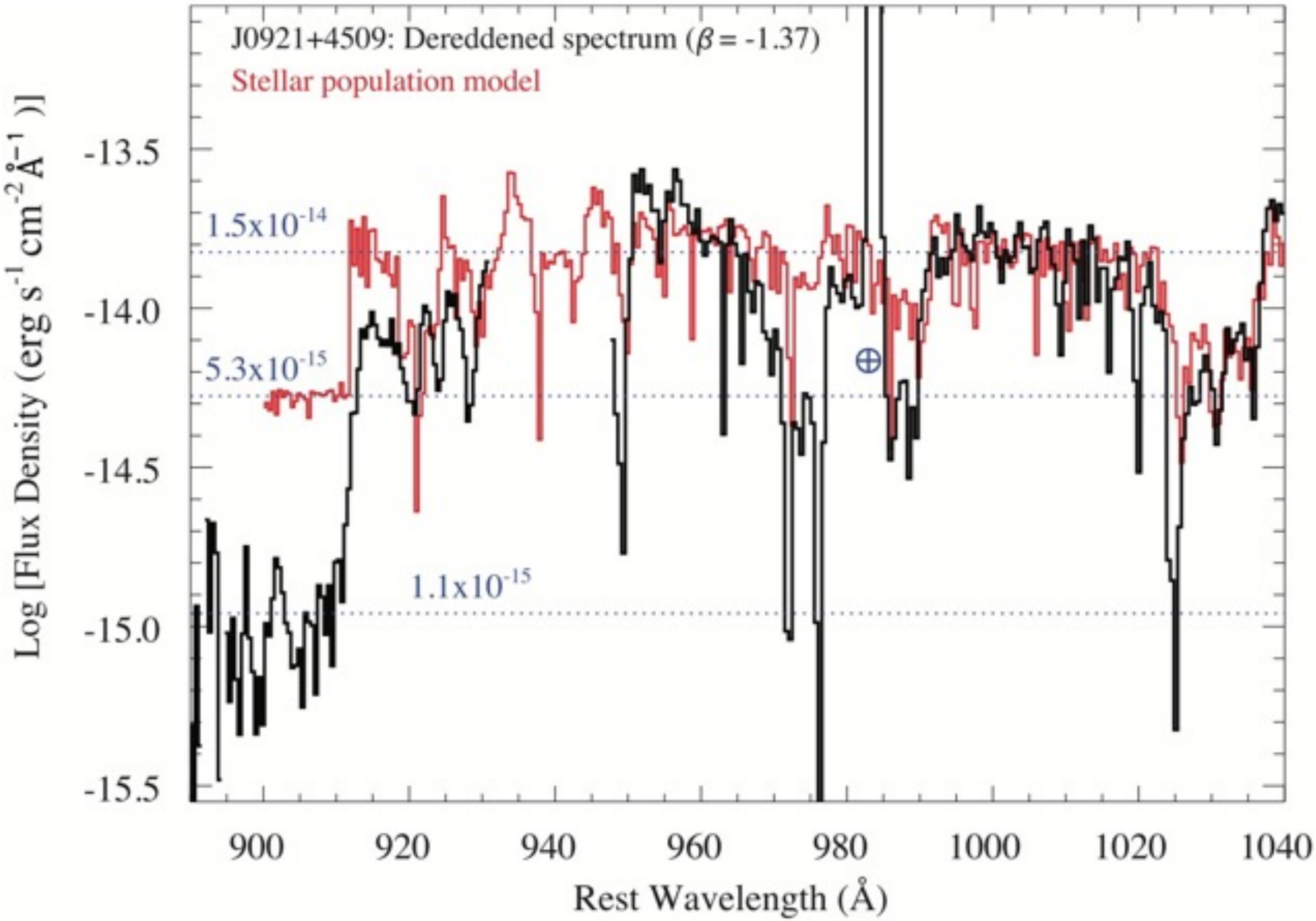
Predicted escape fractions from simulations:



Kimm & Cen 14

- Kimm & Cen (14): 10-20 %
- Paardekooper (+15): f_{esc} = 1-3 %, decreases with M_*
- Ma (+15): 5 %, independent of M_*, z

20 % escape fraction at z=0!



Borthakur+14

Theoretical challenge:

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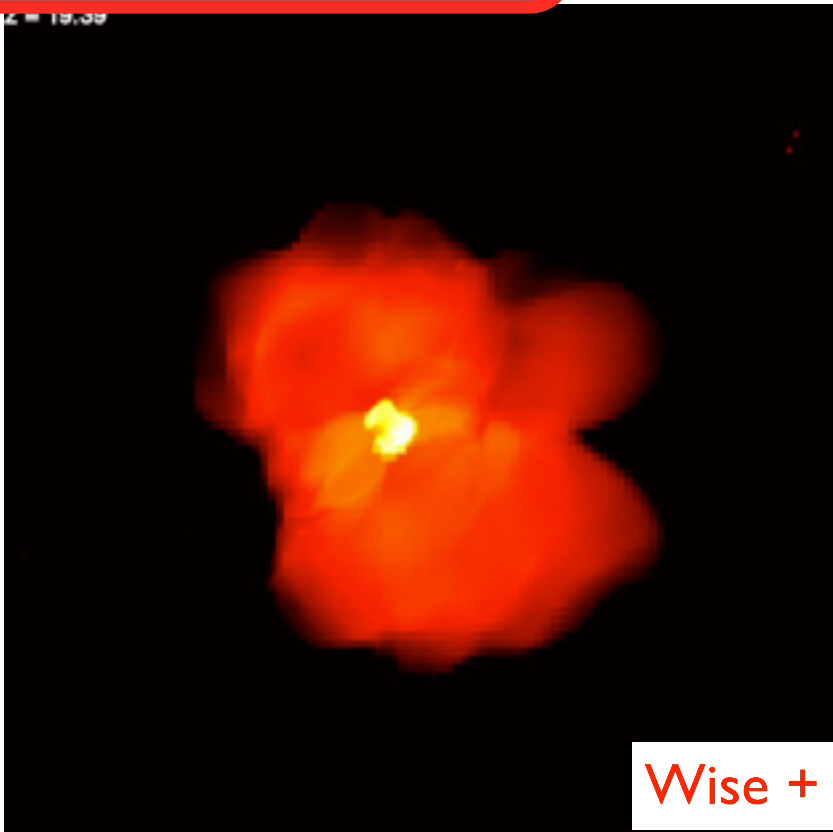
- does this yield realistic reionisation redshift, and amplitude of the UV-background?

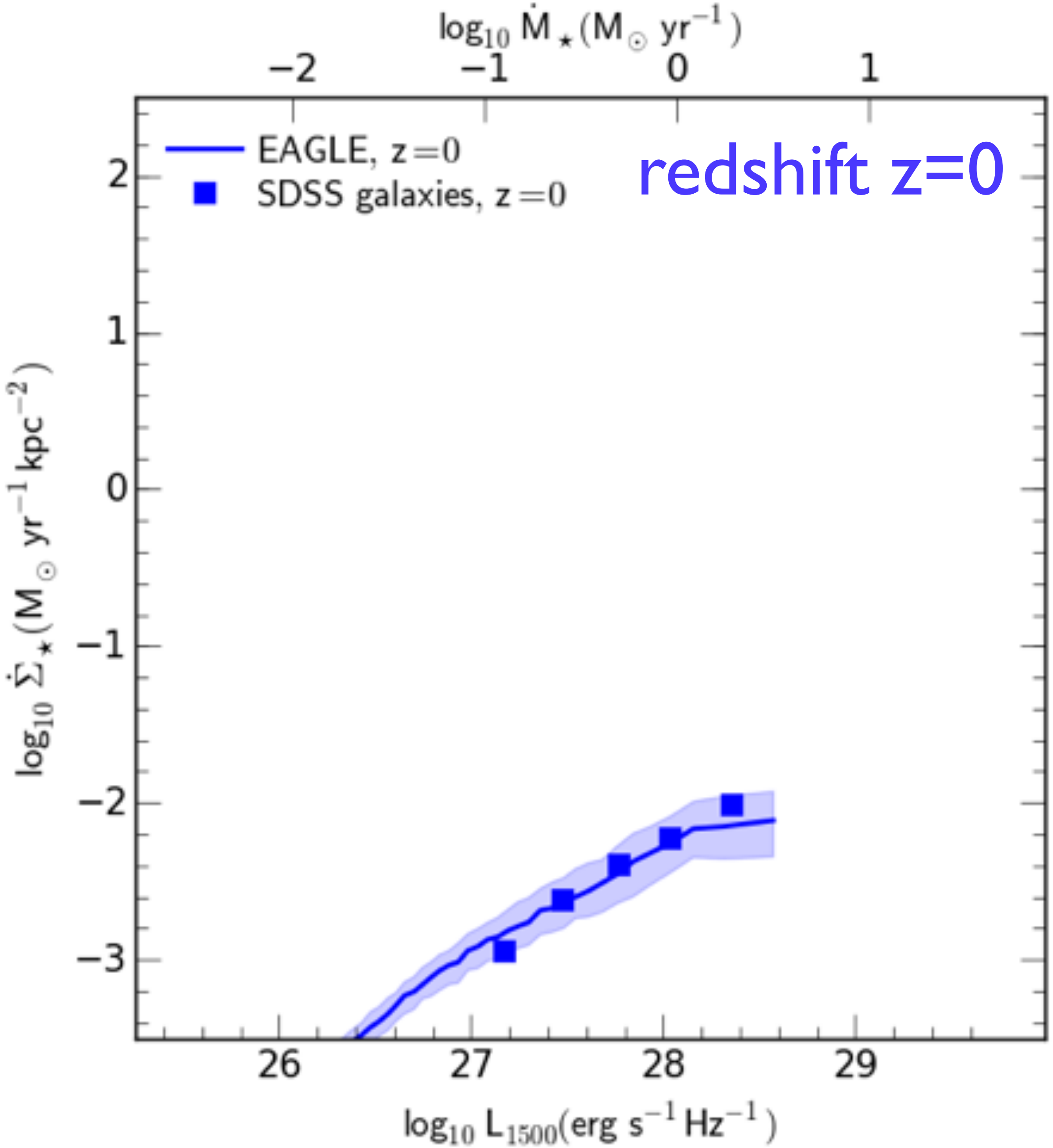
Assumption: escape fraction depends on star formation surface density

Photons escape through channels evacuated by winds



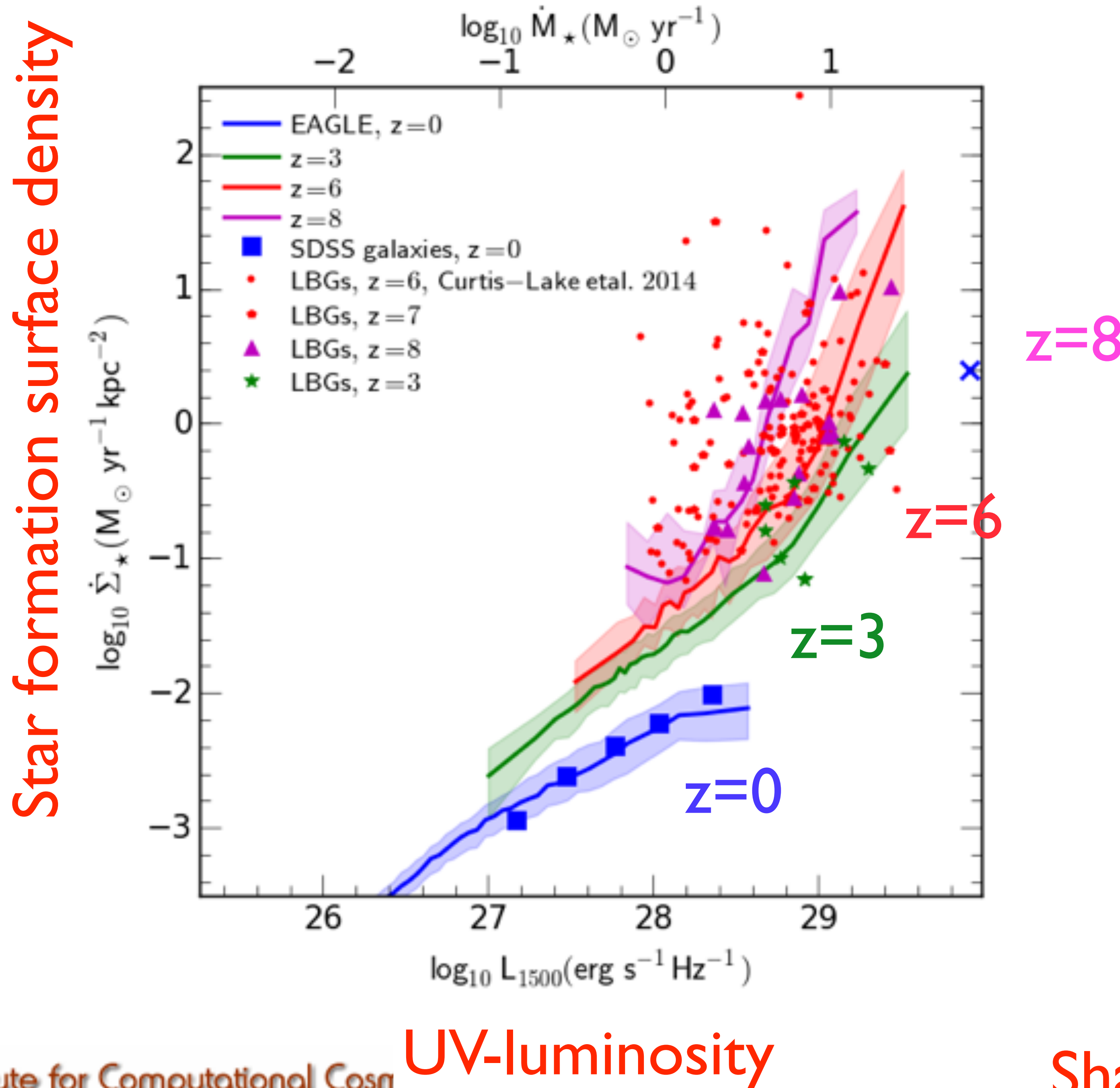
Wise +

Star formation surface density



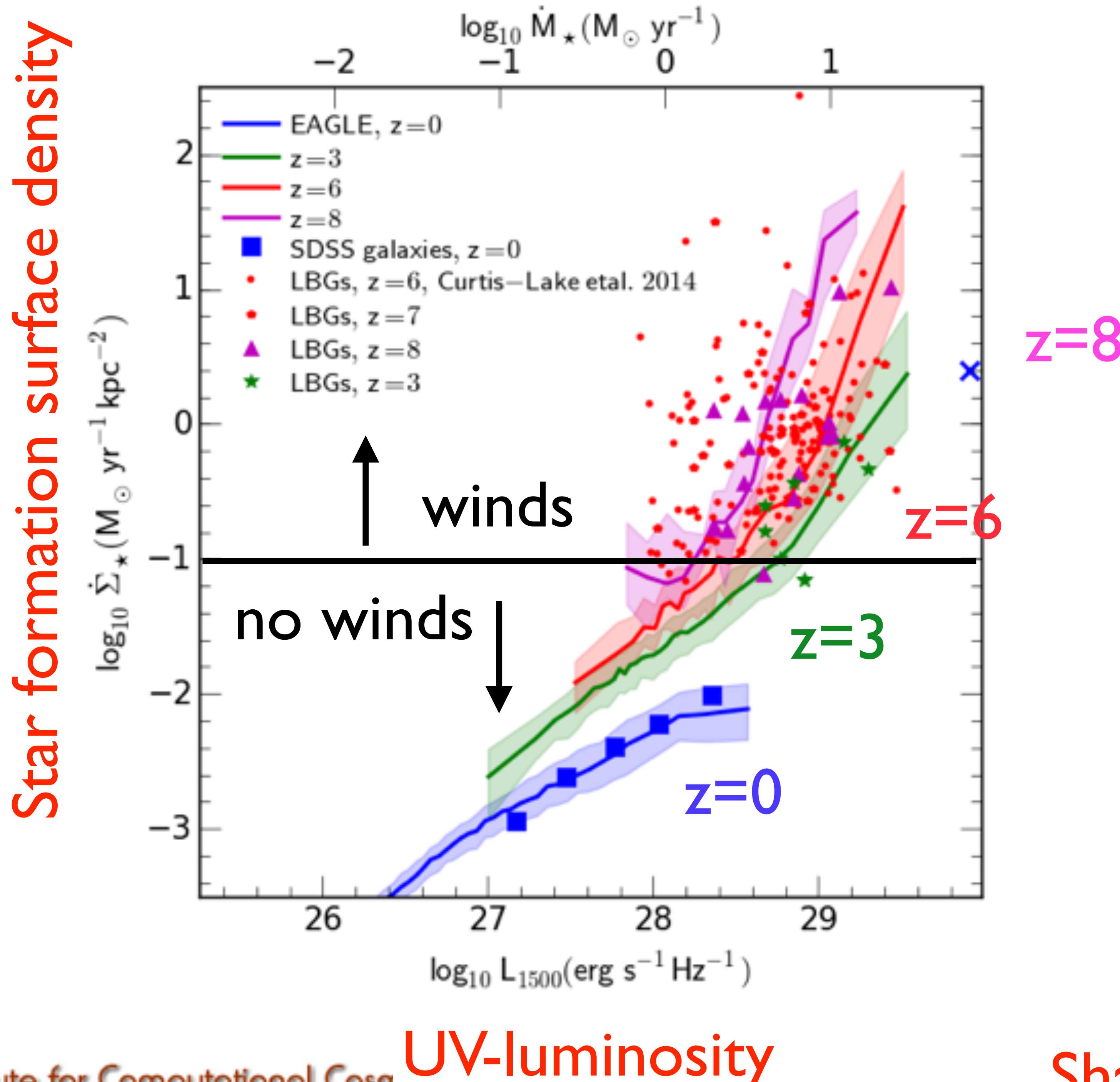
UV-luminosity

Sharma+15



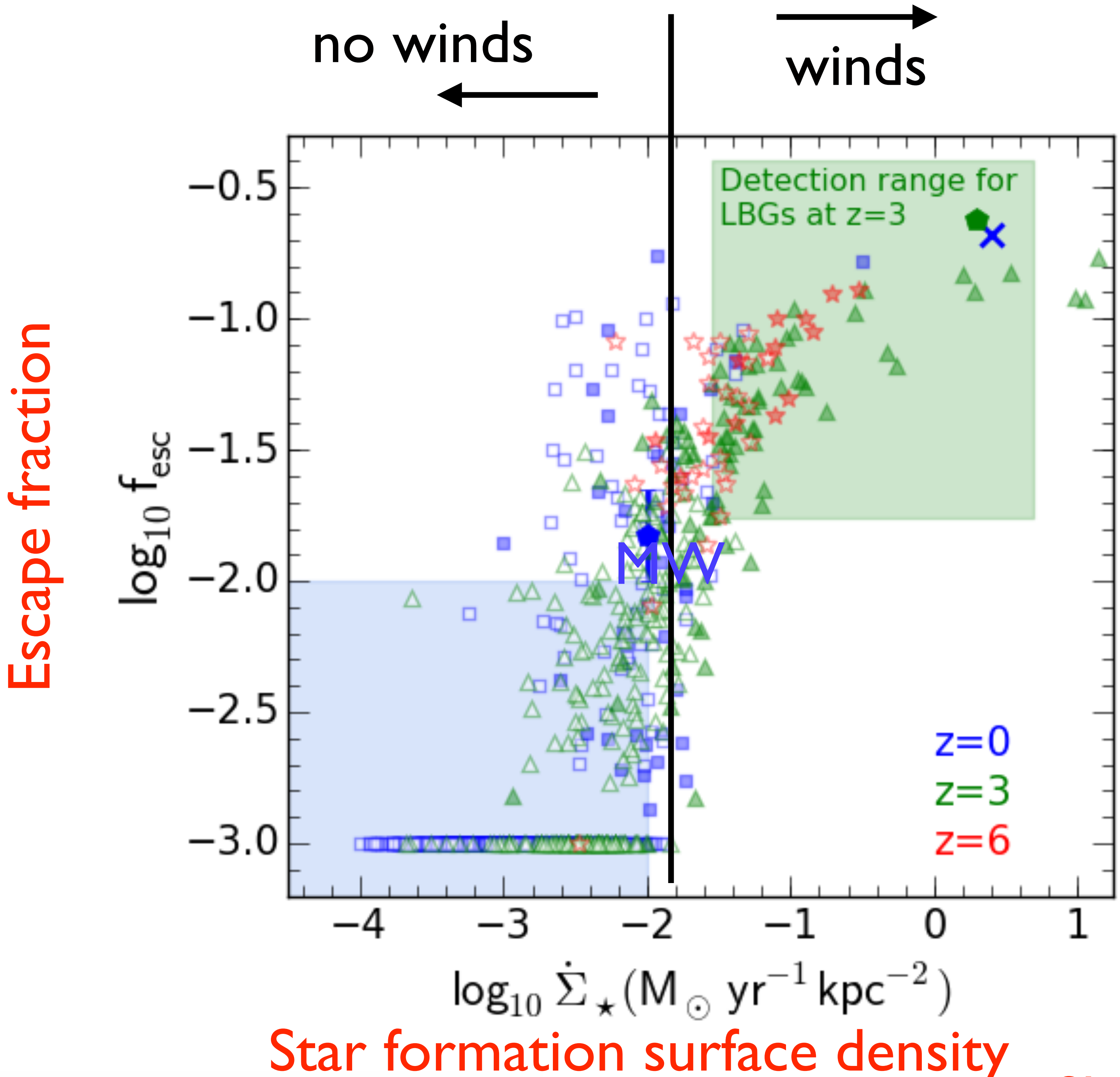
Institute for Computational Cosm

Sharma+15



Star formation surface density
log10 Ṁ★(M⊙ yr−1)
−2
−1
0
1
EAGLE, z=0
z=3
z=6
z=8
SDSS galaxies, z=0
LBGs, z=6, Curtis−Lake etal. 2014
LBGs, z=7
LBGs, z=8
LBGs, z=3
2
1
0
−1
−2
−3
log10 Σ̇★(M⊙ yr−1 kpc−2)
winds
no winds
z=8
z=6
z=3
z=0
26
27
28
29
log10 L1500(erg s−1 Hz−1)
UV-luminosity

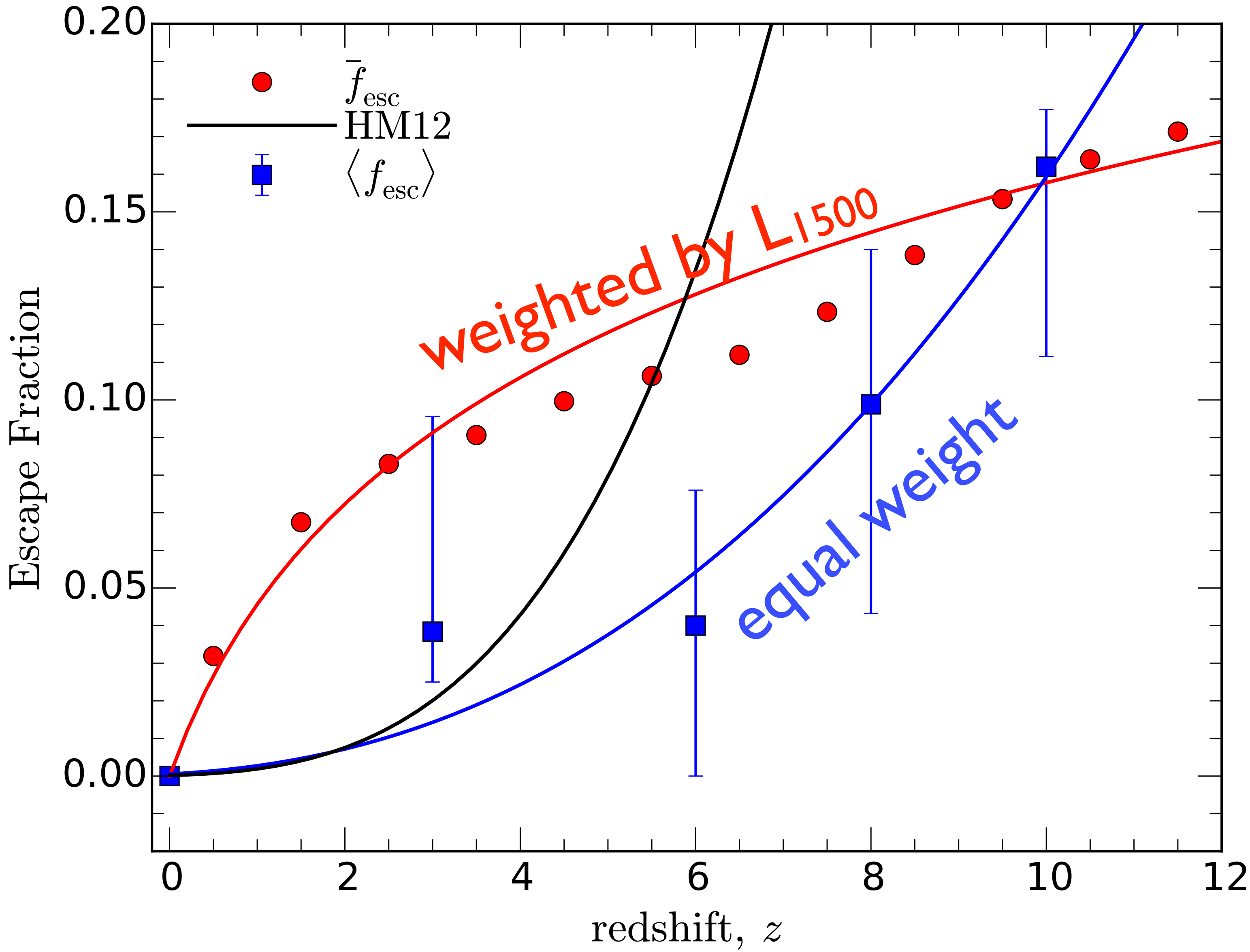
Sharma+15



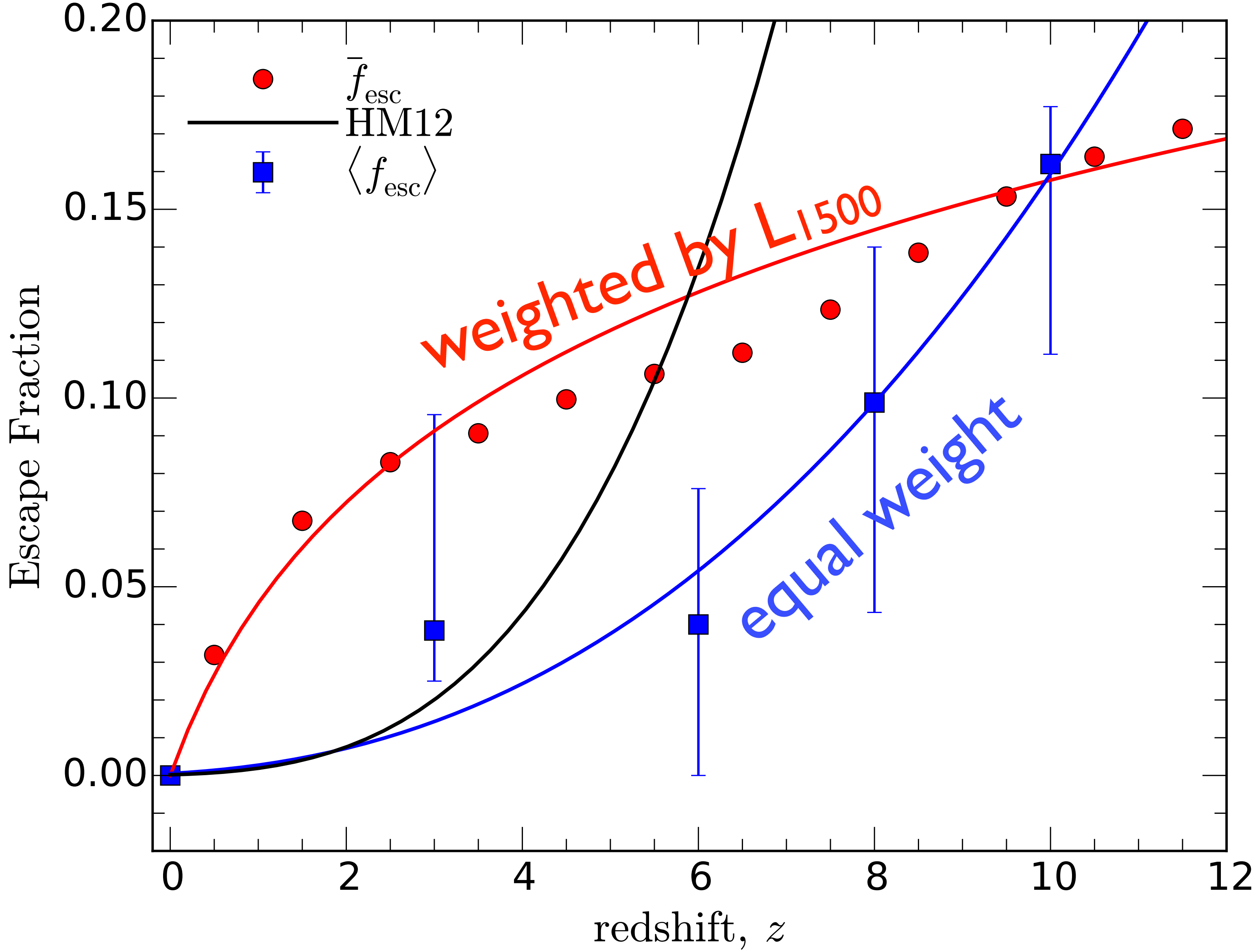
no winds
winds
Detection range for
LBGs at z=3
MW
z=0
z=3
z=6
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−4
−3
−2
−1
0
1
$\log_{10} f_{esc}$
Escape fraction
$\log_{10} \dot{\Sigma}_\star (M_\odot \, yr^{-1} \, kpc^{-2})$
Star formation surface density

Sharma+15

Evolution of the escape fraction

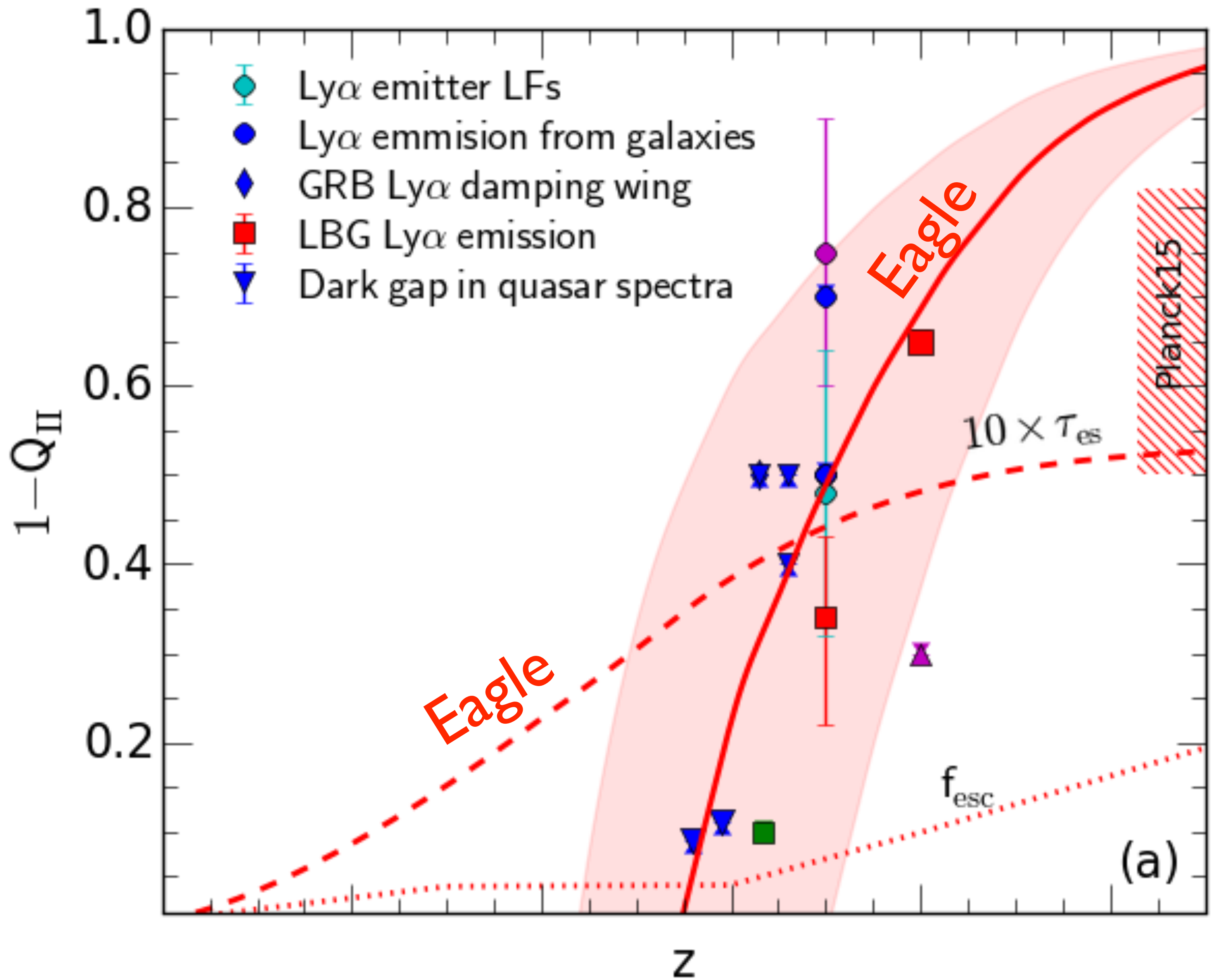


Evolution of the escape fraction



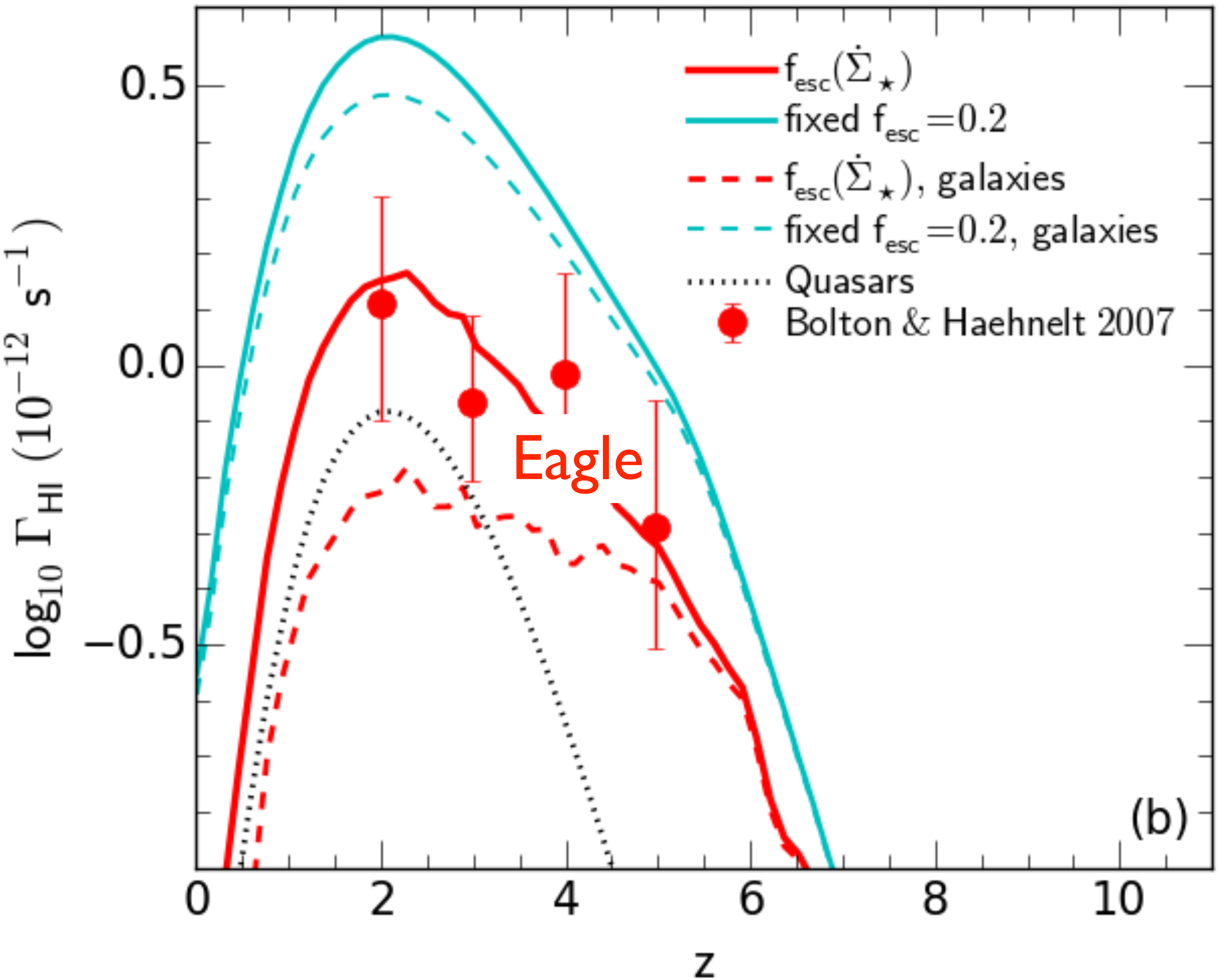
$$\bar{f}_{\rm esc} = 2.45\ \tanh(0.027 \log(1+z))$$

Constraints on reionisation



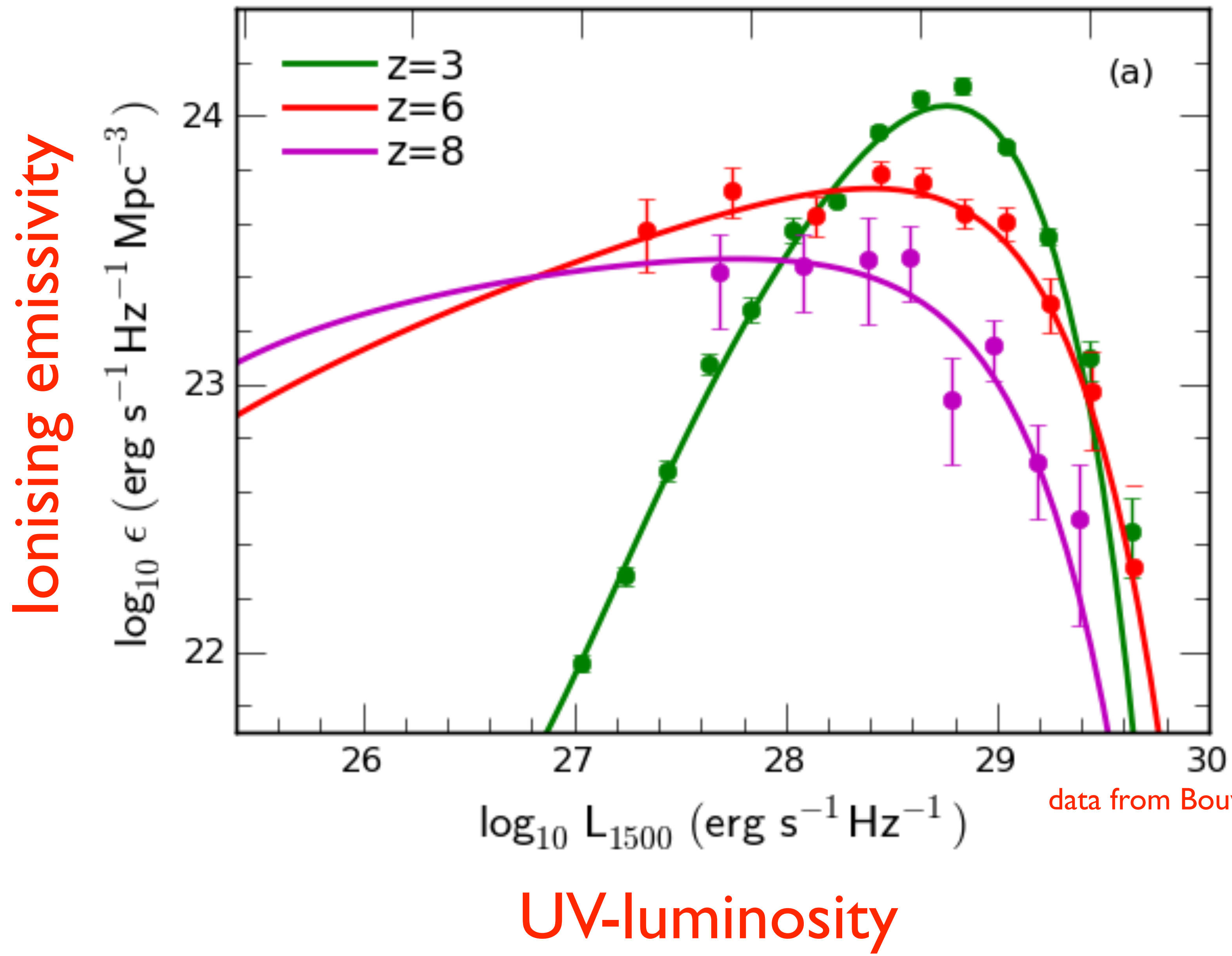
Sharma+15

Constraints after reionisation



Sharma+15

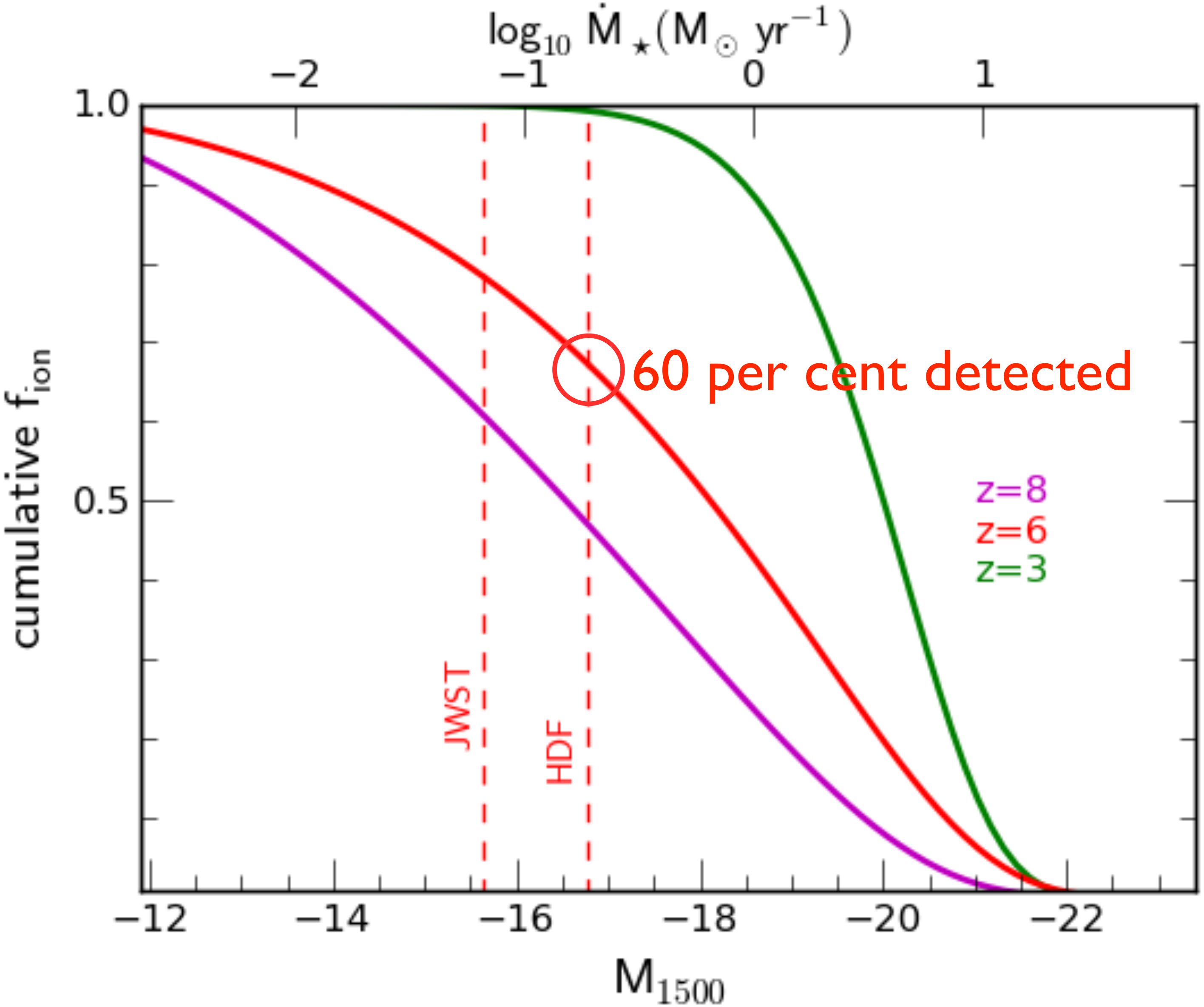
Contribution of galaxies to ionising emissivity



data from Bouwens+, Shapley+

Sharma+15

Cumulative contribution to emissivity

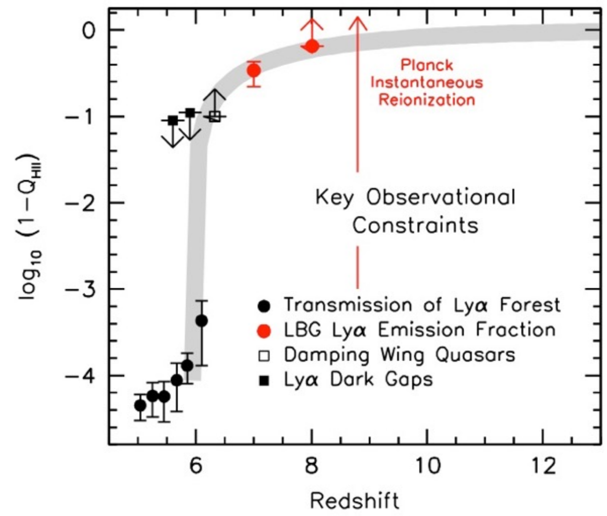


UV-luminosity

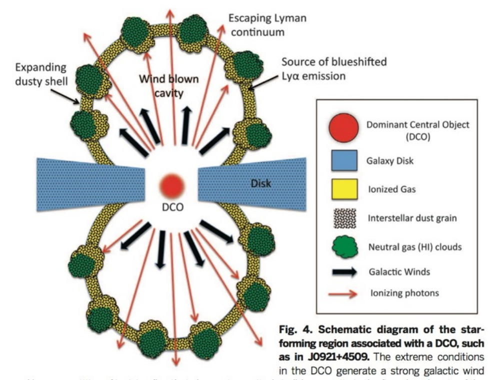
Sharma+15

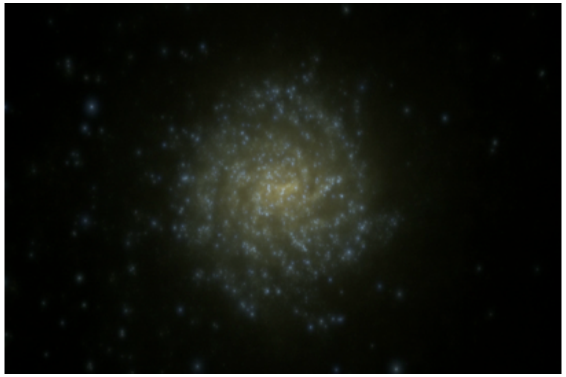
Summary:

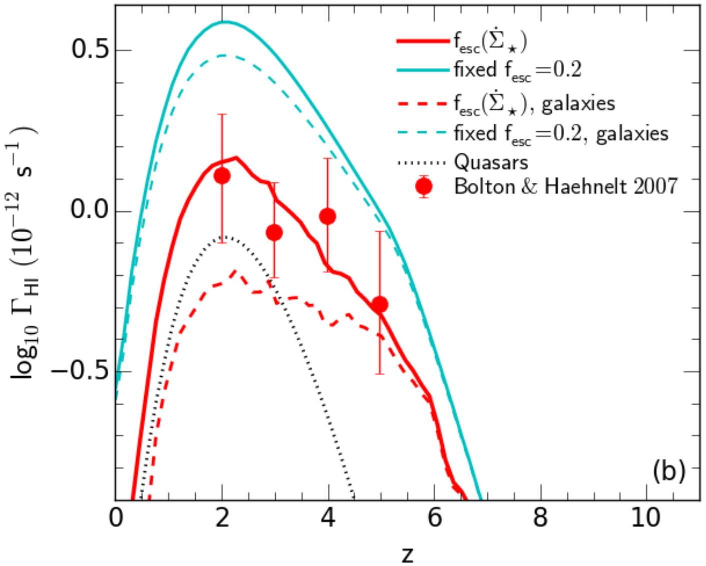
transition of mostly neutral to mostly ionised

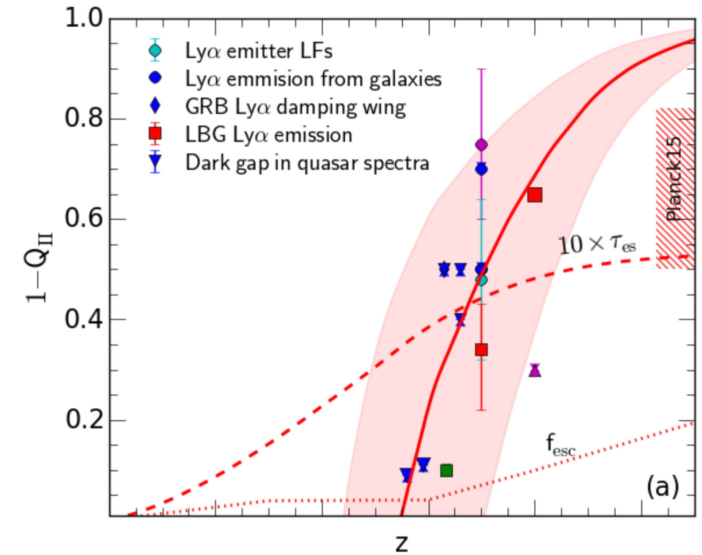


Eagle: reionisation due to "bright" galaxies with high SFR density









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