Reionisation and the build-up of the UV-background in Eagle

Tom Theuns
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for the Eagle collaboration

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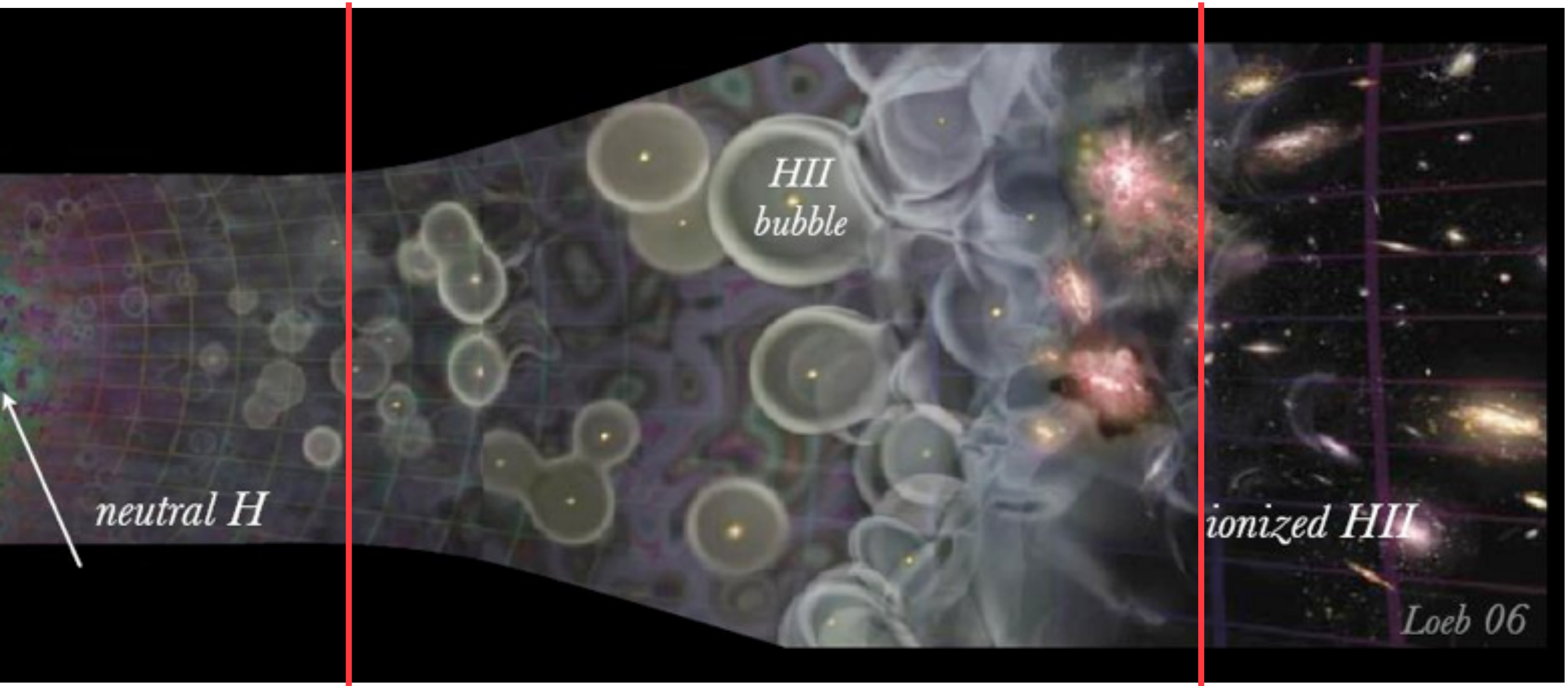
IGM neutral

IGM highly ionised

(with neutral DLAs)



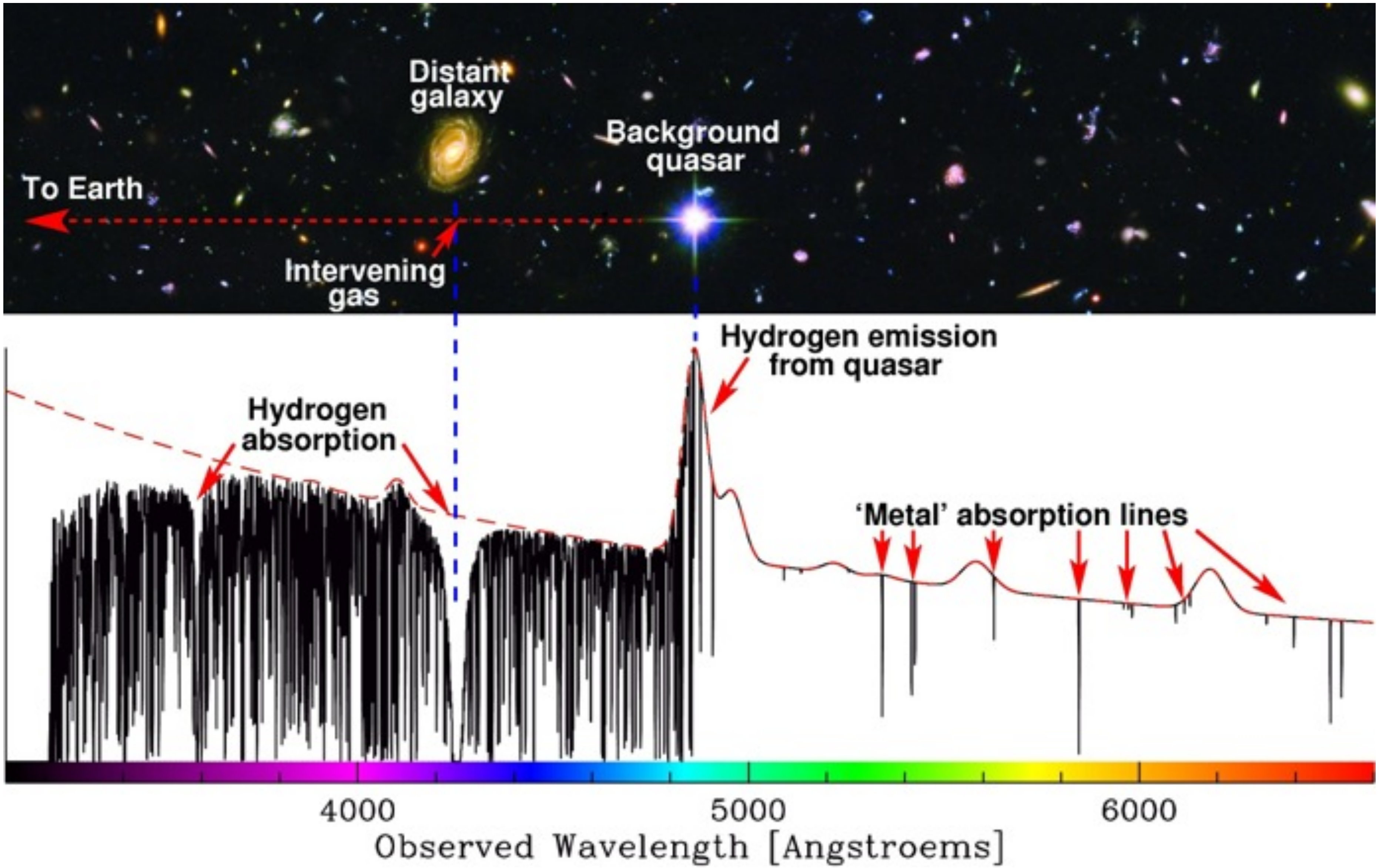
z > 12

epoch of reionisation

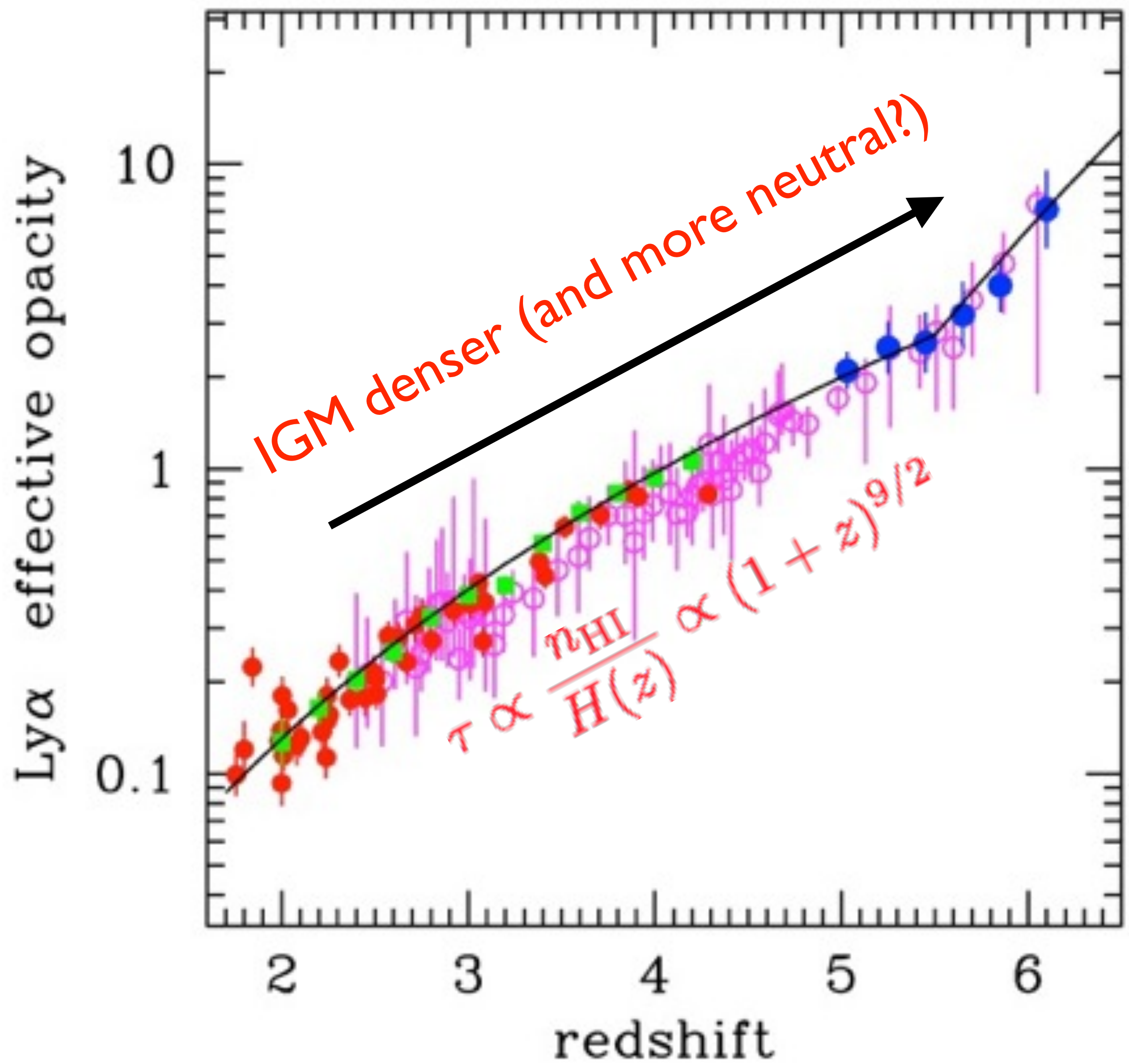
z<5

Observational constraints:

1: Lya optical depth



$$\langle F \rangle \equiv \exp(-\tau_{\rm eff})$$



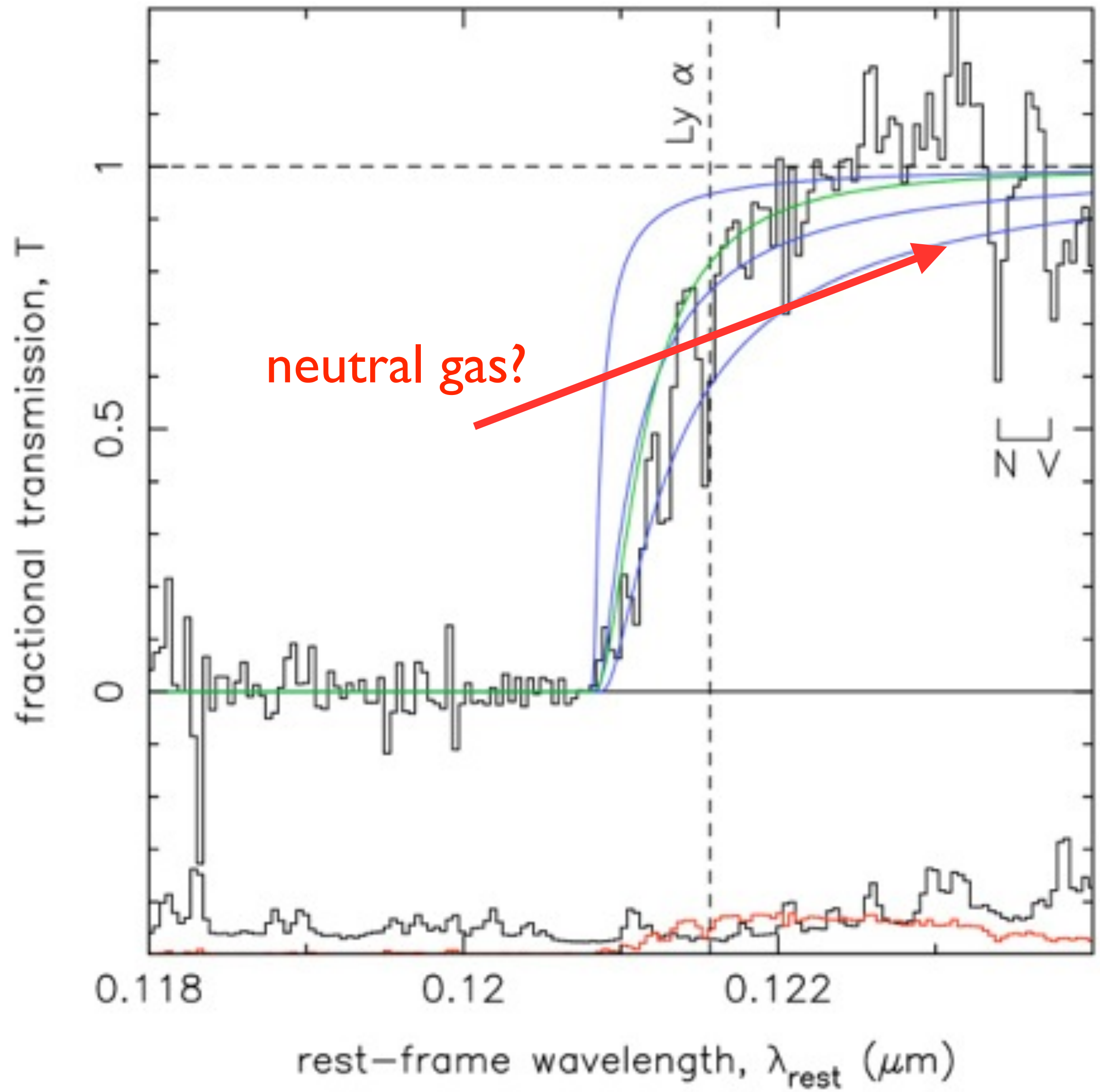
$$\frac{dn_{\rm HI}}{dt} = -\Gamma\, n_{\rm HI} + \alpha n_{\rm HI}\, n_e$$

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

effective optical depth is not optical depth!

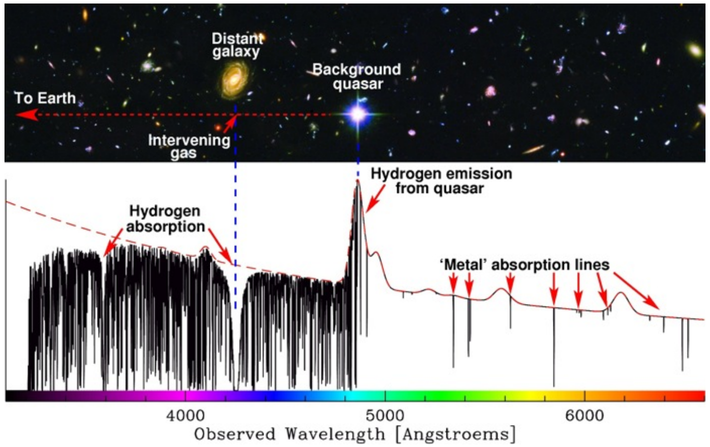
Haardt & Madau '12

2: Damping wings



Mortlock +11

3: Thomson optical depth



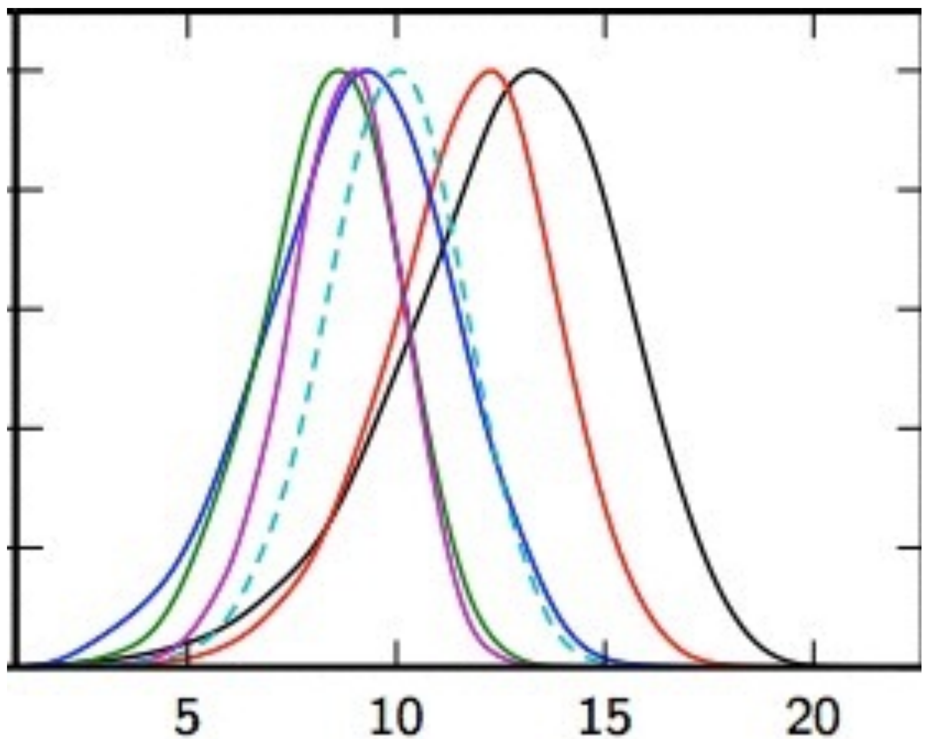
$$\tau = 0.078^{+0.019}_{-0.019},\ z_{re} = 9.9^{+1.8}_{-1.6},\ \textit{Planck}\ \mathrm{TT+lowP}; \quad (17a)$$

$$\tau = 0.070^{+0.024}_{-0.024},\ z_{re} = 9.0^{+2.5}_{-2.1},\ \textit{Planck}\ \mathrm{TT+lensing}; \quad (17b)$$

$$\tau = 0.066^{+0.016}_{-0.016},\ z_{re} = 8.8^{+1.7}_{-1.4},\ \textit{Planck}\ \mathrm{TT+lowP+lensing}; \quad (17c)$$

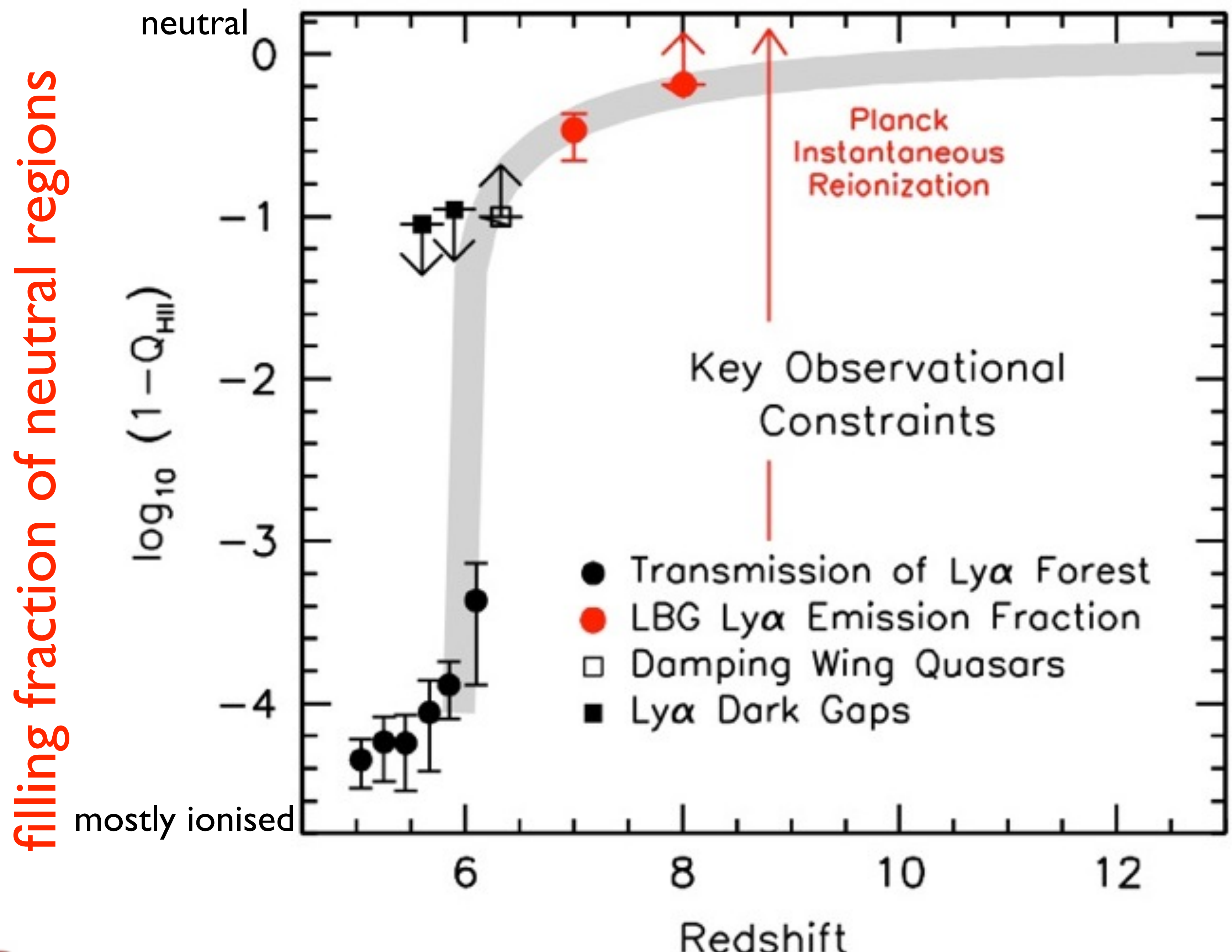
$$\tau = 0.067^{+0.016}_{-0.016},\ z_{re} = 8.9^{+1.7}_{-1.4},\ \textit{Planck}\ \mathrm{TT+lensing+BAO}; \quad (17d)$$

$$\tau = 0.066^{+0.013}_{-0.013},\ z_{re} = 8.8^{+1.3}_{-1.2},\ \textit{Planck}\ \mathrm{TT+lowP+lensing+BAO}. \quad (17e)$$



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

Observational constraints: summary



Bouwens+15

Theoretical description

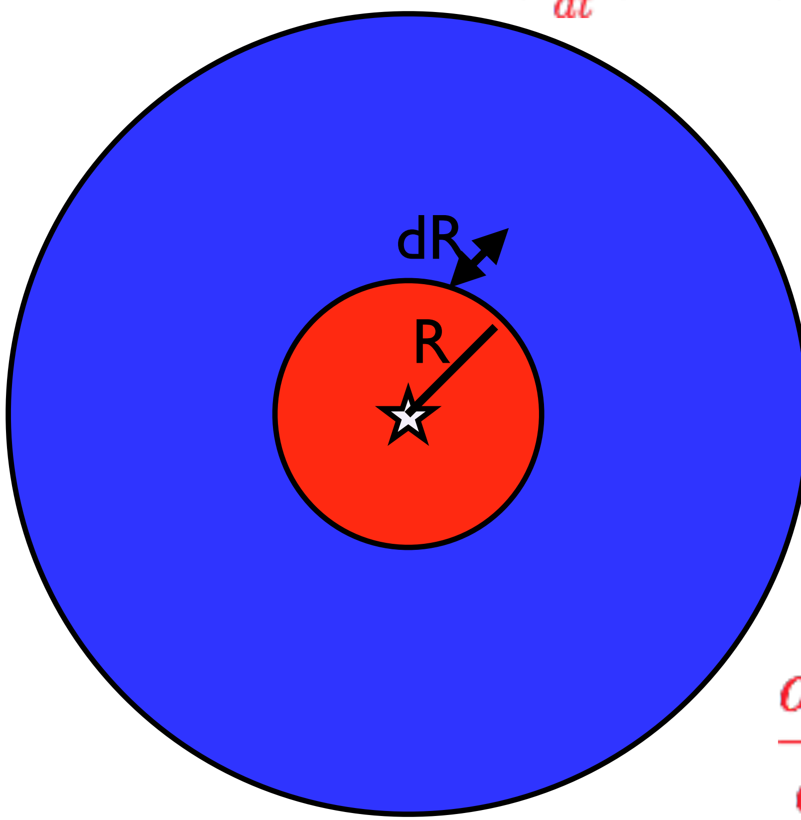
Before reionisation:

Increase in volume of an HII region

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

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

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



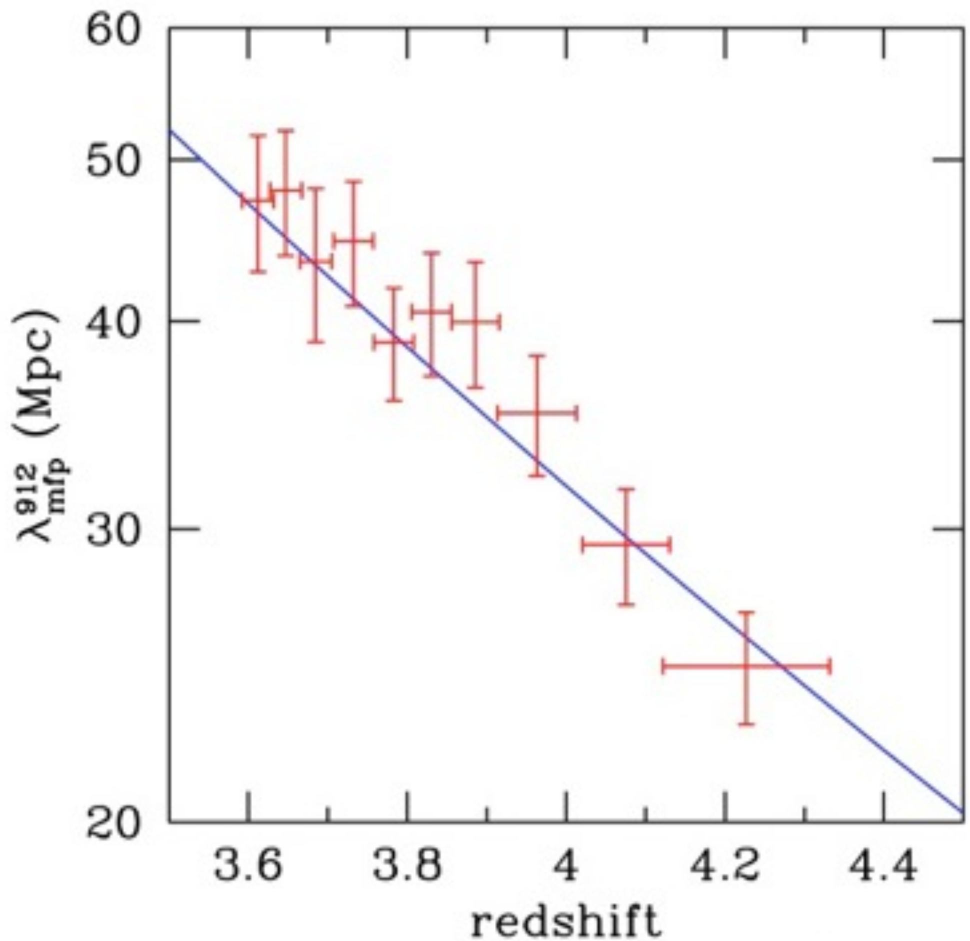
$$\frac{dQ}{dt} = \frac{\dot{n}_\gamma}{n_{\rm H}} - \alpha \frac{\langle n_{\rm H}^2 \rangle}{n_{\rm H}} Q$$

After reionisation:

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

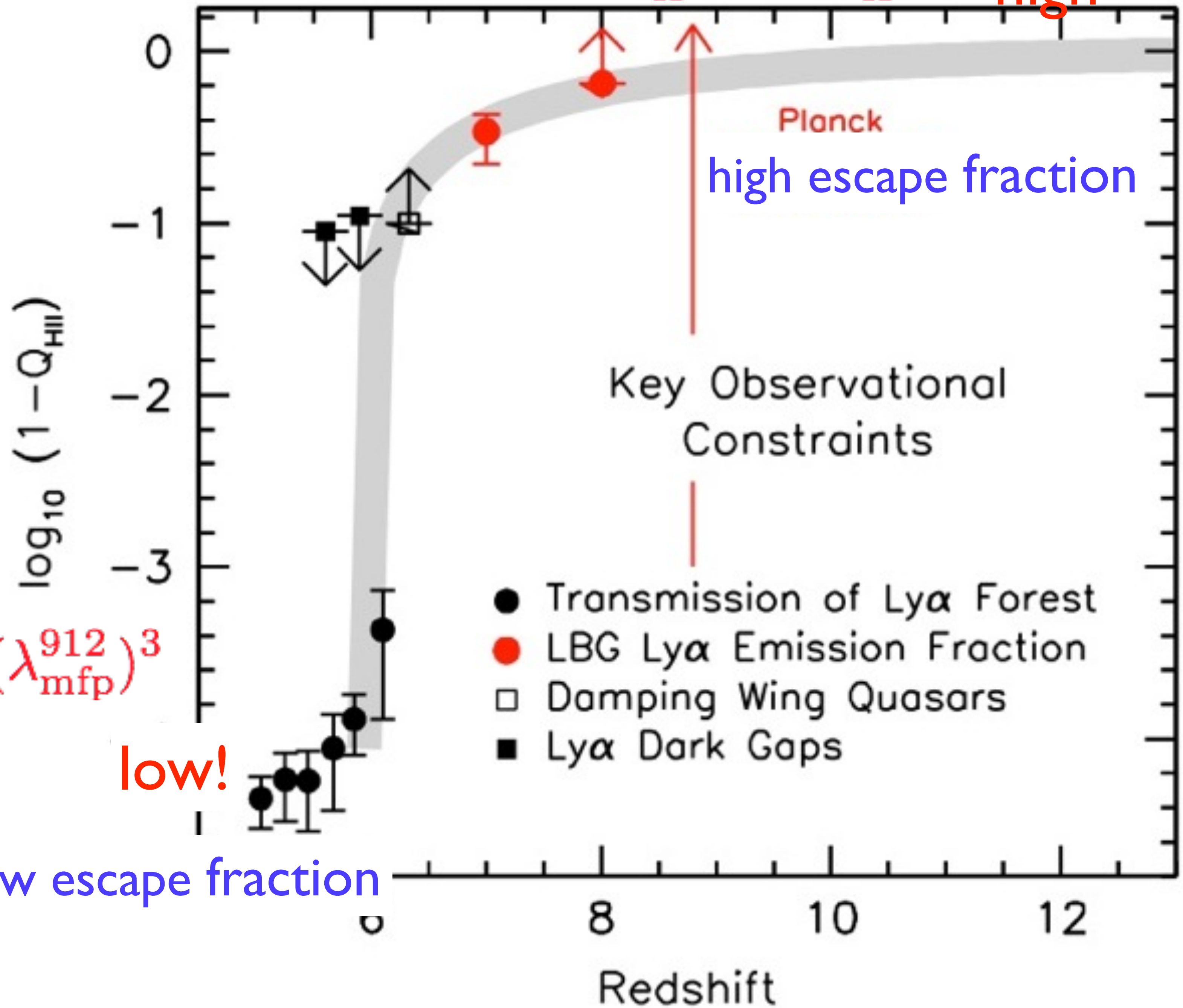
$$\tau_{\rm eff} \propto n_{\rm HI} \propto \frac{1}{\Gamma}$$

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



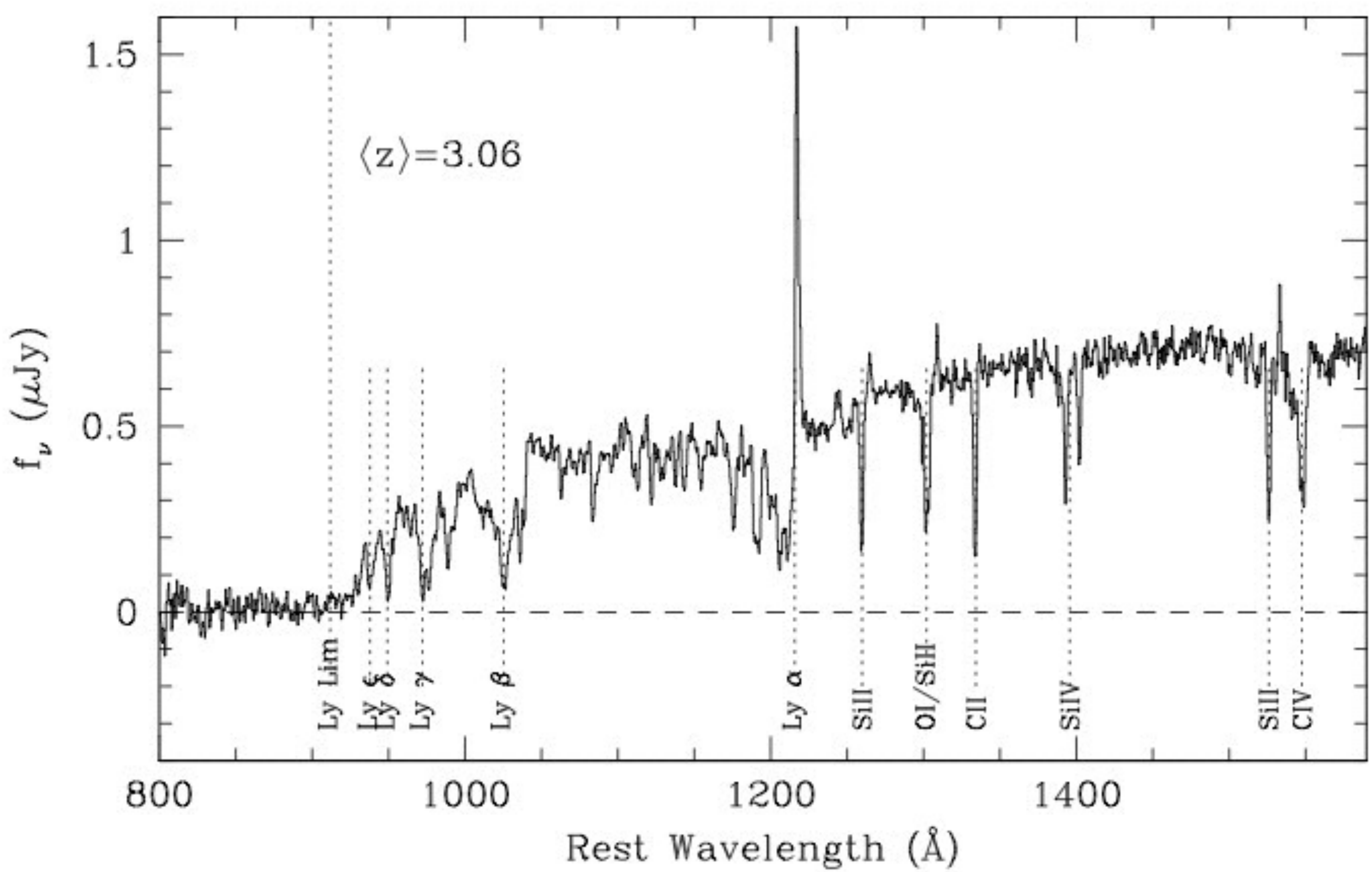
Haardt & Madau12

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



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

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



relative escape fraction of order 10 %

Shapley+06

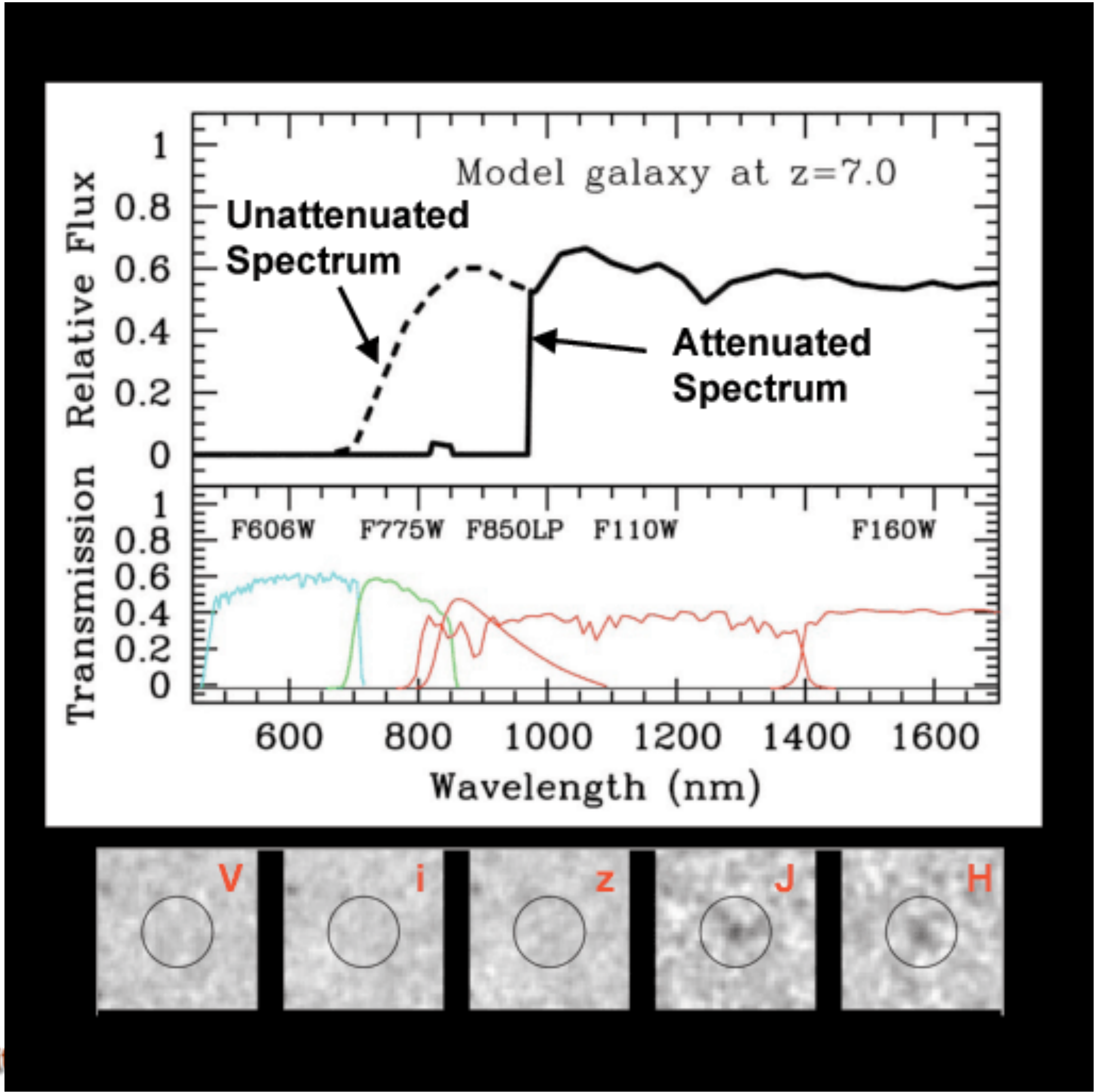
Absolute escape fractions

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

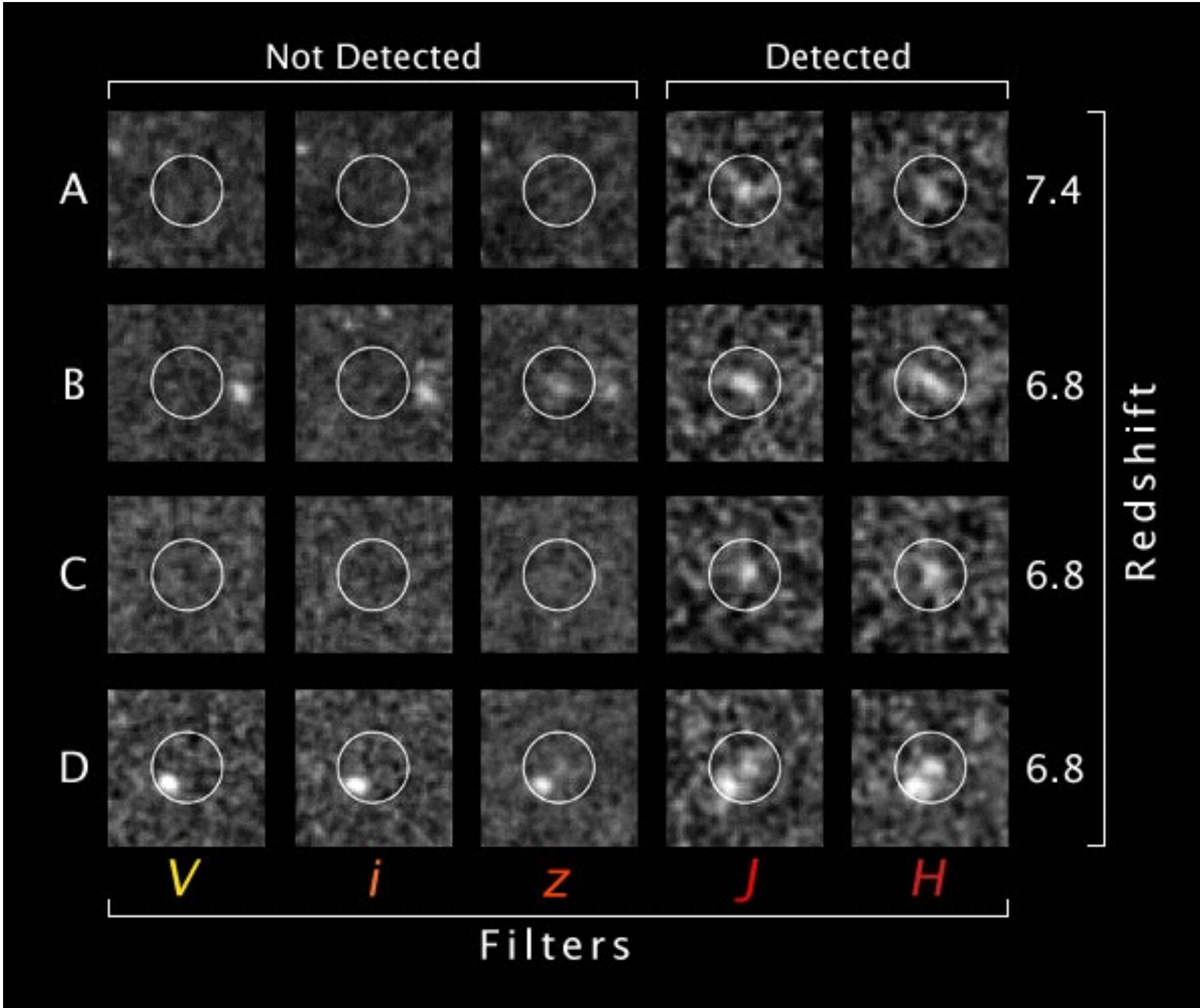
Reference	Sample	$(f_{1500}/f_{900})_{obs}$	$(f_{1500}/f_{900})_{int}$ [a]	$f_{esc,rel}$	f_{esc}
Steidel et al. (2001)	29 LBGs, Average	17.7 ± 3.8	3.0	0.31	
Shapley et al. (2006)	2 LBGs, Direct	12.7 ± 1.8, 7.5 ± 1.0	3.0	0.43, 0.72	
Shapley et al. (2006)	14 LBGs, Average	58 ± 25	3.0	0.094	
This work	7 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

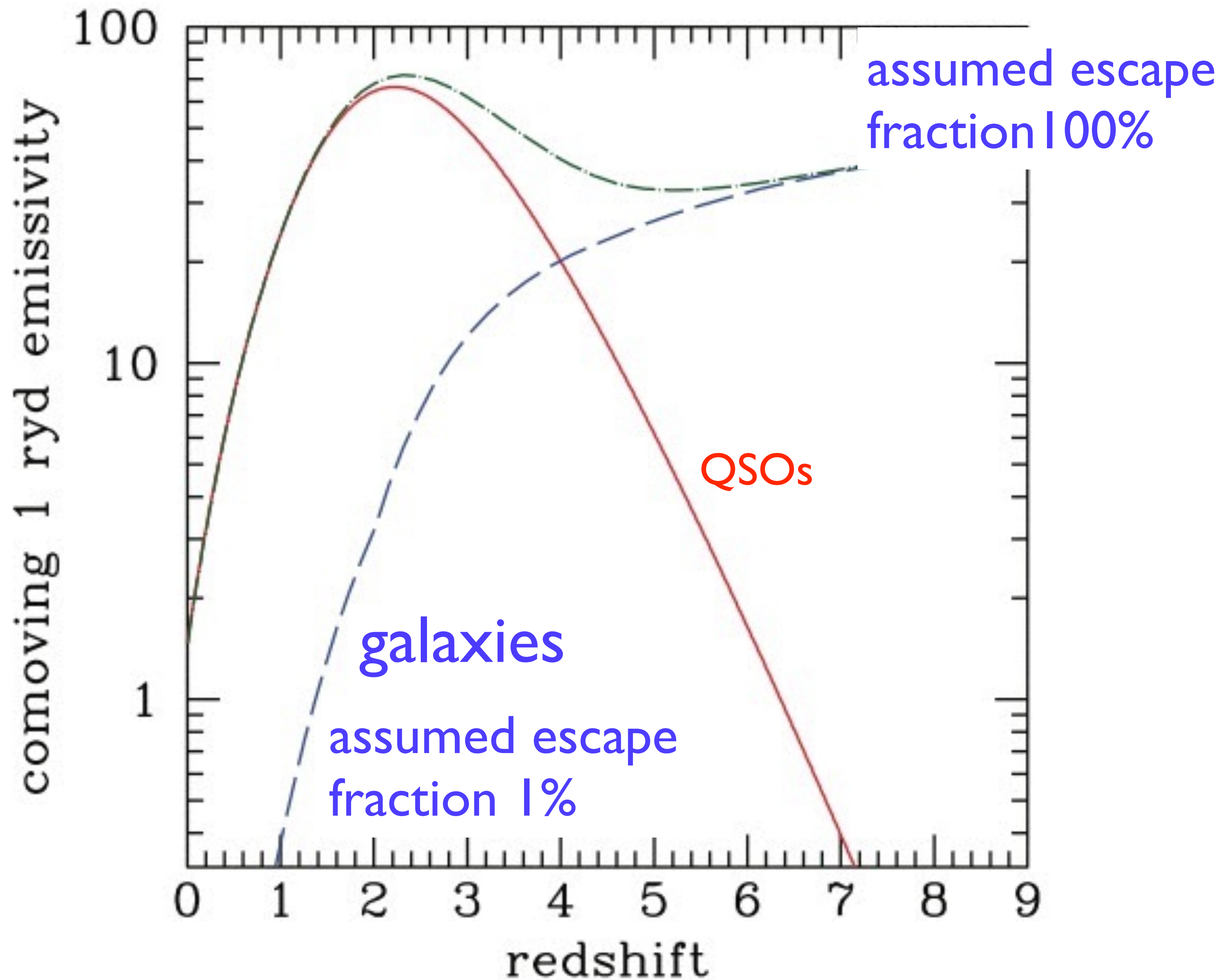
Lyman-break technique



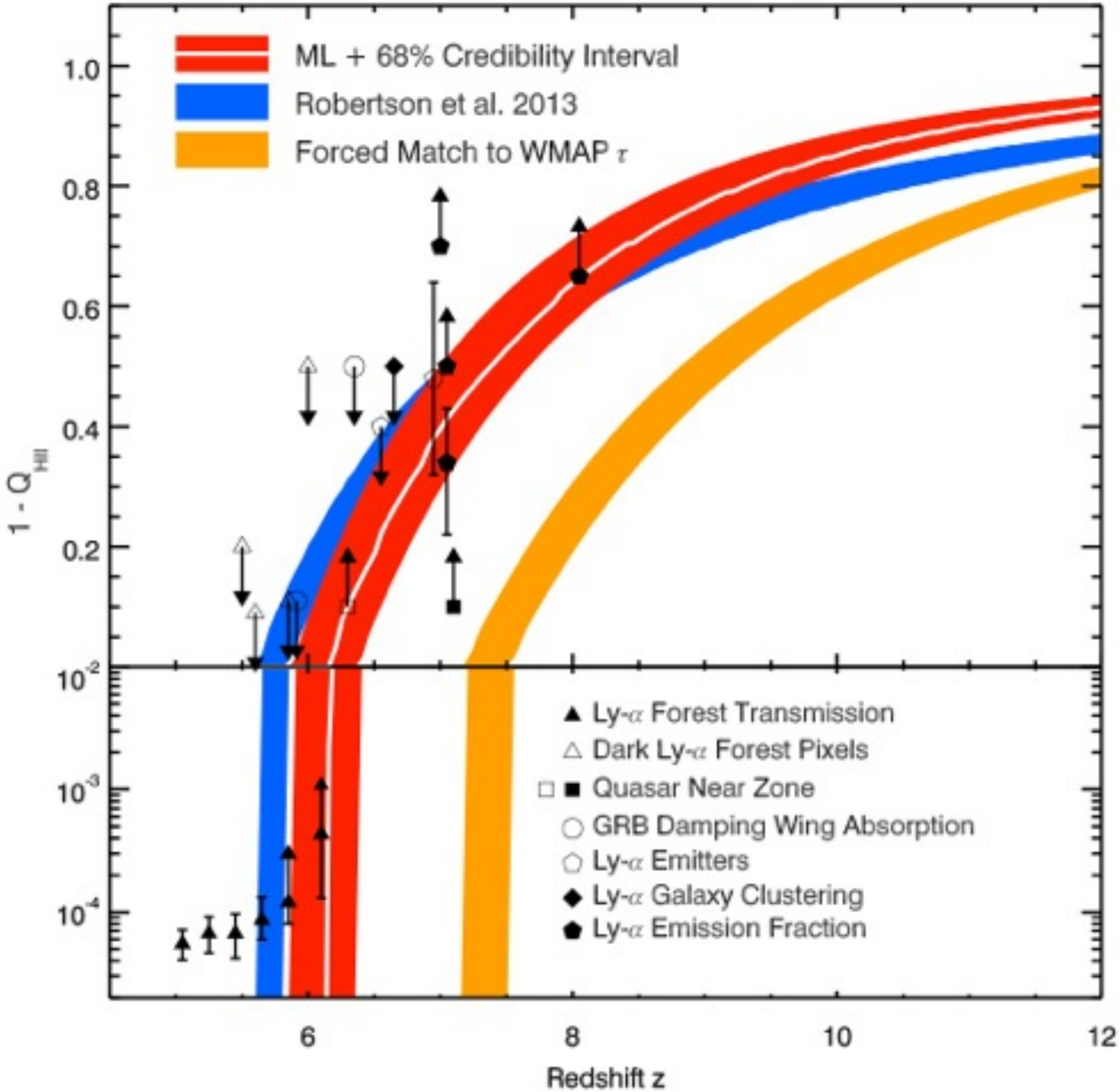
Tom Theuns



Not Detected
Detected
A
B
C
D
7.4
6.8
6.8
6.8
Redshift
V
i
z
J
H
Filters

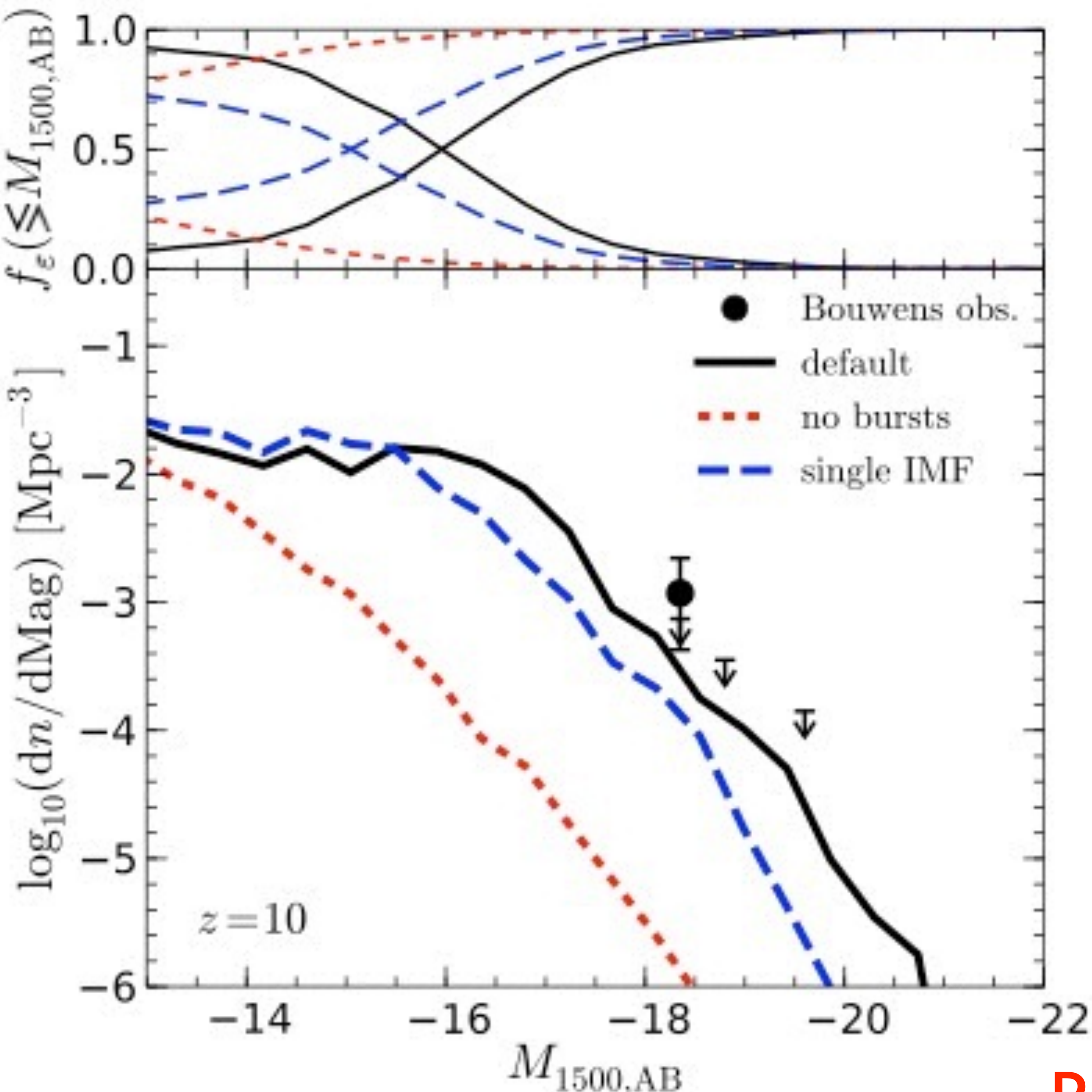


Haardt & Madau 12



Robertson+15

Constant escape fraction: faint (unobserved) galaxies dominate reionisation



Raicevic+10

Theoretical challenge:

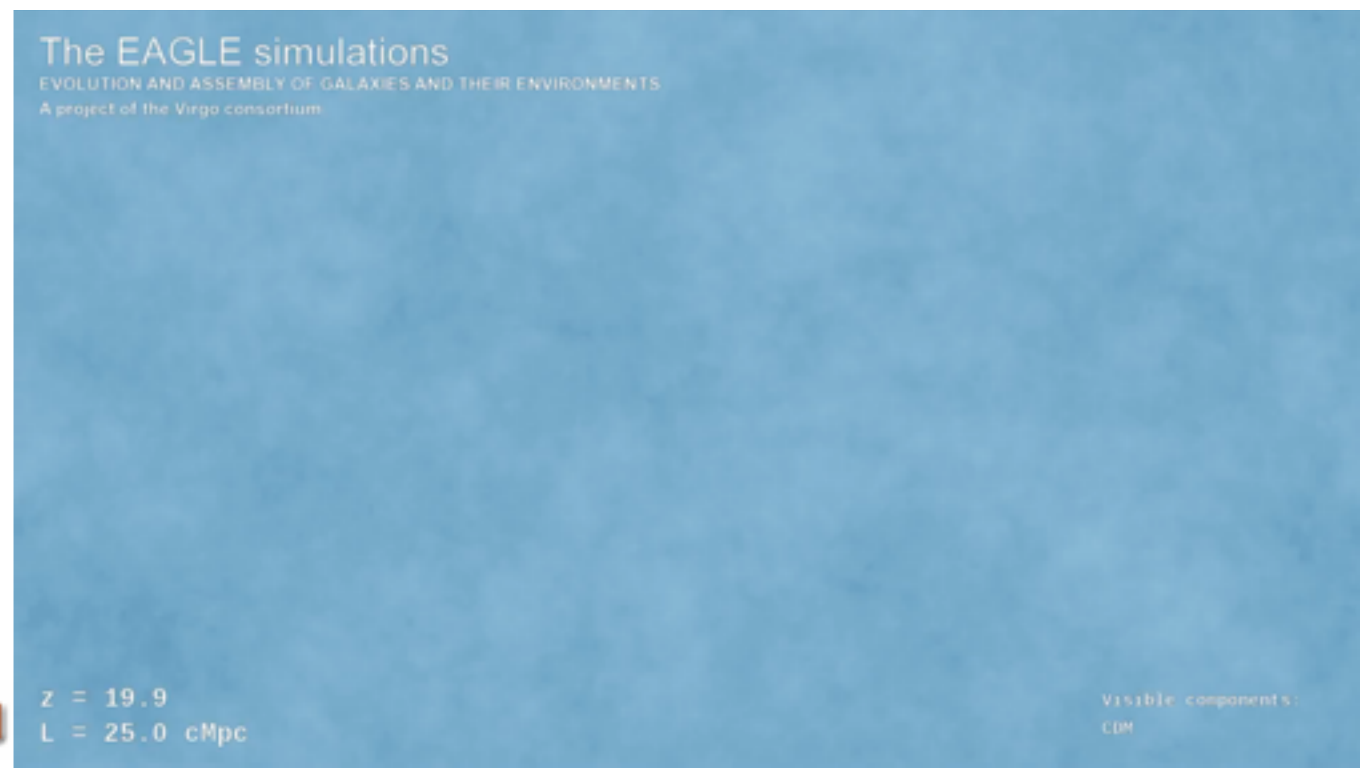
- can we find a local property of galaxies that yields high escape fraction of UV-photons at high-z, and a low escape fraction at low z
- does this yield realistic reionisation redshift as well as a realistic amplitude of the UV-background after reionisation?

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

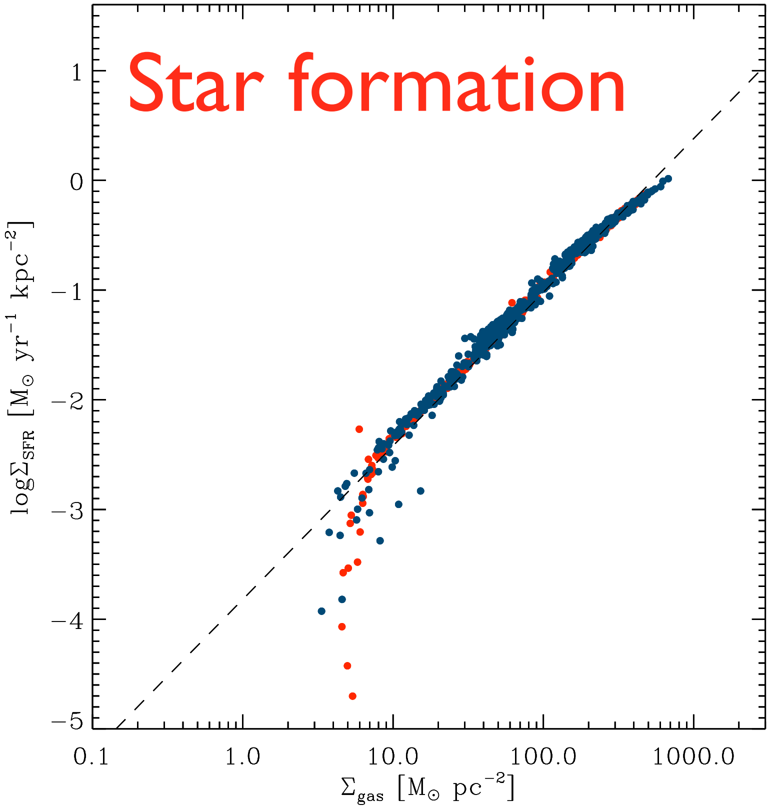
Joop Schaye,[1*] Robert A. Crain,[1] Richard G. Bower,[2] Michelle Furlong,[2] Matthieu Schaller,[2] Tom Theuns,[2,3] Claudio Dalla Vecchia,[4,5] Carlos S. Frenk,[2] I. G. McCarthy,[6] John C. Helly,[2] Adrian Jenkins,[2] Y. M. Rosas-Guevara,[2] Simon D. M. White,[7] Maarten Baes,[8] C. M. Booth,[1,9] Peter Camps,[8] Julio F. Navarro,[10] Yan Qu,[2] Alireza Rahmati,[7] Till Sawala,[2] Peter A. Thomas,[11] James Trayford[2]

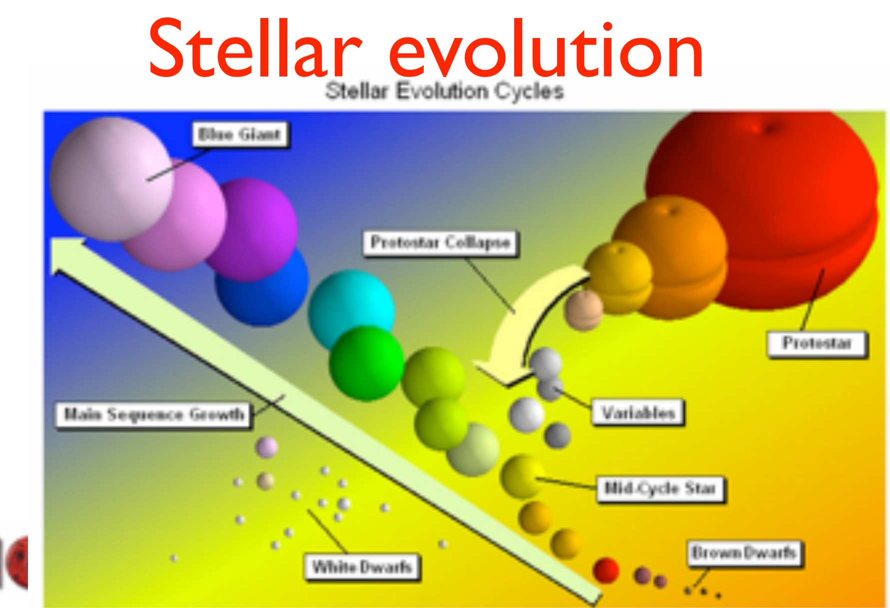
[1] Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, the Netherlands

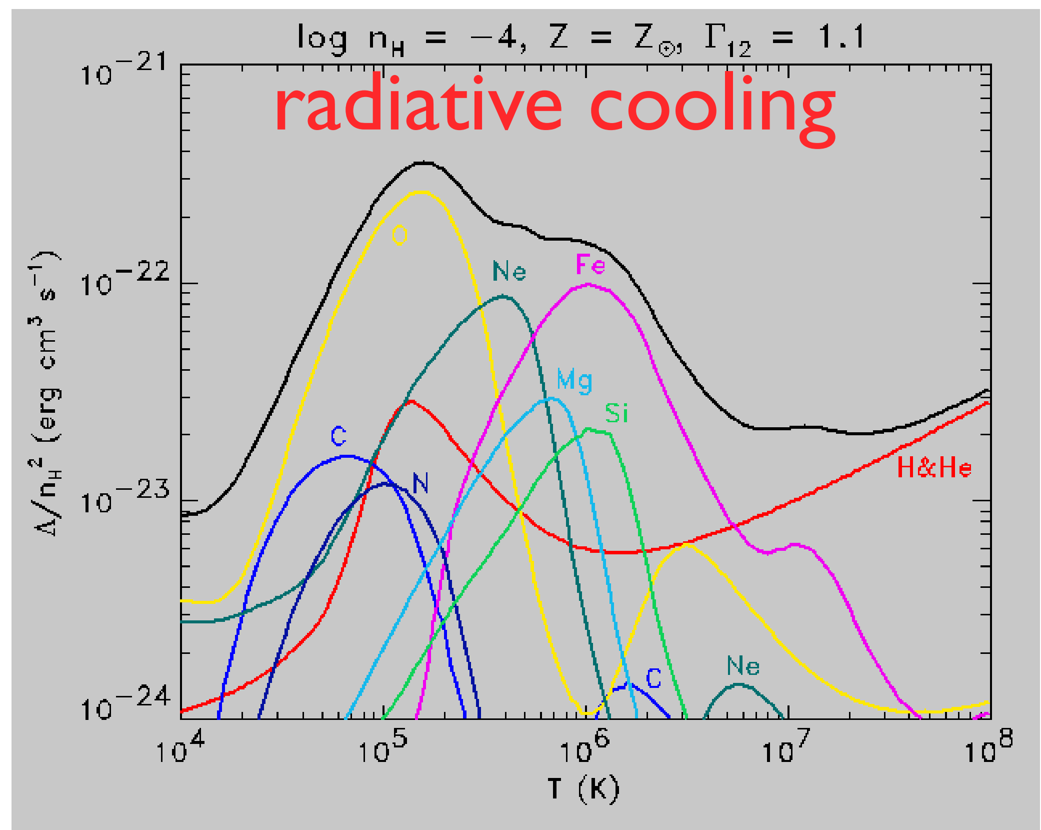
- 1504^3 Gadget 3 simulation
- $(100\ \mathrm{Mpc})^3$ volume
- baryonic mass $10^6\ M_{sun}$
- Calibrated to stellar MF
- Local physics



The subgrid physics in Eagle



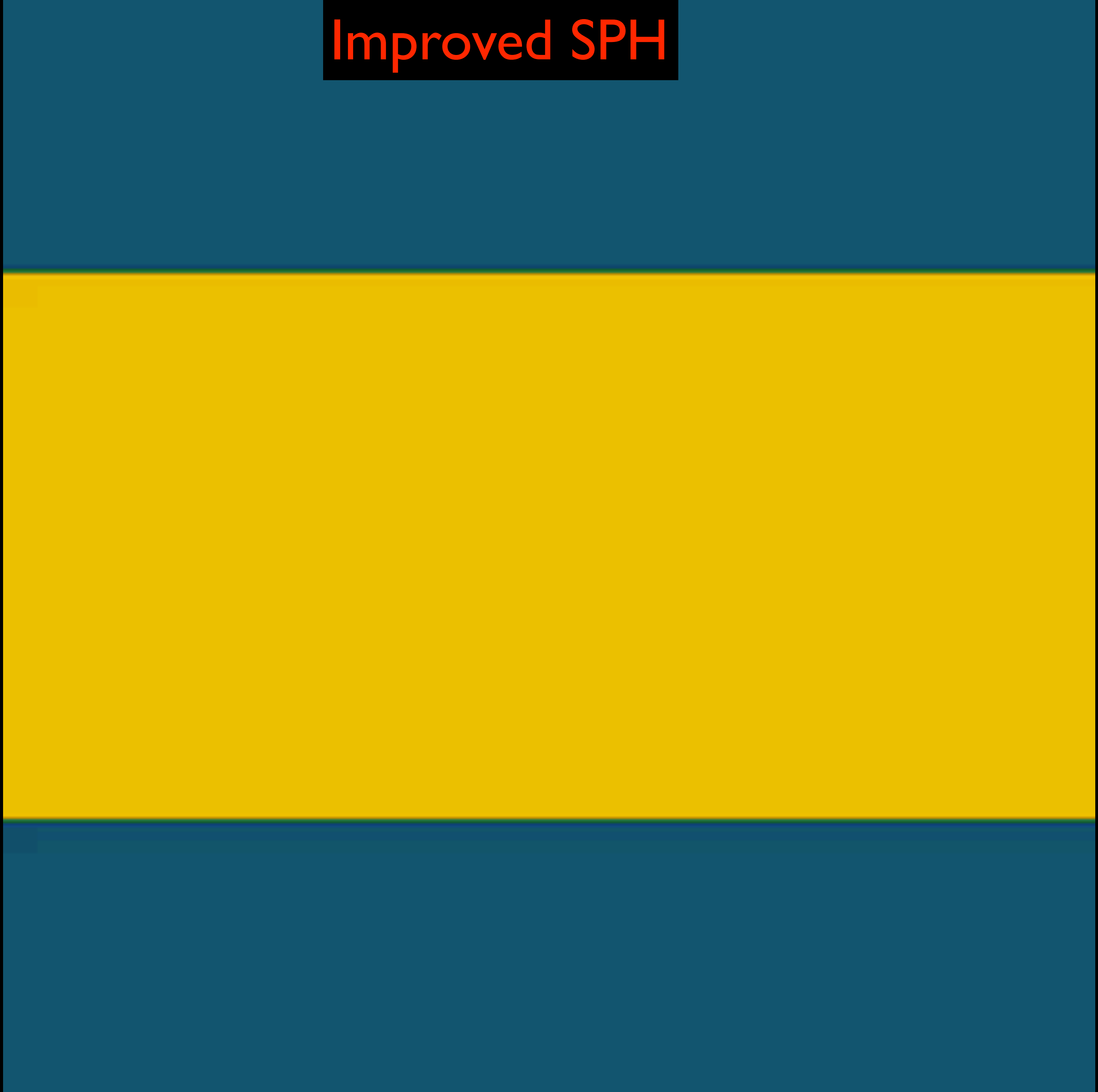


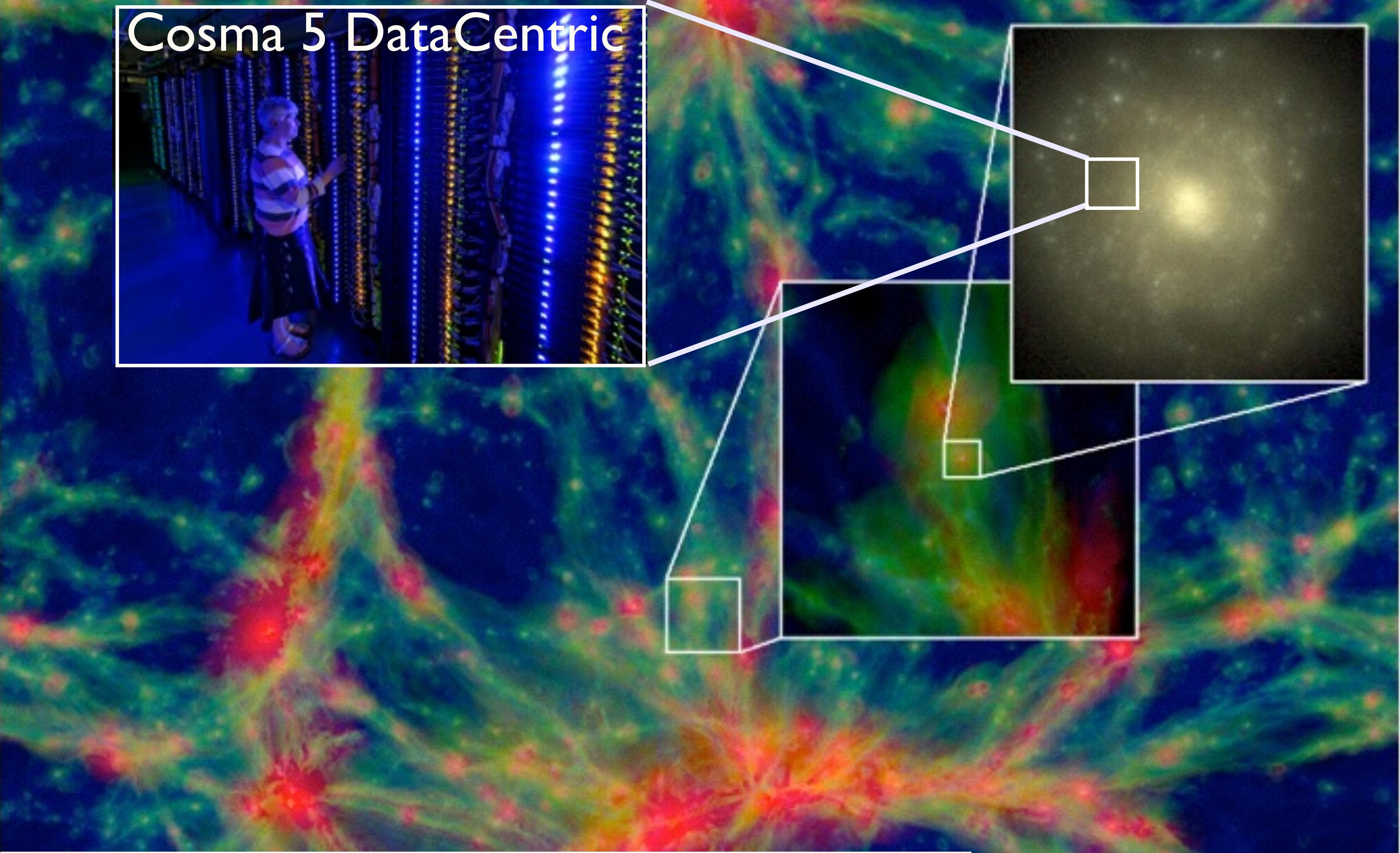


Improved SPH

“Anarchy” (Dalla Vecchia+)

Kelvin-Helmholtz instability



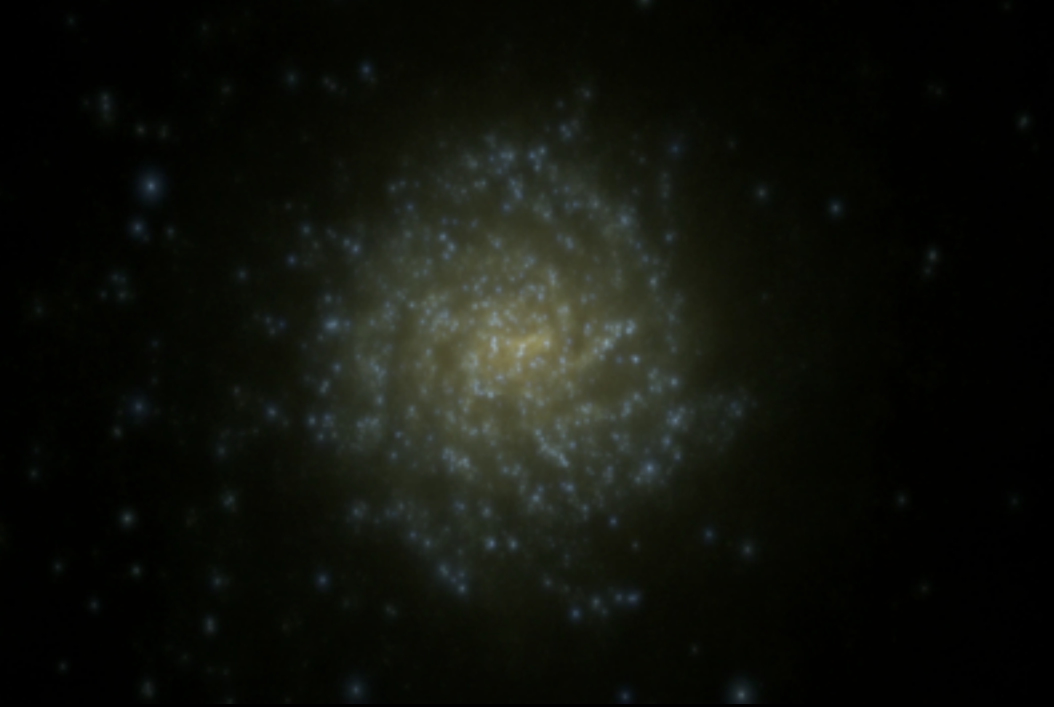


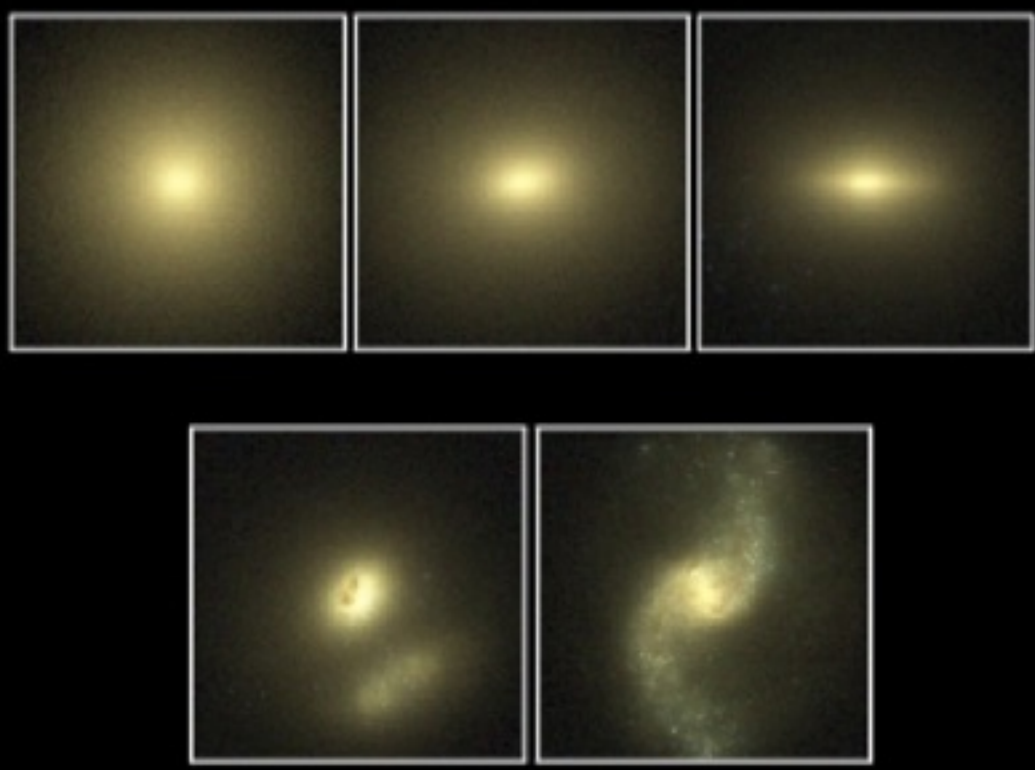
Name	L (comoving Mpc)	N	m_g ($M_\odot$)	m_{dm} ($M_\odot$)	ϵ_{com} (comoving kpc)	ϵ_{prop} (proper kpc)
L025N0376	25	376^3	1.81×10^6	9.70×10^6	2.66	0.70
L025N0752	25	752^3	2.26×10^5	1.21×10^6	1.33	0.35
L050N0752	50	752^3	1.81×10^6	9.70×10^6	2.66	0.70
L100N1504	100	1504^3	1.81×10^6	9.70×10^6	2.66	0.70

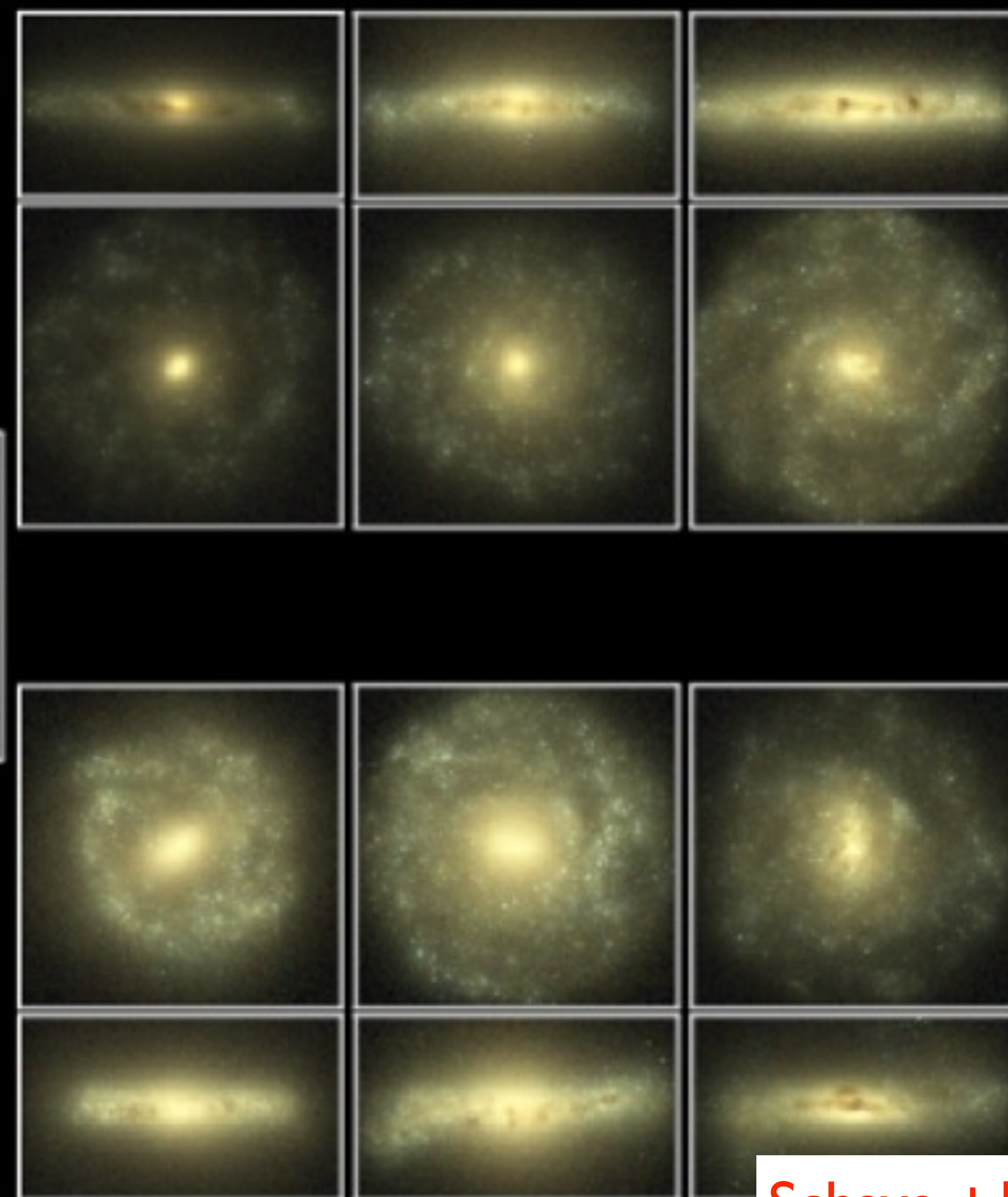
7 M CPU hours

Schaye +14

The Hubble Sequence



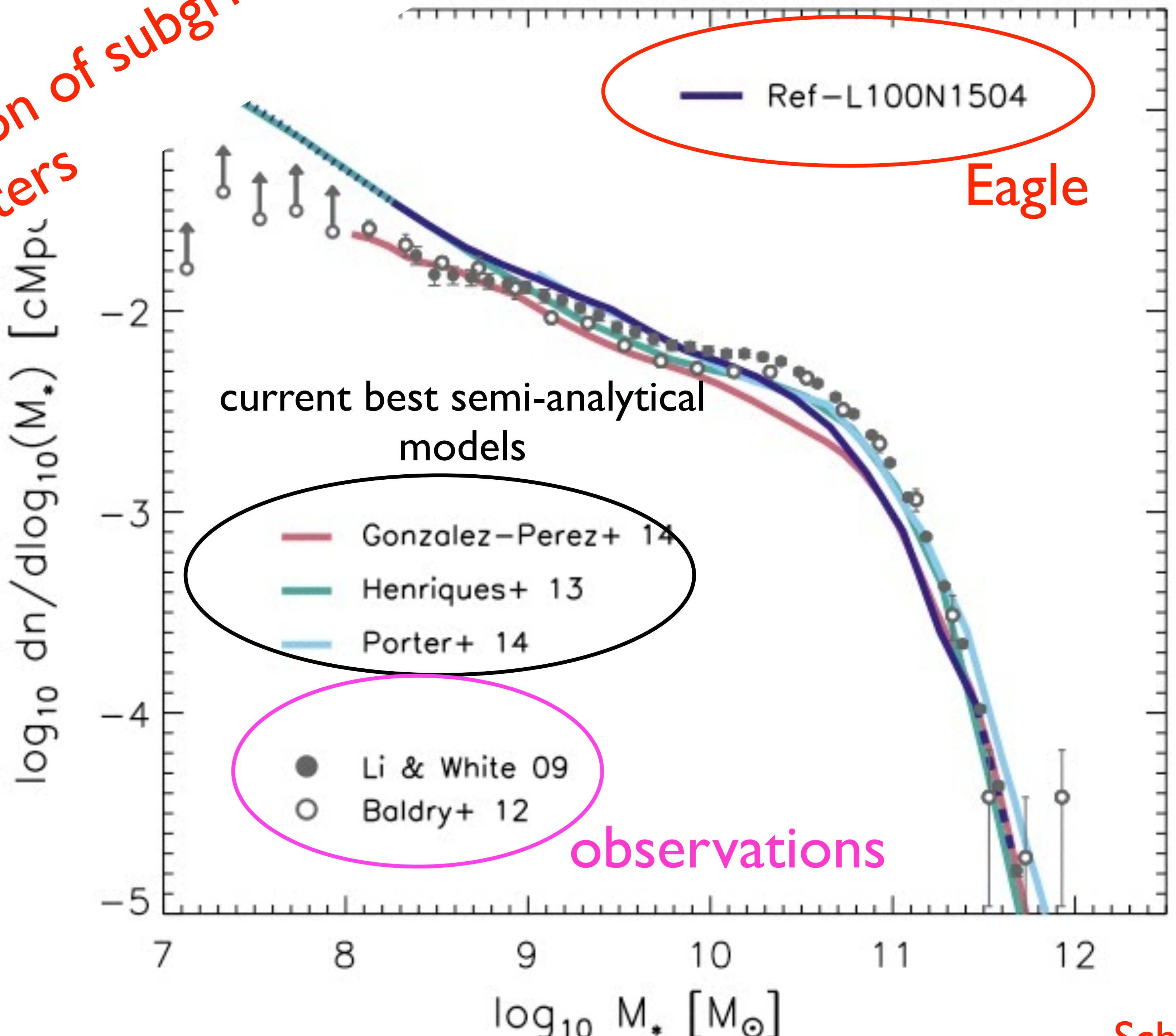




Schaye +14

...ellar mass function

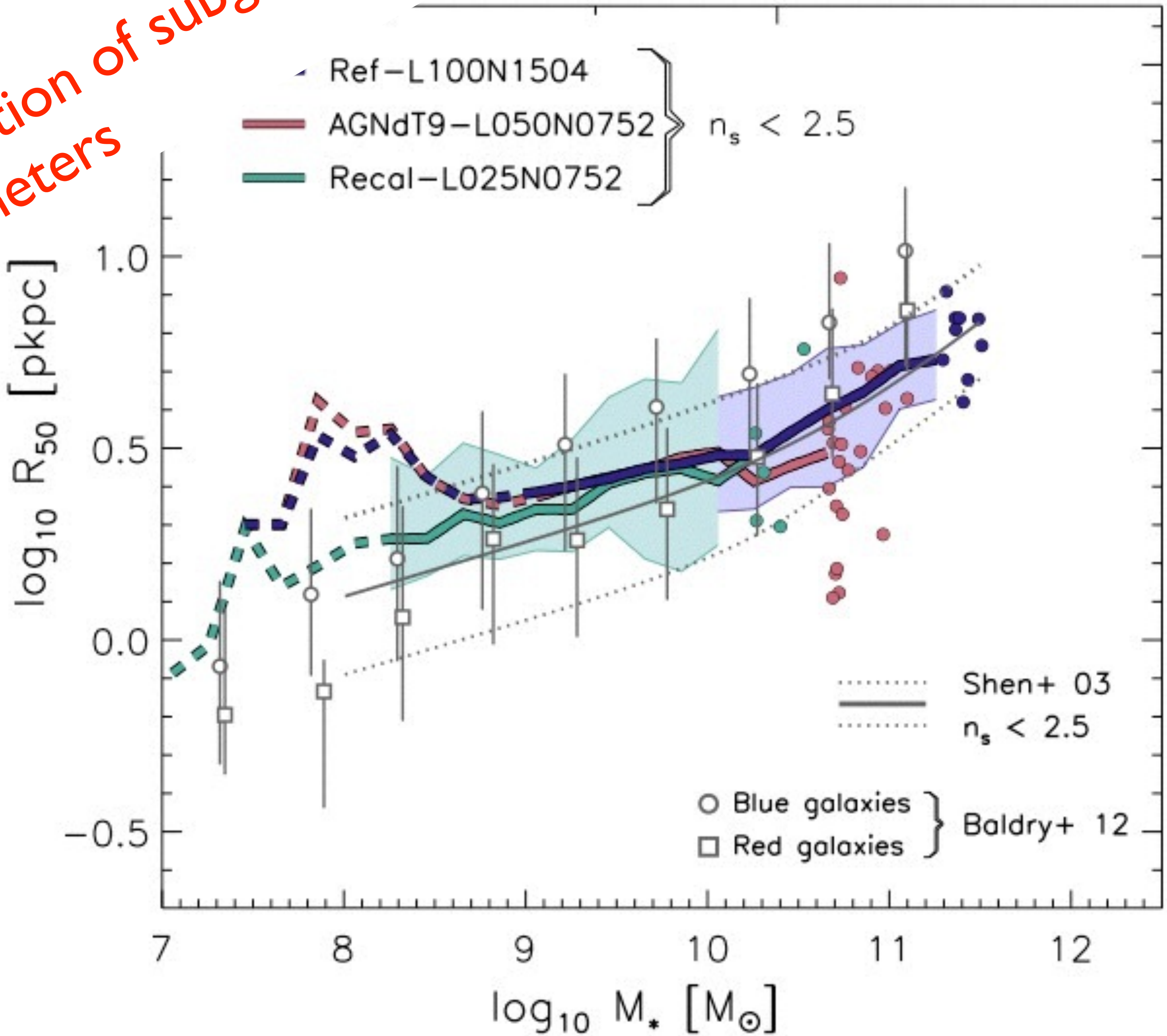
Calibration of subgrid parameters



Schaye +14

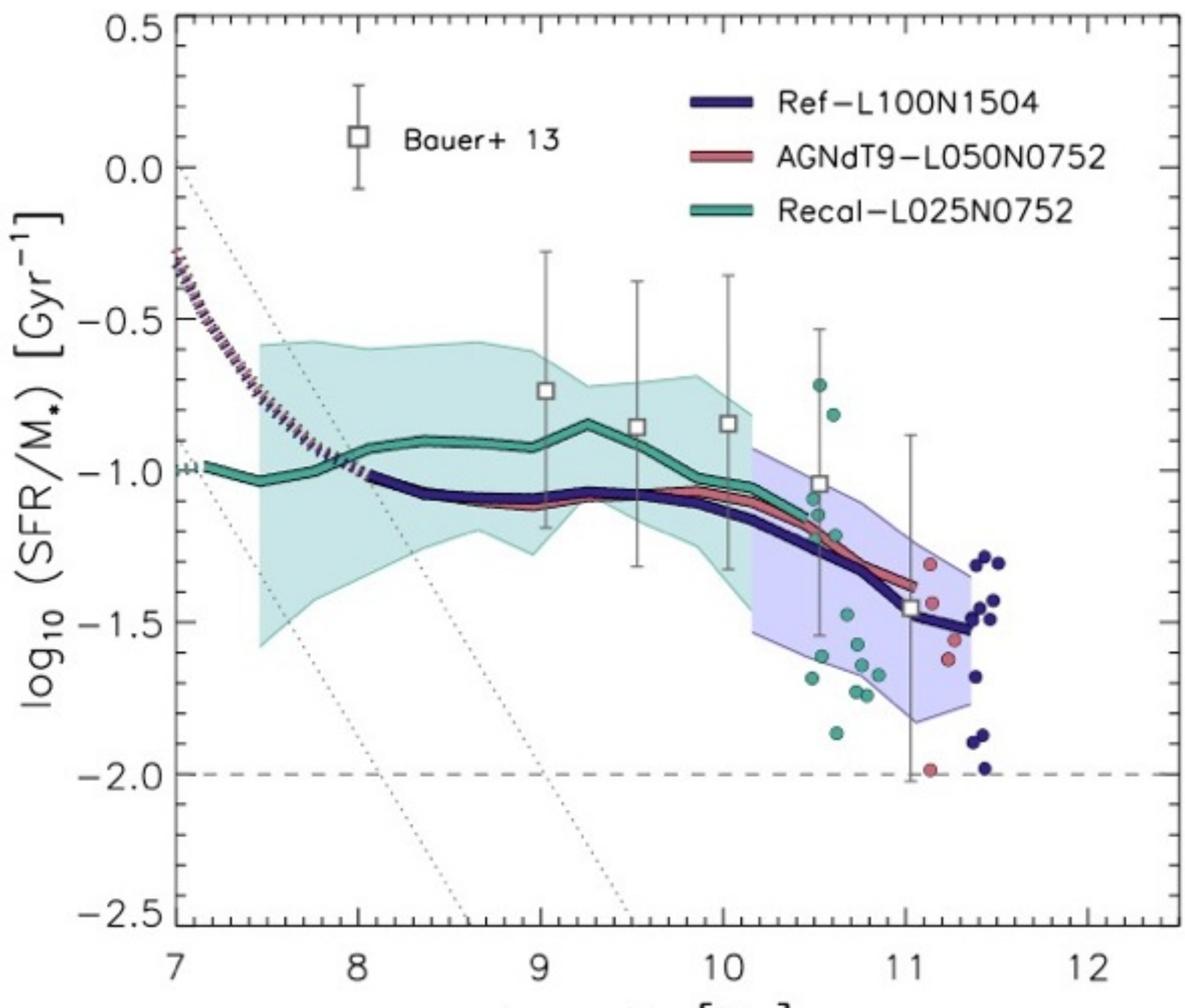
Galaxy sizes

Calibration of subgrid parameters



Schaye +14

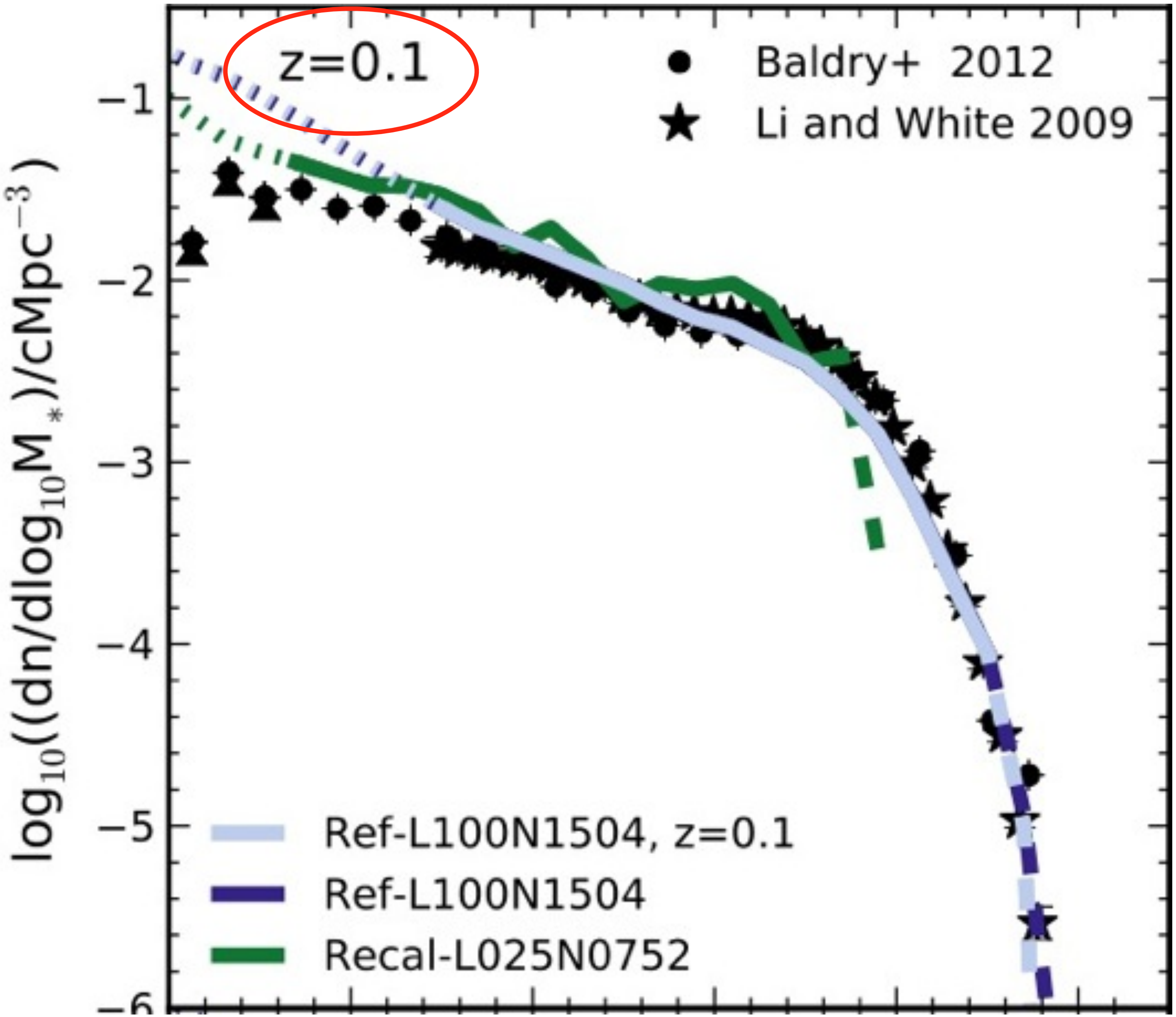
Specific star formation rate as function of galaxy stellar mass



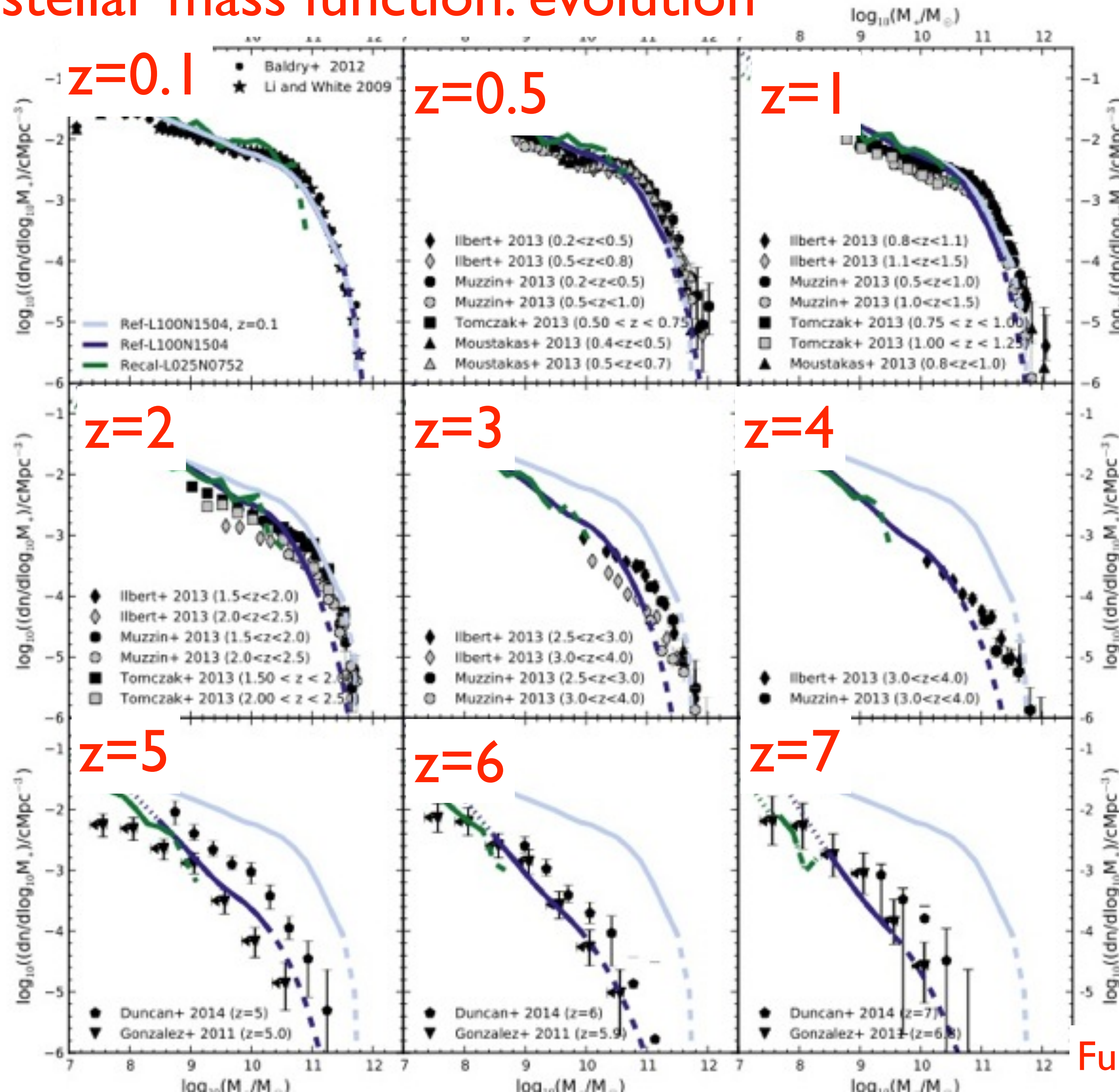
Schaye +14

Galaxy stellar mass function: evolution

Furlong +14a (Durham)



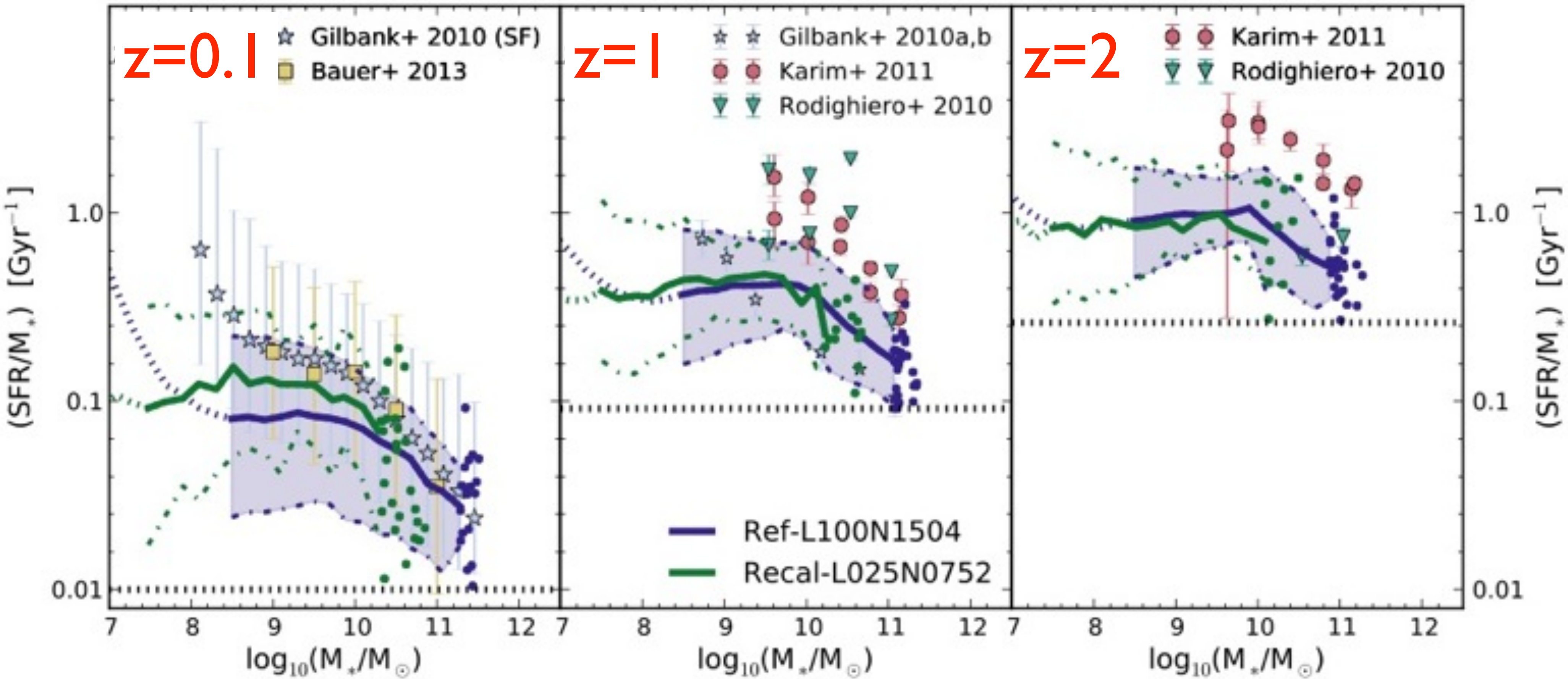
Galaxy stellar mass function: evolution



ICC

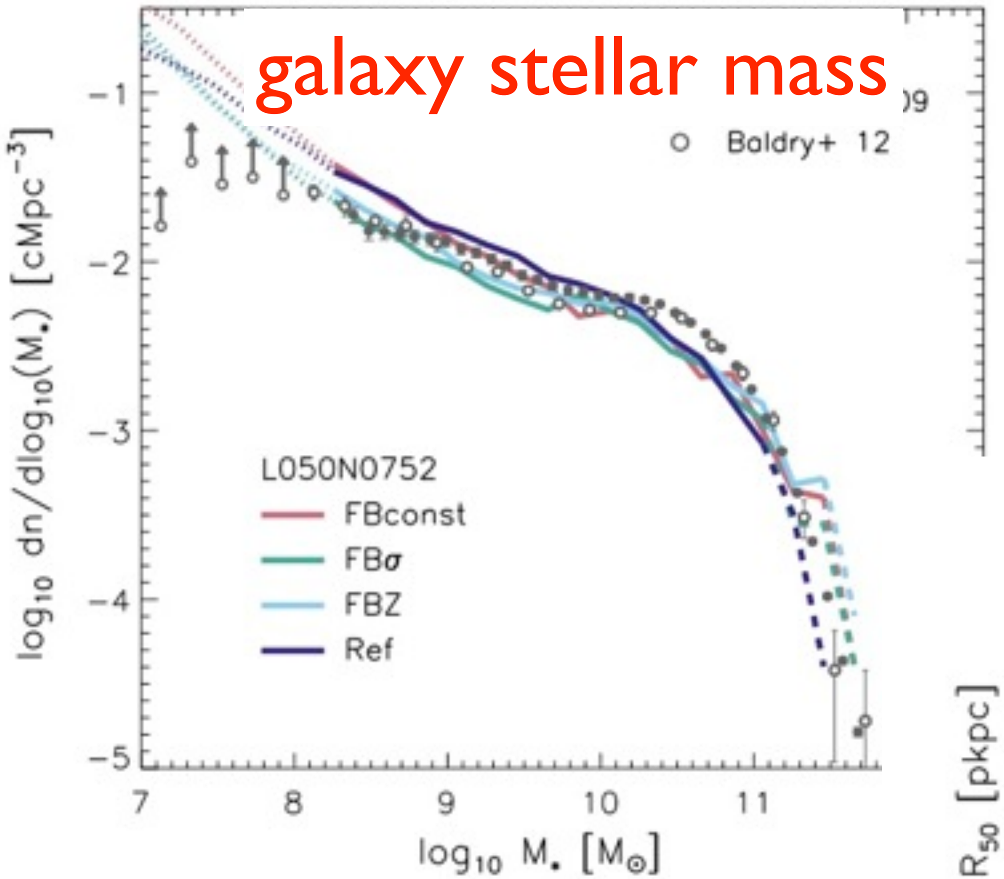
Furlong +,14a

Specific star formation rate: evolution

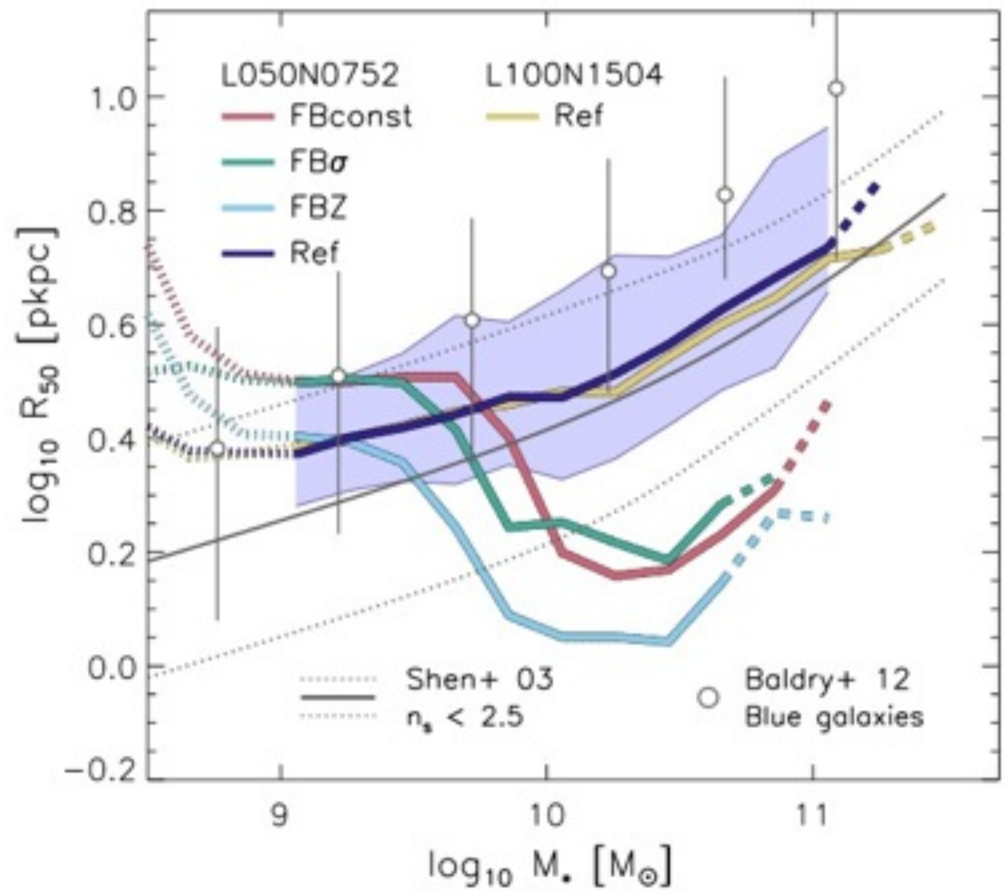


Furlong +,14a

Calibration: enough, but not too much



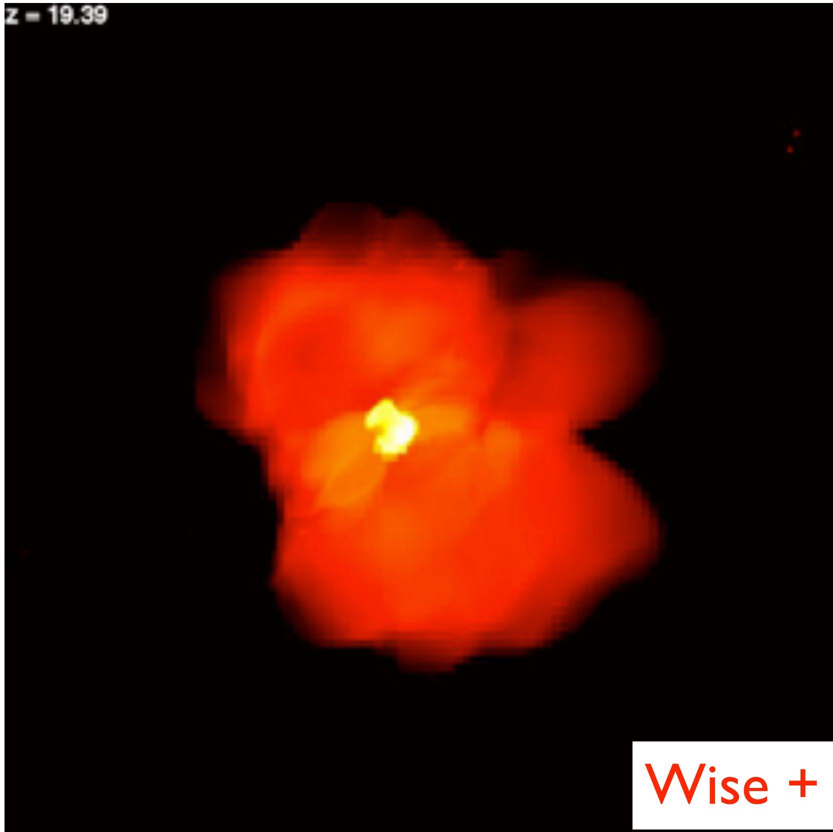
Galaxy sizes



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



Wise +

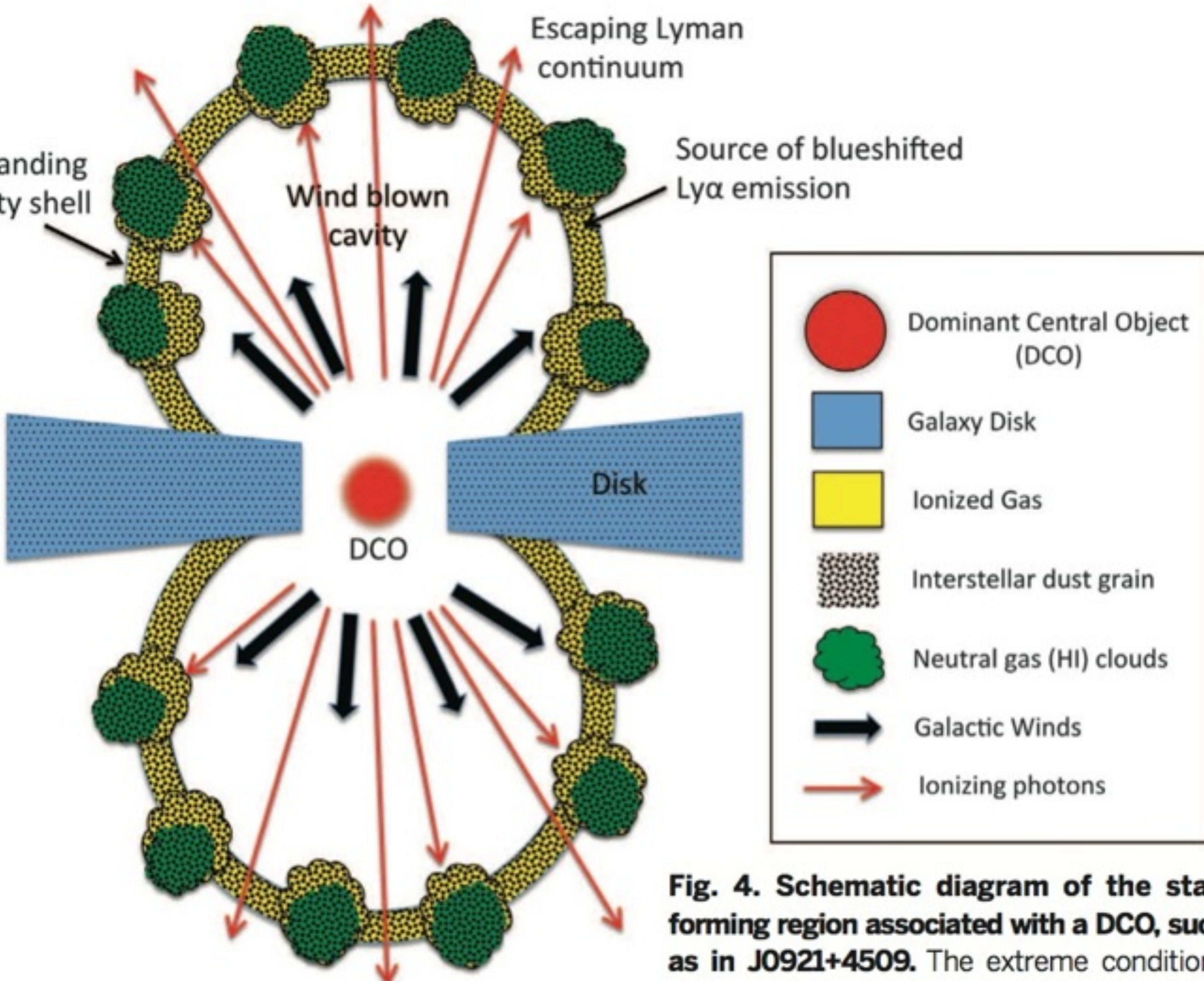
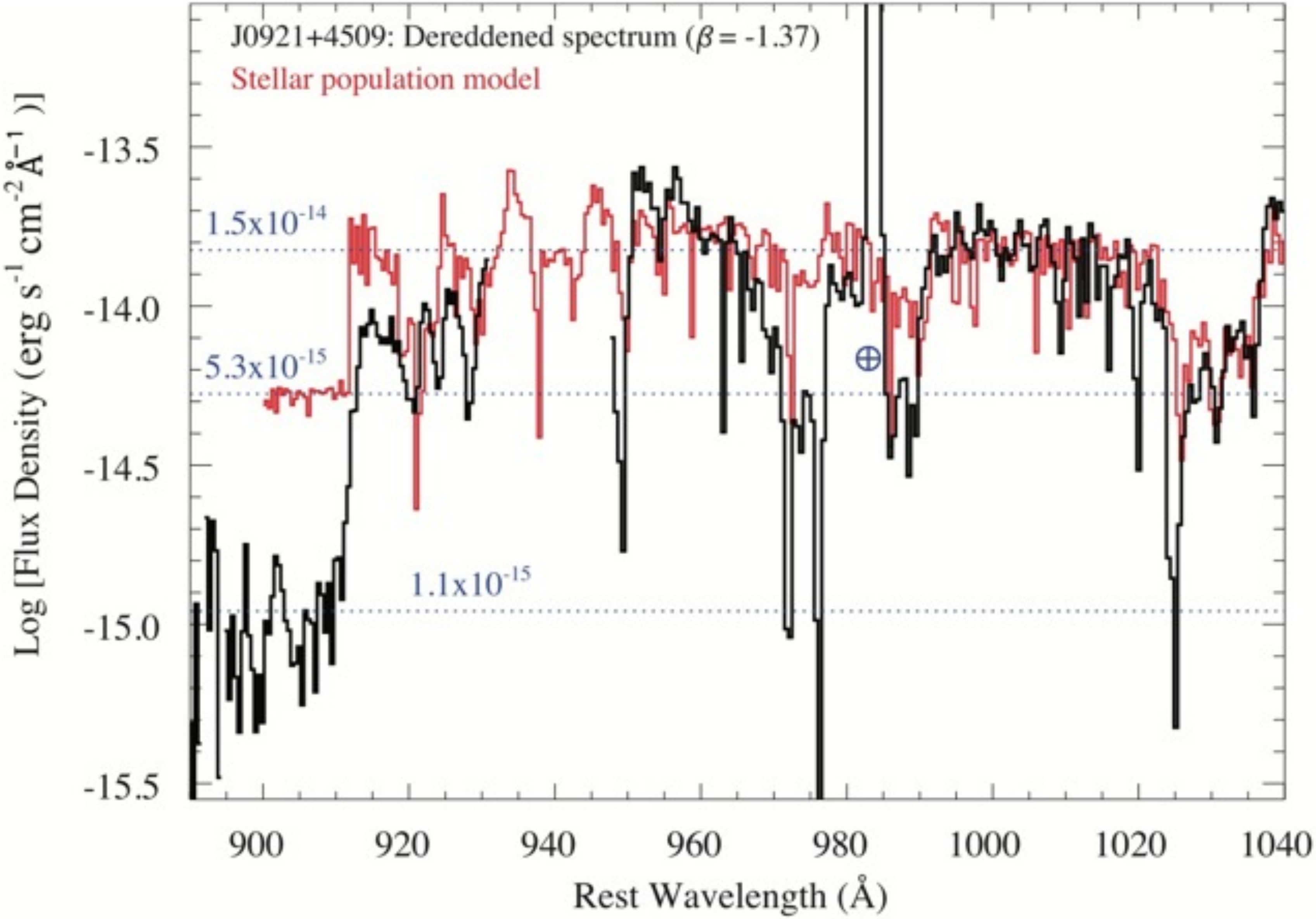


Fig. 4. Schematic diagram of the star-forming region associated with a DCO, such as in J0921+4509. The extreme conditions in the DCO generate a strong galactic wind

Borthakur+14

20 % escape fraction at z=0!



Borthakur+14

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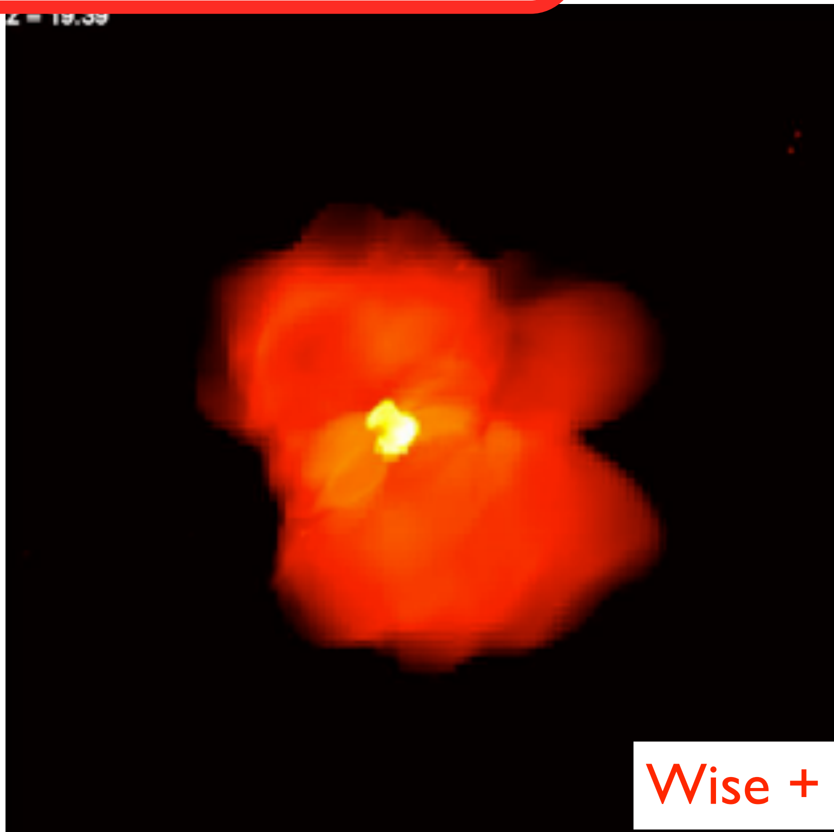
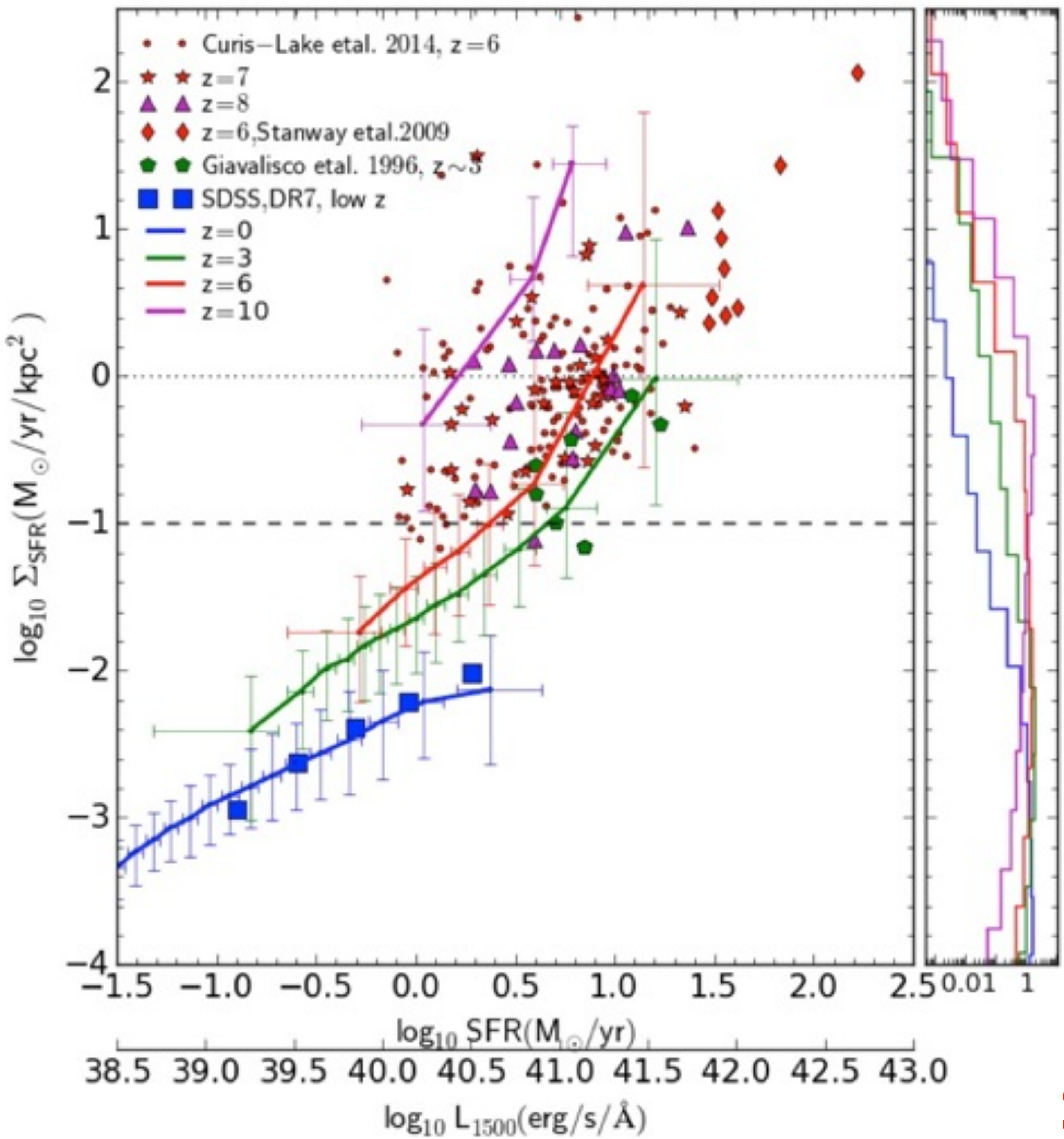


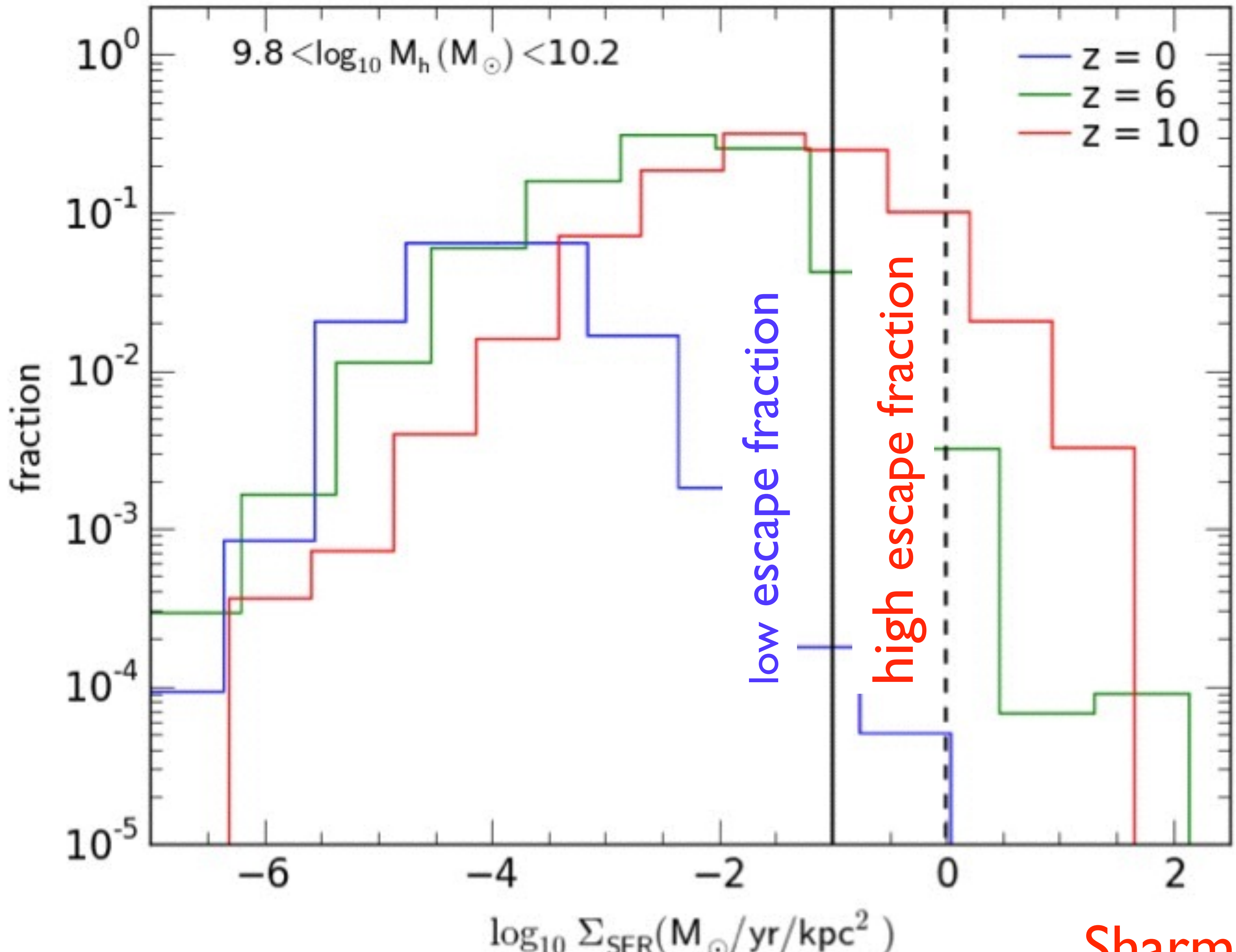
Wise +

Evolution of star formation rate density: Eagle compared to observations



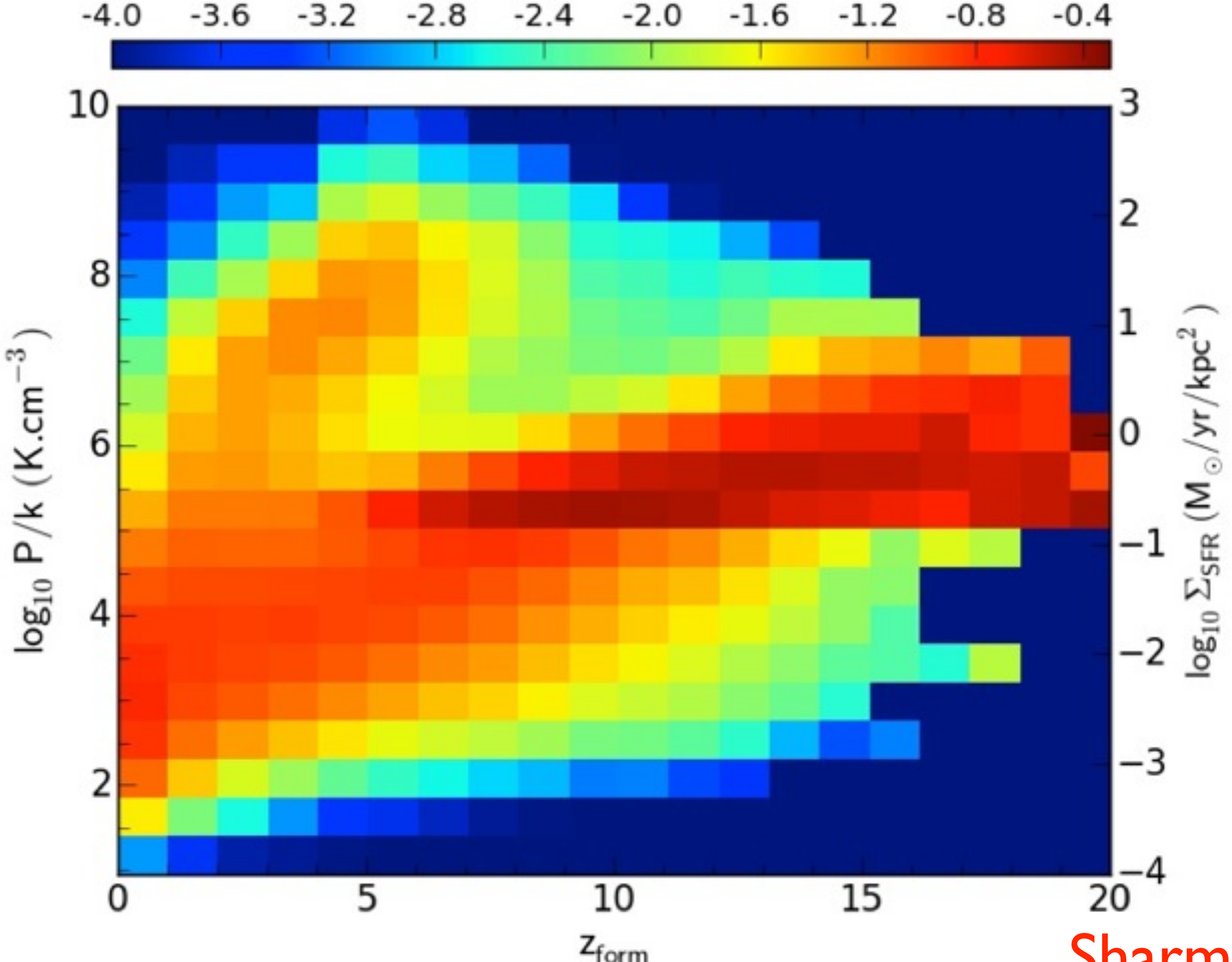
Sharma +15

Evolution of PDF of star formation in Eagle



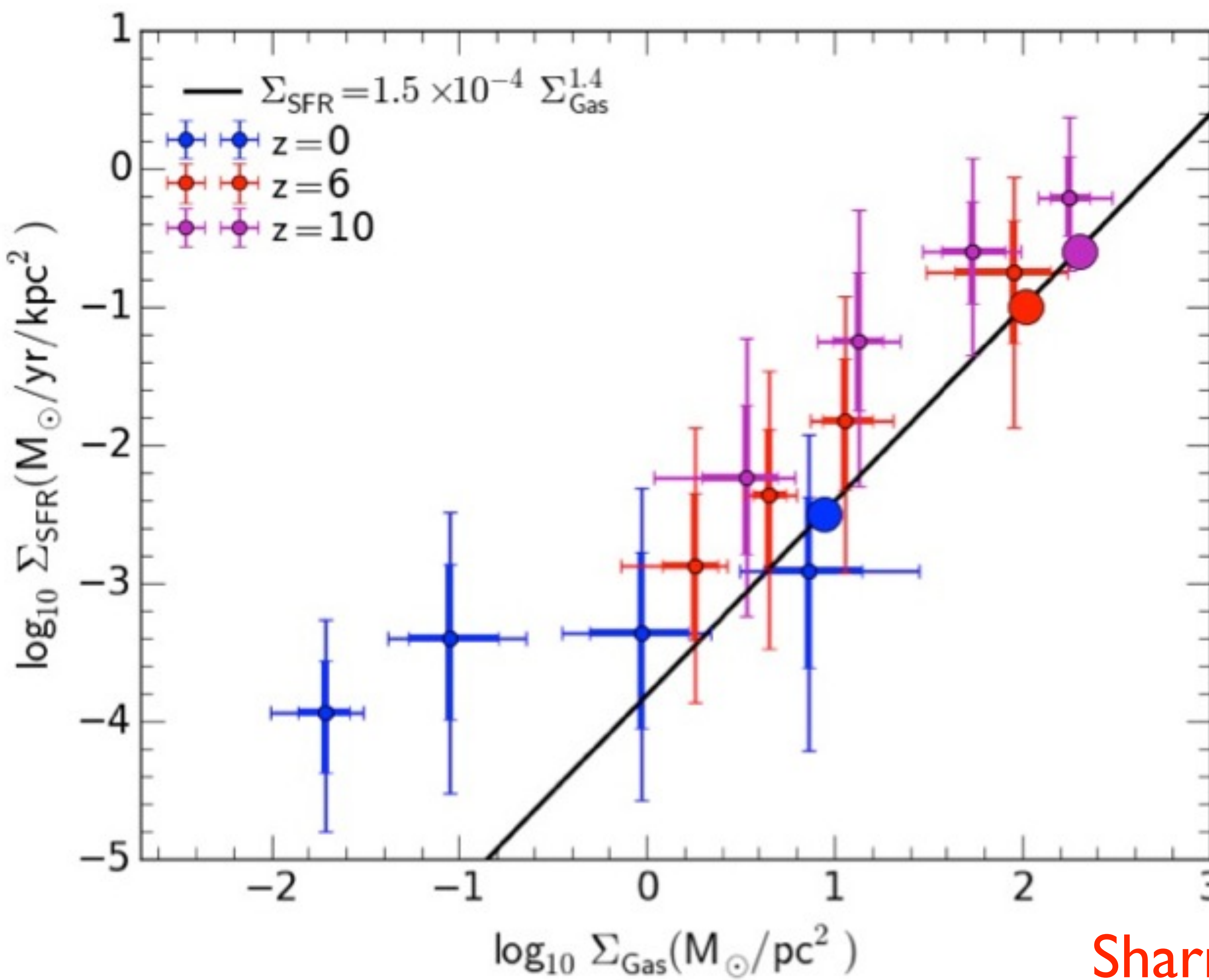
Sharma +15

Strong evolution in Eagle (and real Universe) due to increase in pressure of star forming gas

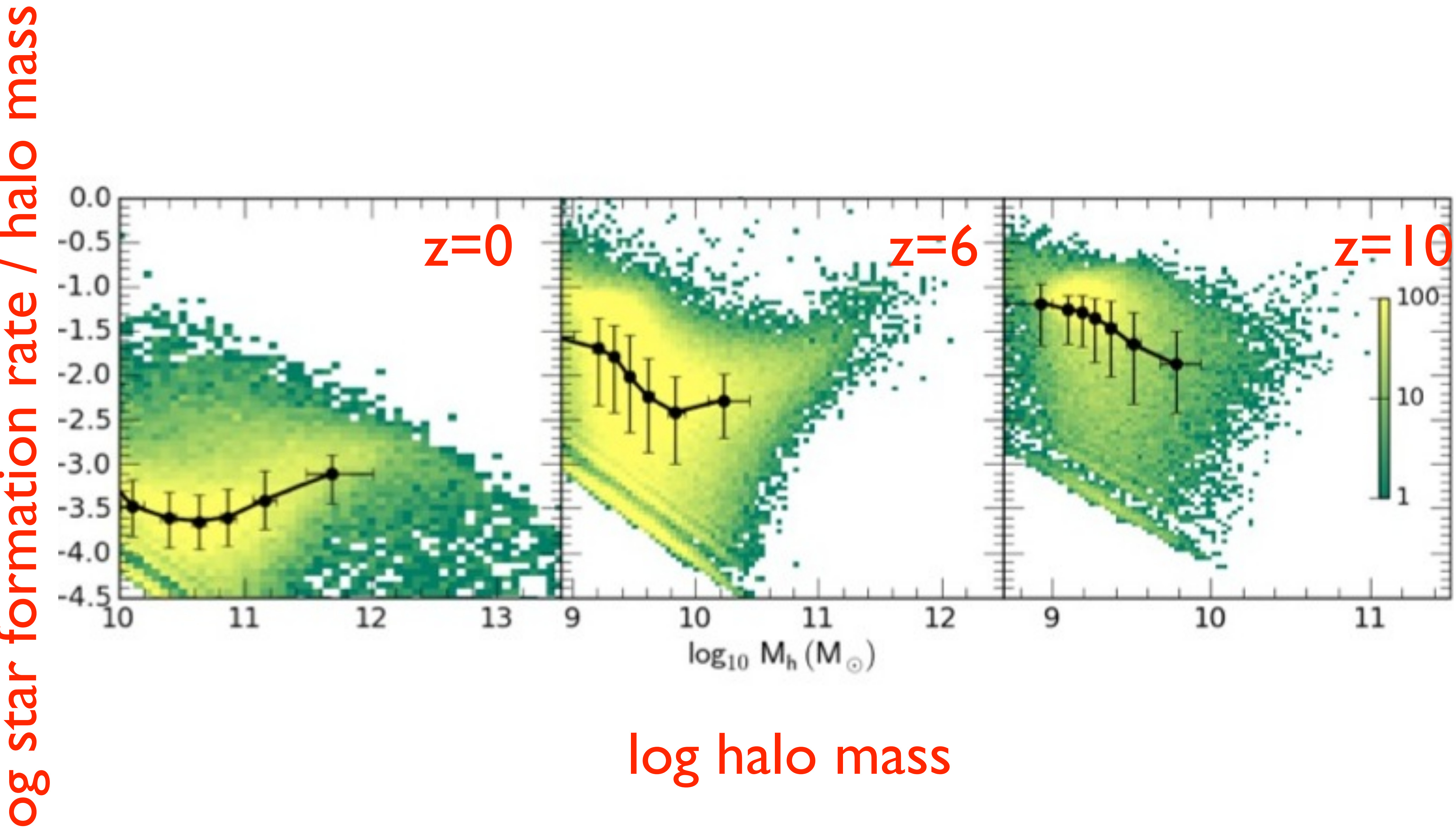


Sharma +15

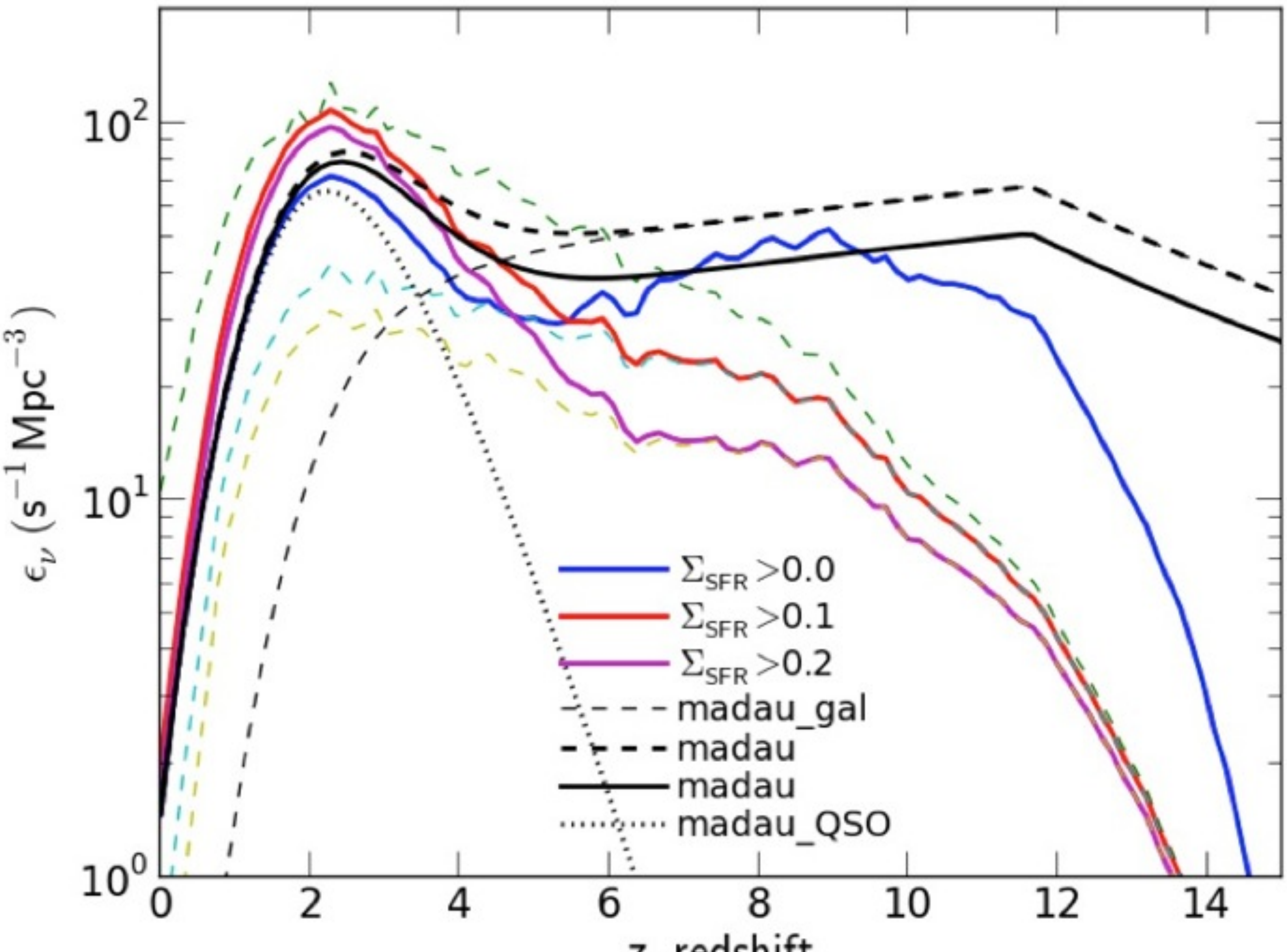
Galaxies evolve along the Kennicutt-Schmidt relation towards star bursts



Sharma +15

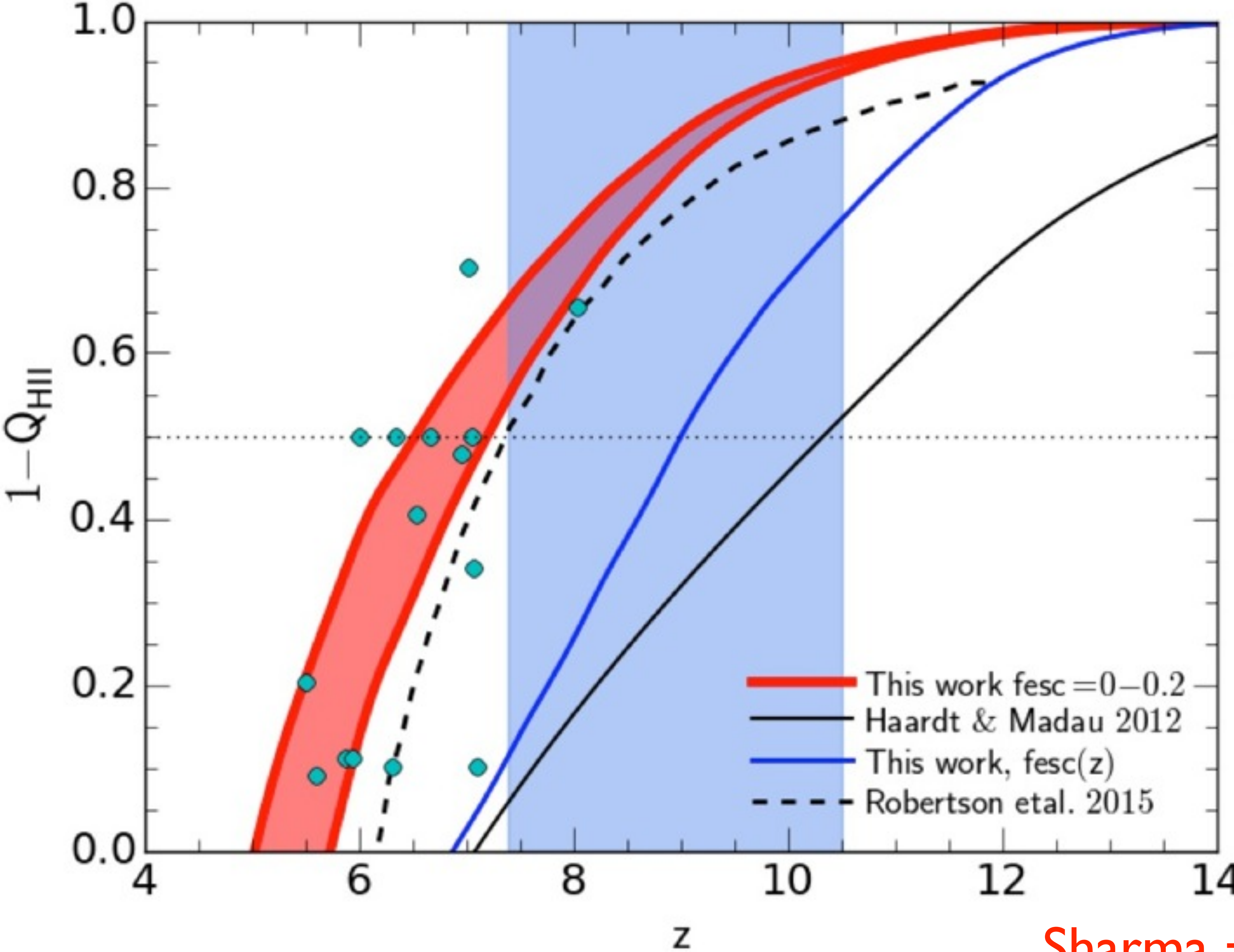

log star formation rate / halo mass
z=0
z=6
z=10
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
10
11
12
13
9
10
11
12
9
10
11
100
10
1
$\log_{10} M_h\ (M_\odot)$
log halo mass

Build-up of emissivity



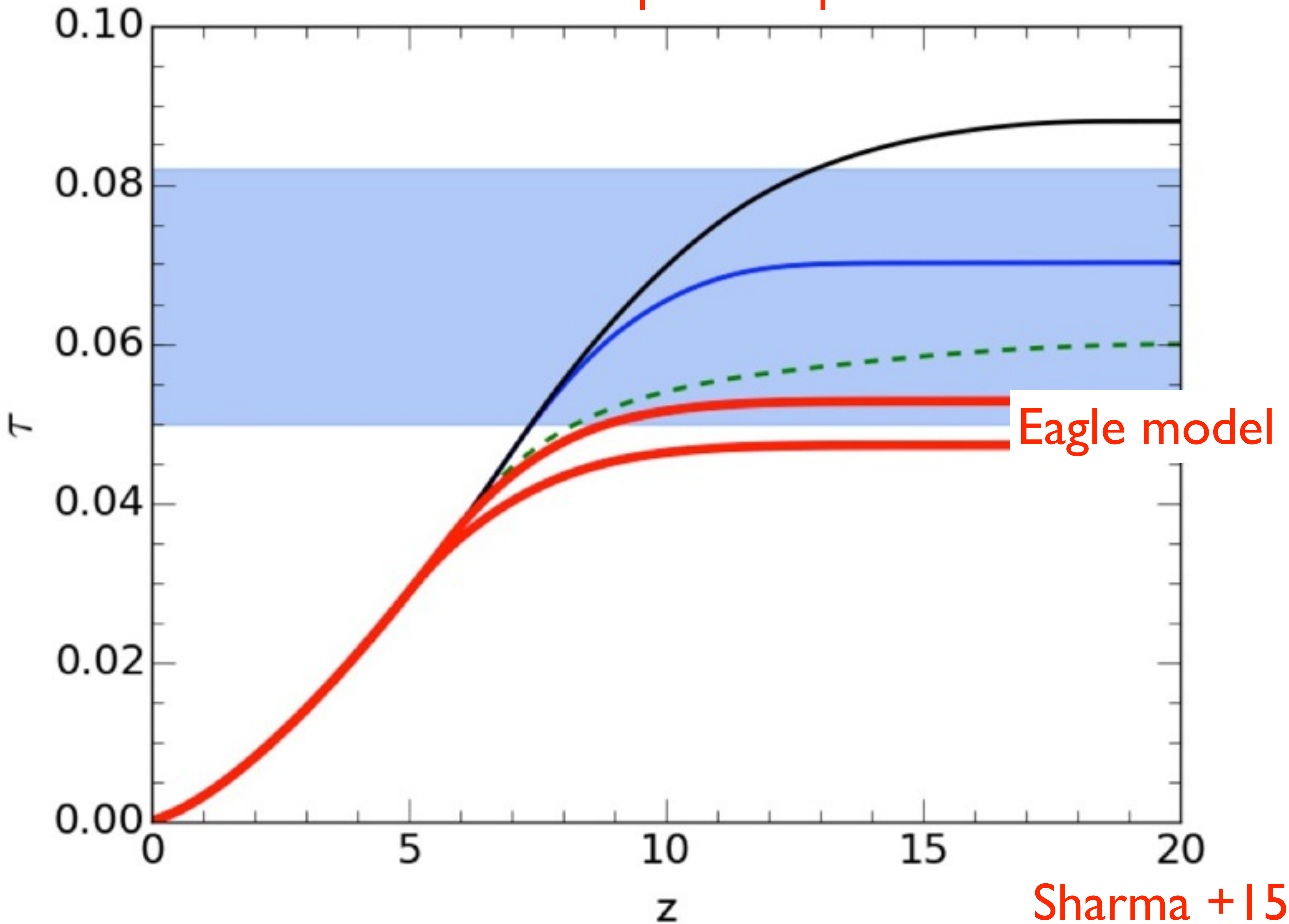
Sharma +15

Evolution of neutral/ionised fraction



Sharma +15

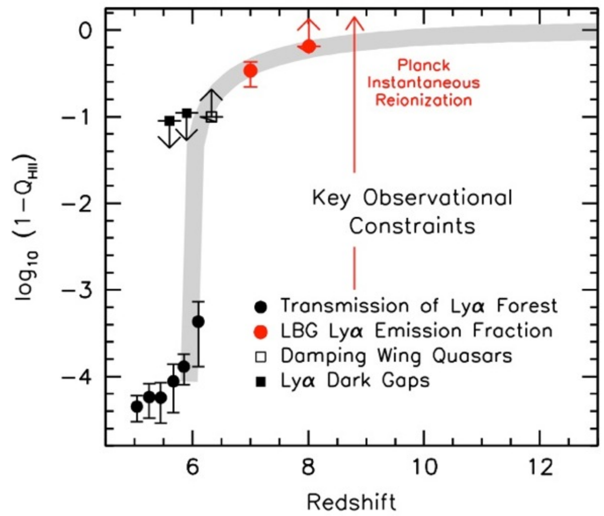
Thomson optical depth



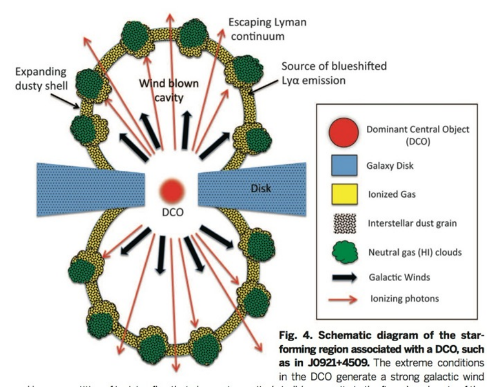
Sharma +15

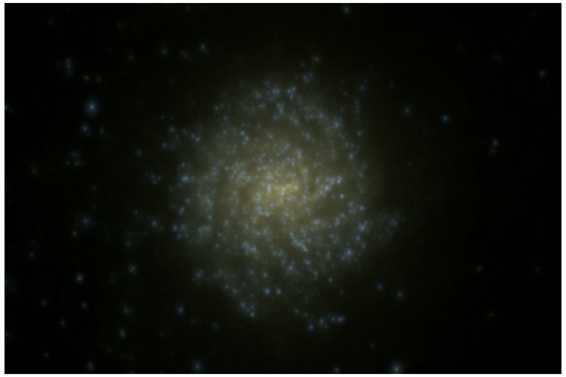
Summary:

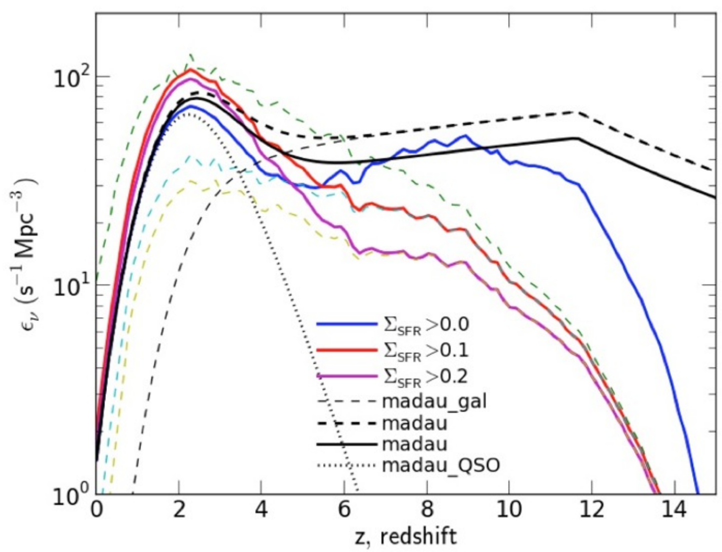
transition of mostly neutral to mostly ionised

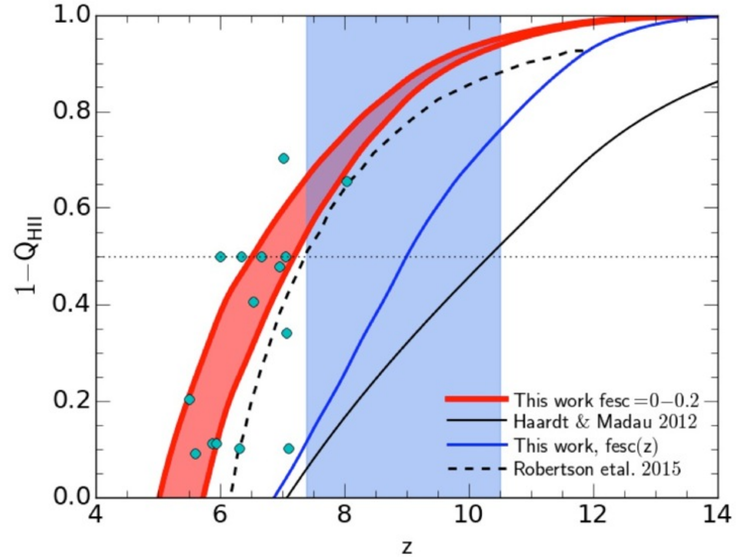


Eagle: reionisation due to bright galaxies with high SFR density









Reionisation and the build-up of the UV-background in Eagle

Tom Theuns
ICC, Durham
for the Eagle collaboration

Mahavir Sharma
ICC, Durham

Swift: SPH on current/future architectures

Gonnet, Schaller, Theuns, Chalk

SWIFT: Task-based parallelism, hybrid shared/distributed-memory parallelism, and SPH simulations

arXiv:1309.3783

Task-based parallelism dramatically improves load balance and overlaps communication and computation

Algorithms for SPH

Hybrid shared/distributed-memory parallelism

Durham University