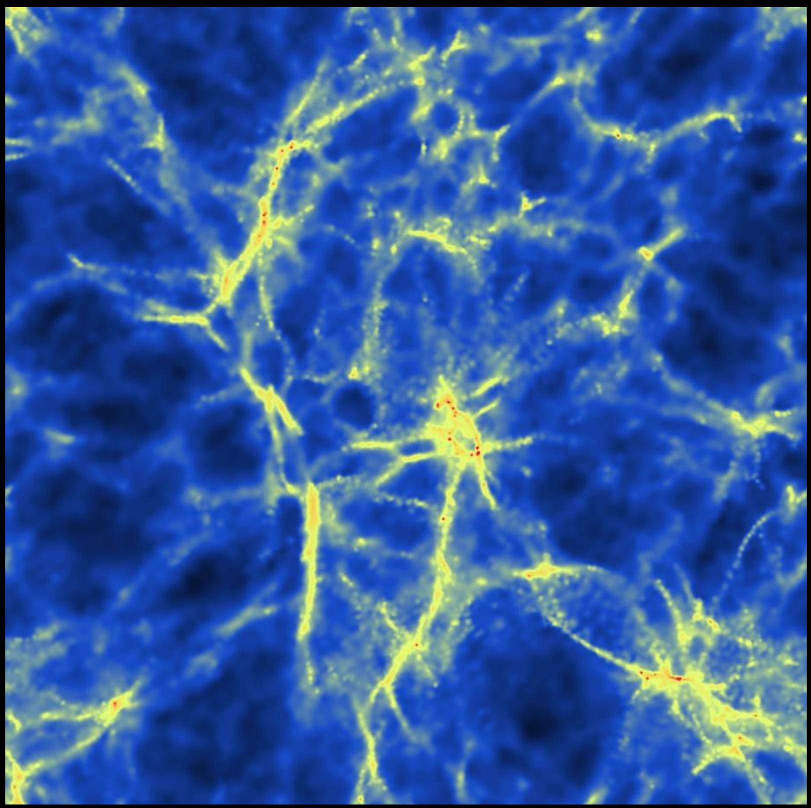
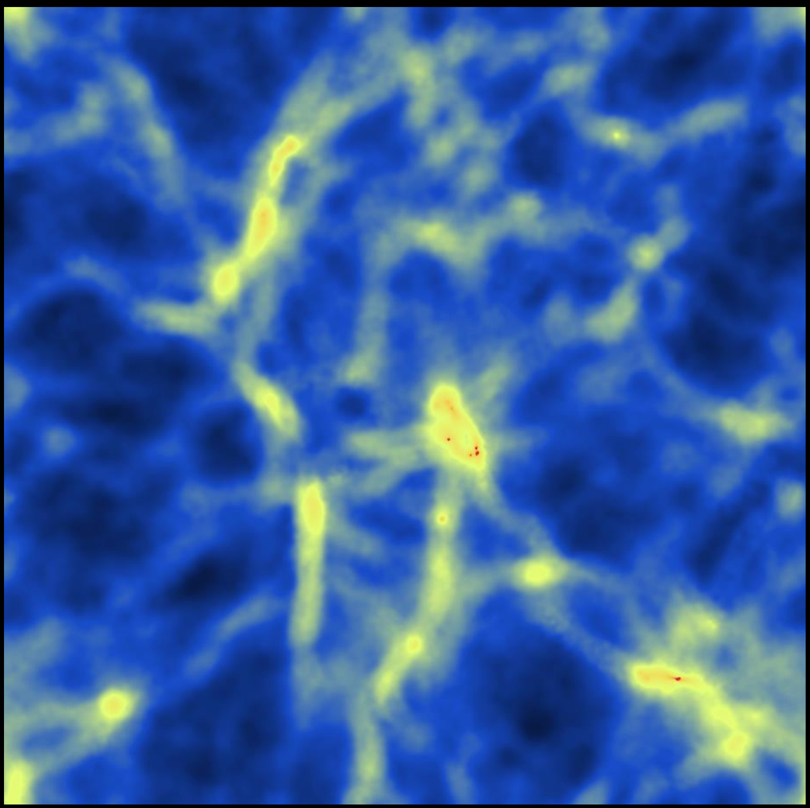
Simulations of galaxy formation and reionization





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Outline

1. Simulating the epoch of reionization
2. The Aurora radiation hydrodynamical simulations
3. Semi-analytic models of the epoch of reionization based on the EAGLE simulation

Some questions about the epoch of reionisation

- When did reionisation end?
- How long did it last?
- What is the topology of the HII regions?
- What types of sources are responsible?
- What are the main photon sinks?
- How many photons/baryon are required?
- What is the impact of reionisation on:
  - Galaxy formation
  - Galaxy evolution
  - The intergalactic medium

Simulations of the epoch of reionisation

- Reionisation is by definition a radiative transfer problem
- Radiative feedback:
  - Negative: floor on T_{vir} of galaxy halo
  - Negative: dissociation of molecules
  - Positive: Pressure smoothing reduces recombination rate
- Reionisation is thus a radiation-*hydrodynamics* problem

Simulations of the epoch of reionisation

- Mass of objects quenched by
  - photo-heating: $\sim 10^8\ M_\odot$ → 25 cMpc box for 1000^3 particles and 100 particles per halo
  - Photo-dissociation: $\sim 10^5\ M_\odot$ → 3 cMpc box for 1000^3 particles and 100 particles per halo
- To begin to resolve the cold ISM phase, we need particle mass << $10^3\ M_\odot$ → 1 cMpc box for 1000^3 particles
- Consequences:
  - ➢ Cannot do radiation-hydrodynamics for simulation volumes appropriate for 21cm experiments
  - ➢ Cannot accurately predict efficiency of stellar feedback
    - → Need to calibrate (to observed luminosity function)
  - ➢ Cannot accurately predict escape fraction
    - → Need to calibrate (to reionisation history)

Simulations of the epoch of reionisation

Cannot predict from first principles

- Galaxy mass and SFR functions
- Reionisation history

Simulations of the epoch of reionisation

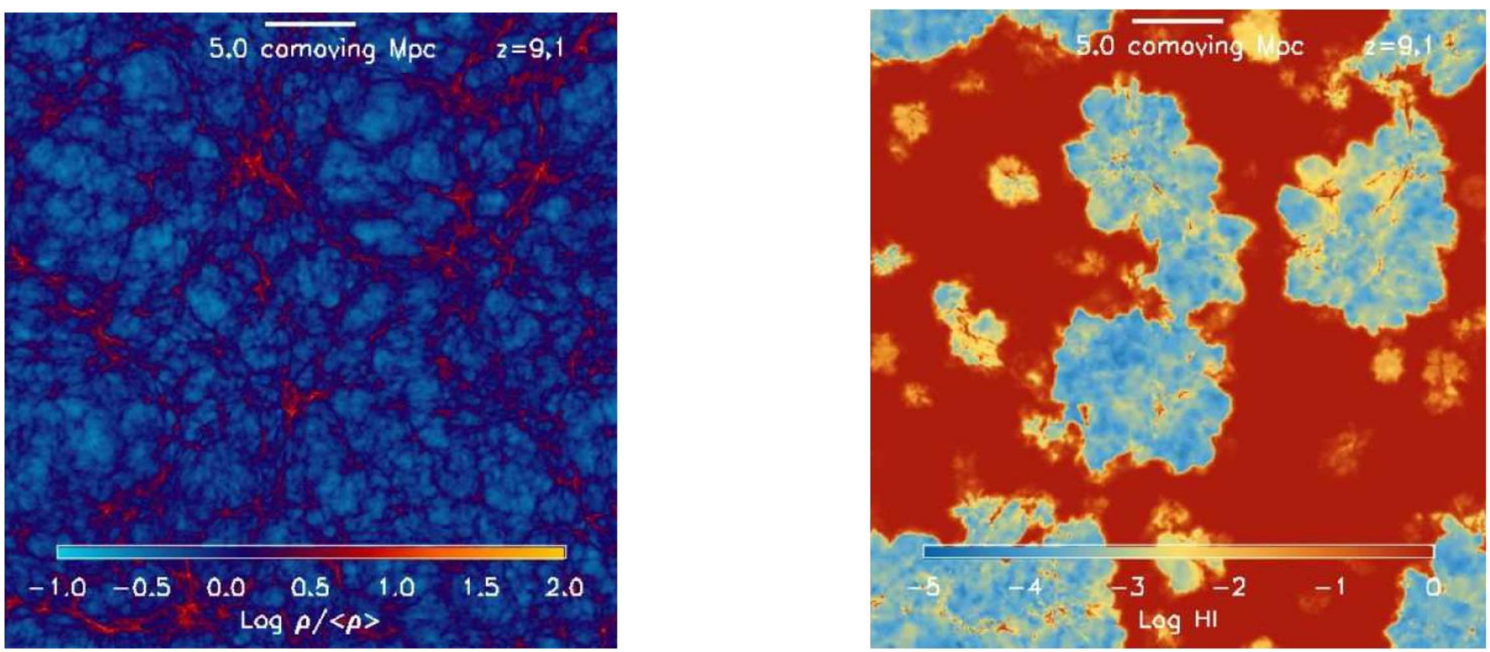
- Most reionisation simulations:
  - Post-process dark matter simulations
  - Use a radiative transfer method that is not spatially adaptive → extremely poor resolution, e.g. 500^3 in 100 cMpc box gives cell size of 200 ckpc
  - Group sources
  - Use radiative transfer with and accuracy that is limited and that cannot be controlled
- Most radiative transfer simulations similar to semi-numerical methods, which have therefore not yet been tested

Spatially adaptive radiation-hydrodynamical simulations of galaxy formation during cosmological reionization

Andreas H. Pawlik[1⋆], Joop Schaye[2], Claudio Dalla Vecchia[3,4] 2015, MNRAS, 451, 1586

The Aurora radiation-hydrodynamical simulations of reionization: calibration and first results.

Andreas H. Pawlik[1⋆], Alireza Rahmati[2], Joop Schaye[3], Myoungwon Jeon[4], Claudio Dalla Vecchia[5,6] 2016, MNRAS, submitted (arXiv:1603.00034)

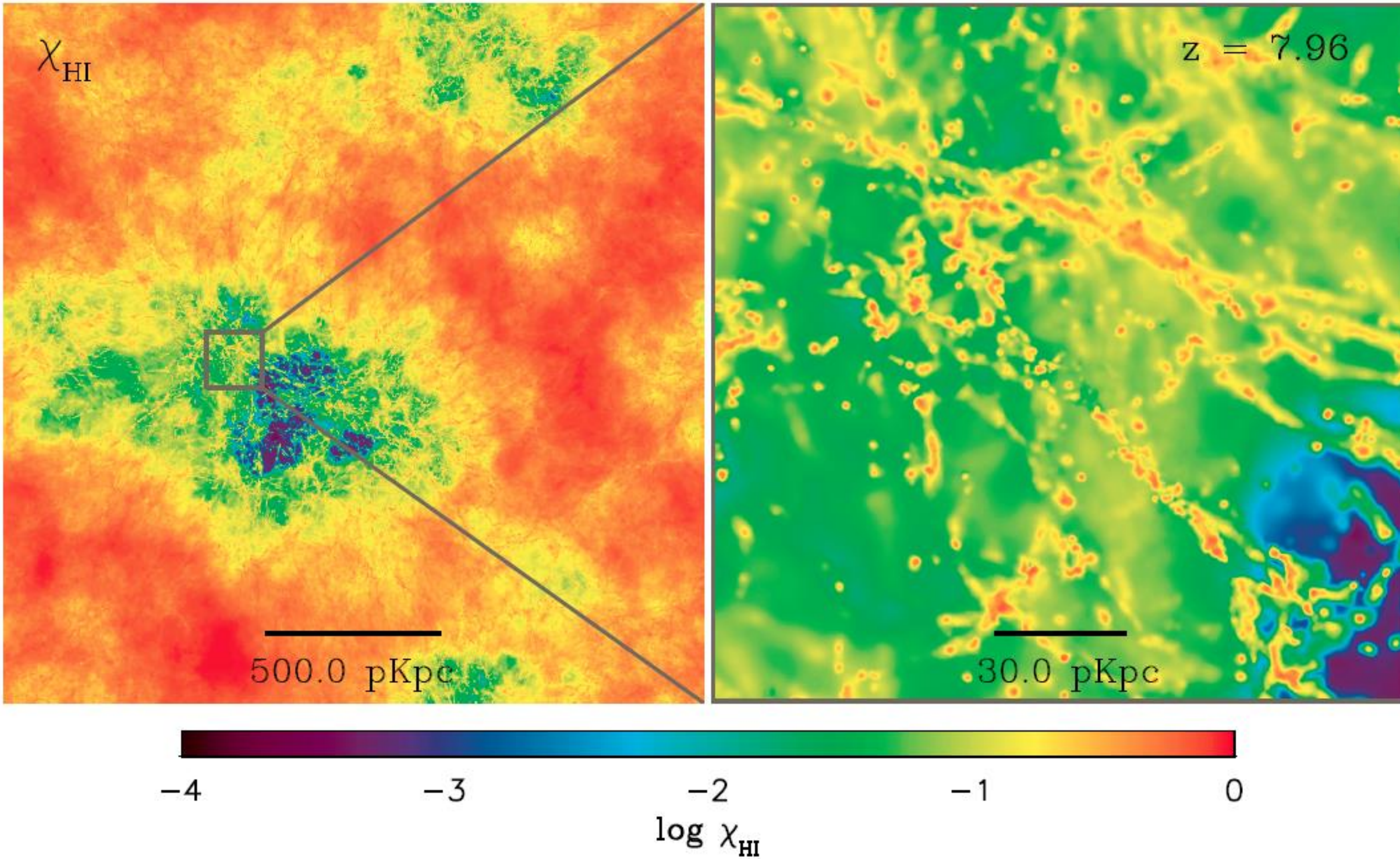


The Aurora project

- Spatially adaptive, accurate radiation hydrodynamics with TRAPHIC (Pawlik & JS ‘08, ‘11)
- Cosmological simulations, box size up to 100 Mpc
- Up to $2x1024^3$ particles, equivalent to $\sim 26{,}000^3$ uniform grid
- Highest resolution ~1 kpc comoving, $\sim 3x10^5\ M_\odot$
- For each resolution and box size:
    - Subgrid stellar feedback calibrated to z=7 SFR function
    - Subgrid escape fraction calibrated to achieve reionization at z = 8.3
- Supernova feedback and photoheating individually turned on and off

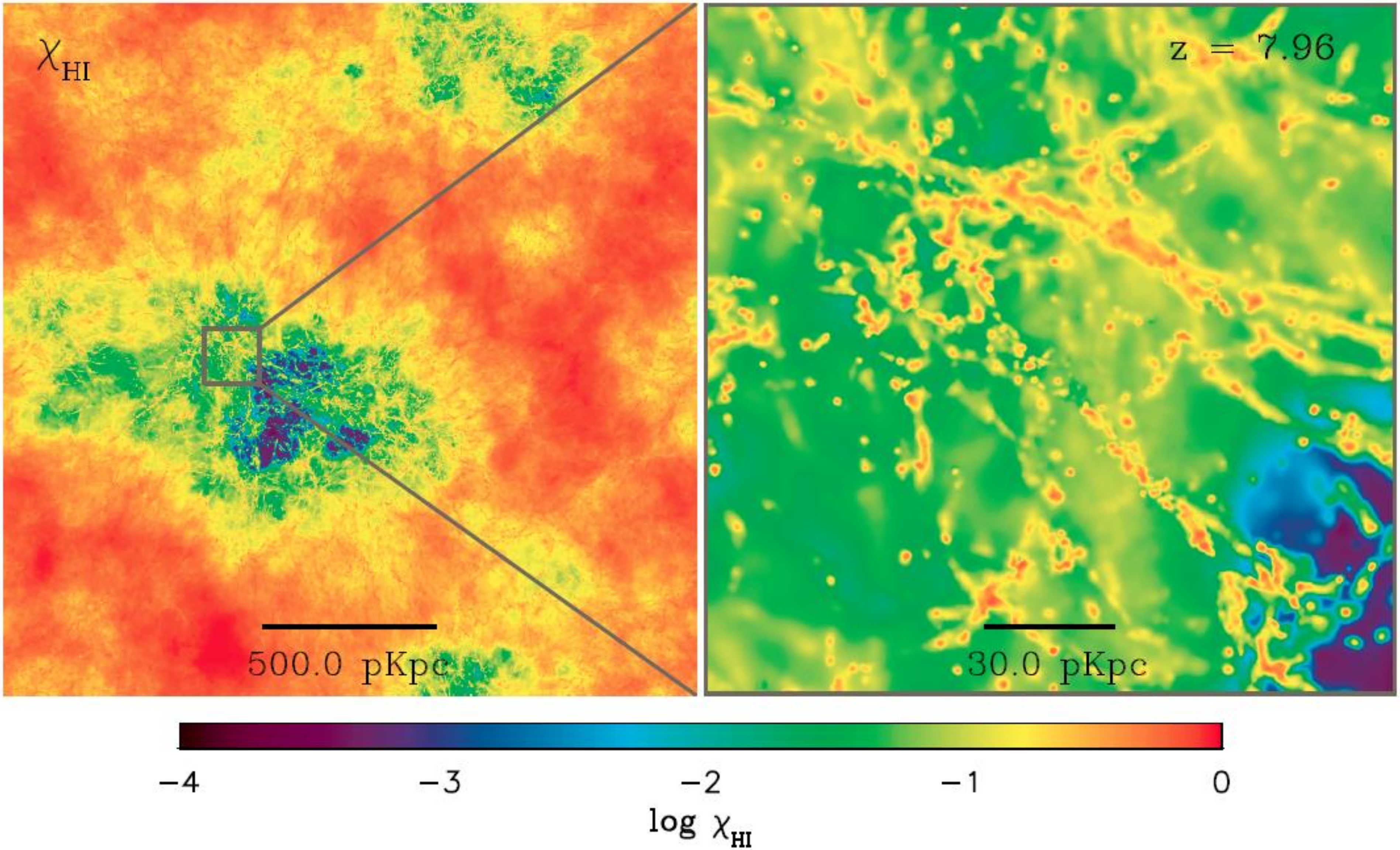
Pawlik, Rahmati, JS+ (2016)

The Aurora project



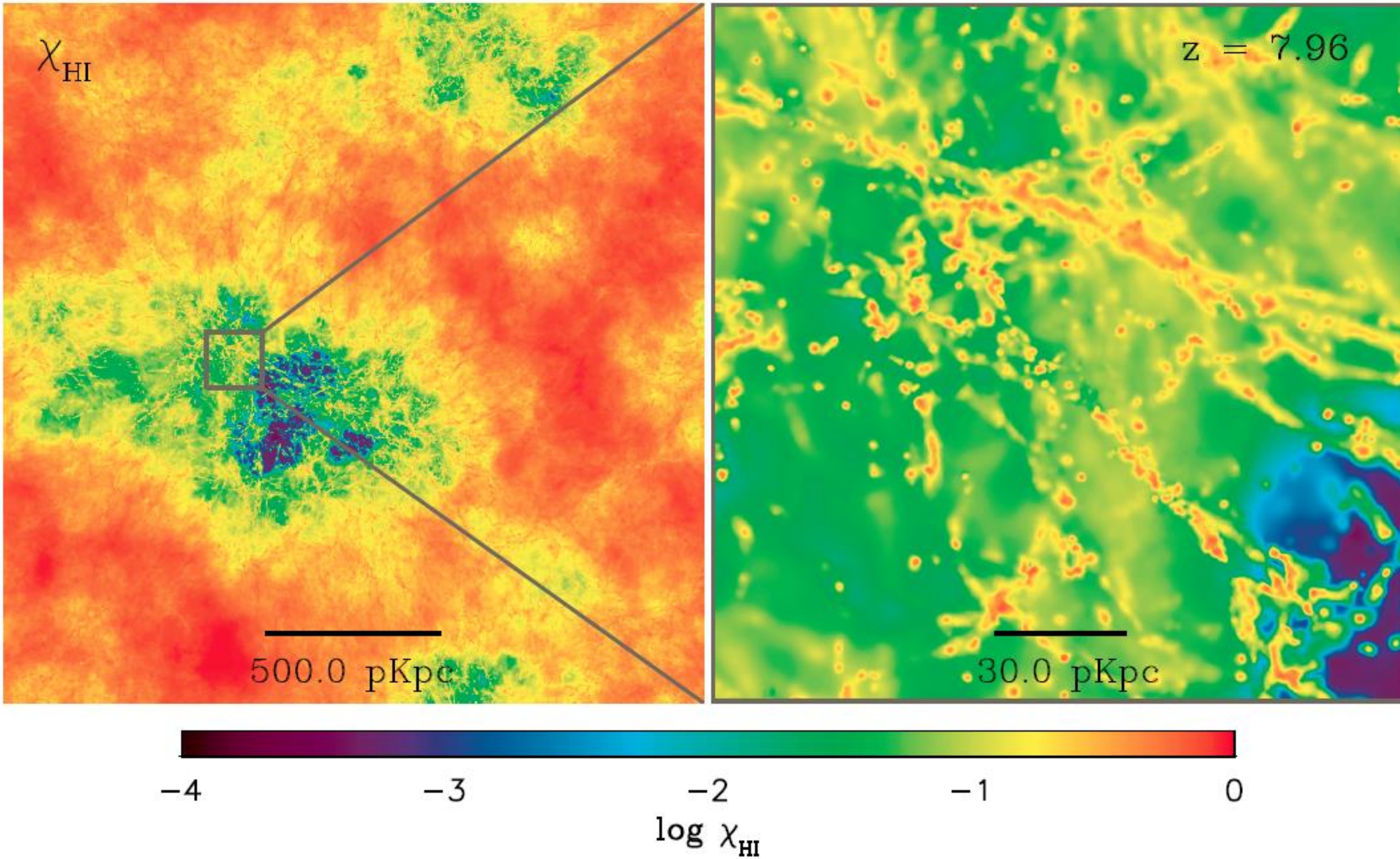
Pawlik, Rahmati, JS+ (2016)

The Aurora project



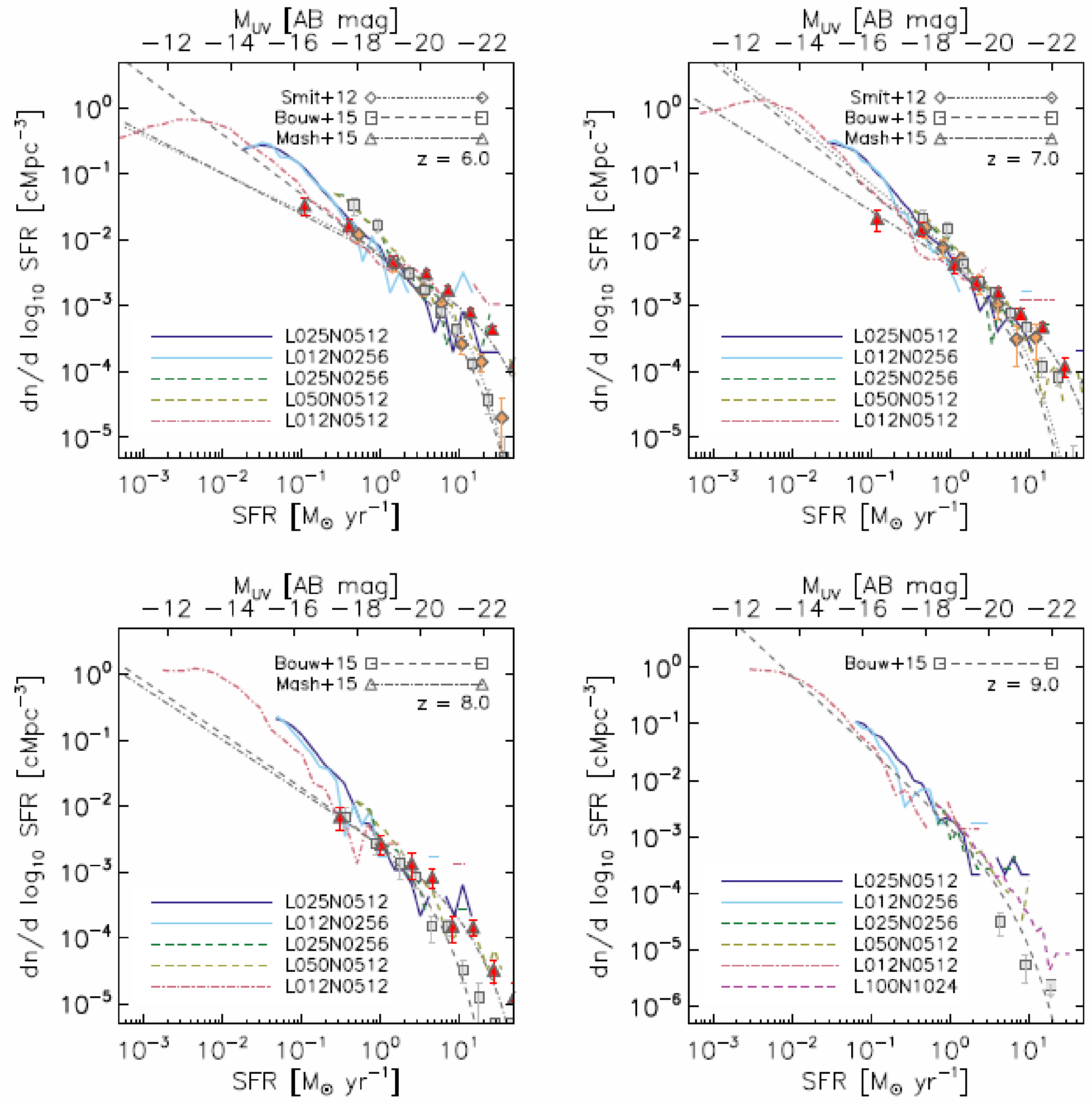
Pawlik, Rahmati, JS+ (2016)

The Aurora project



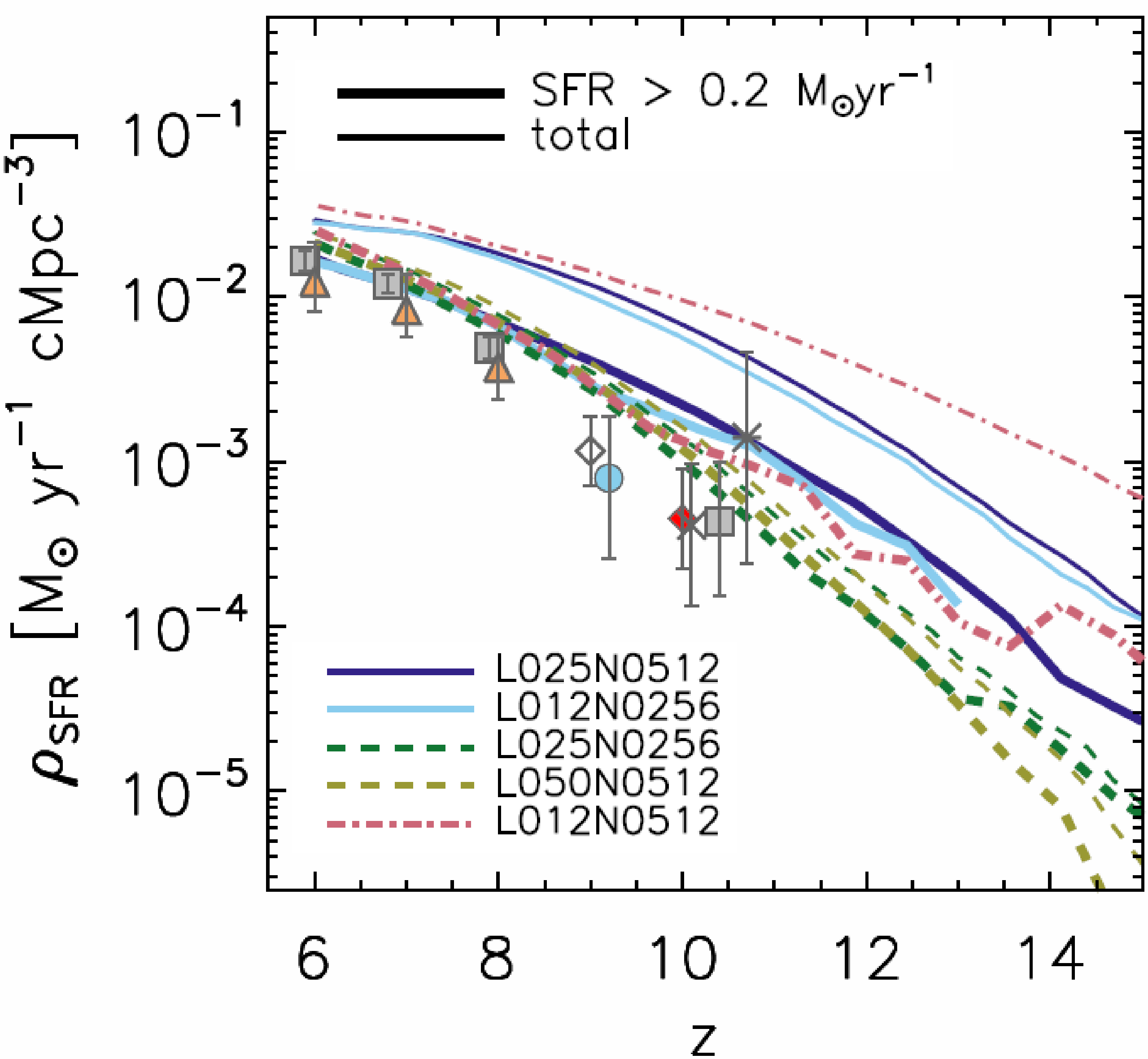
Pawlik, Rahmati, JS+ (2016)

Evolution of the SFR function



Pawlik, Rahmati, JS+ (2016)

Cosmic star formation history



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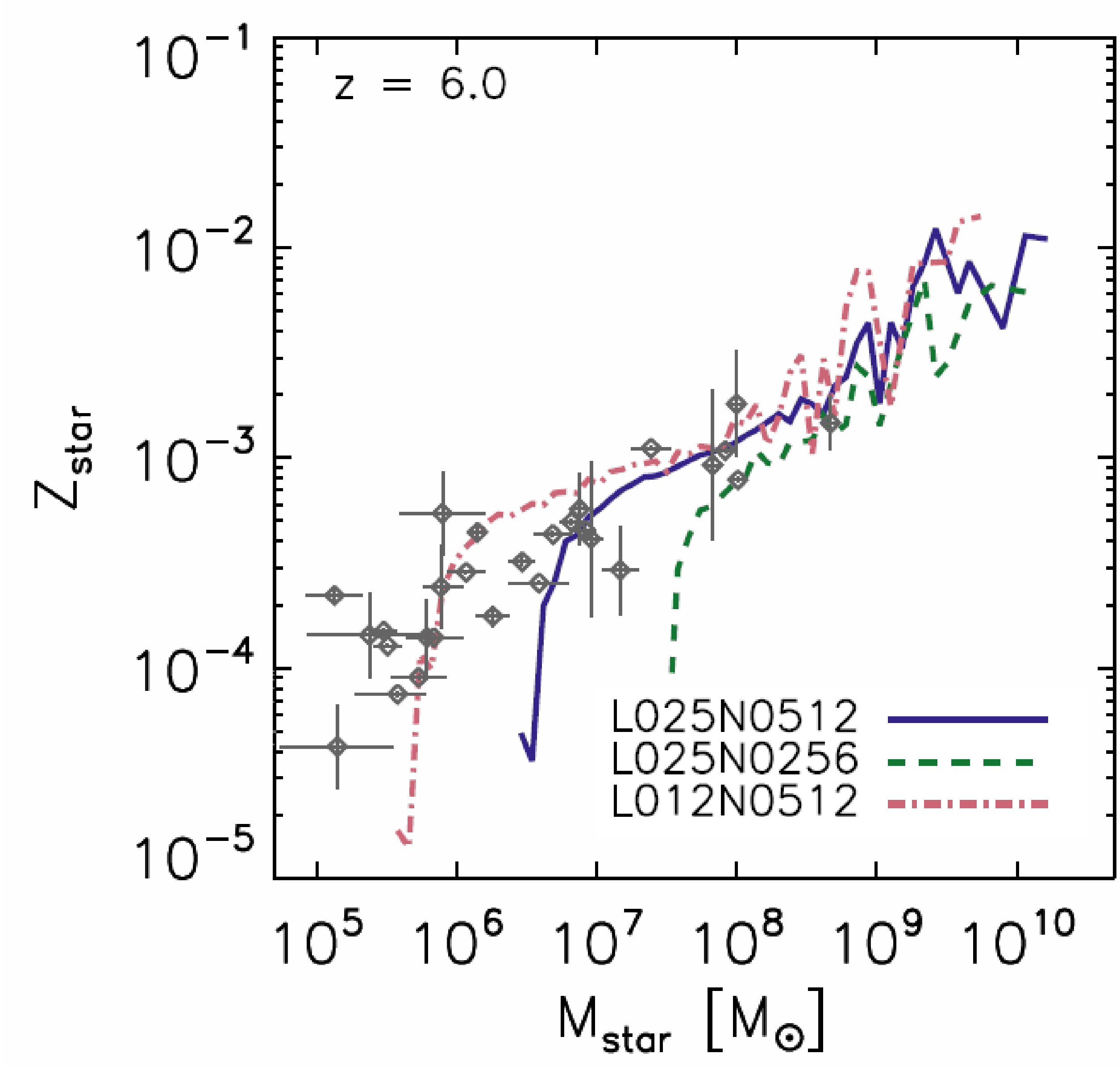
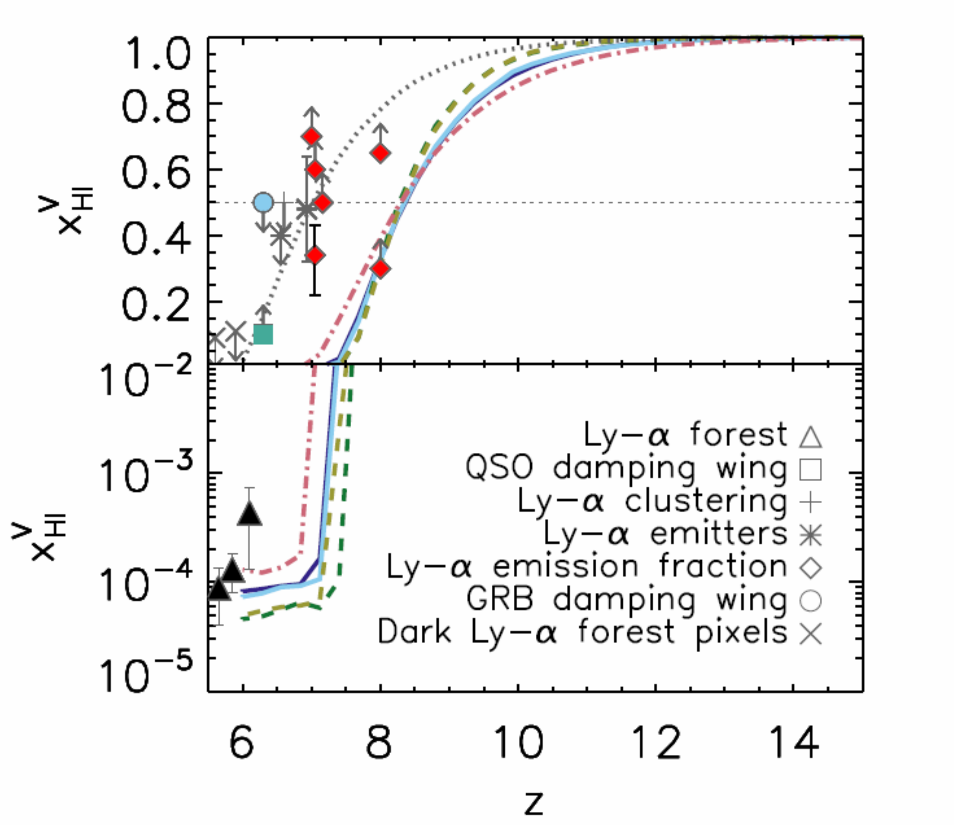
Stellar metallicity



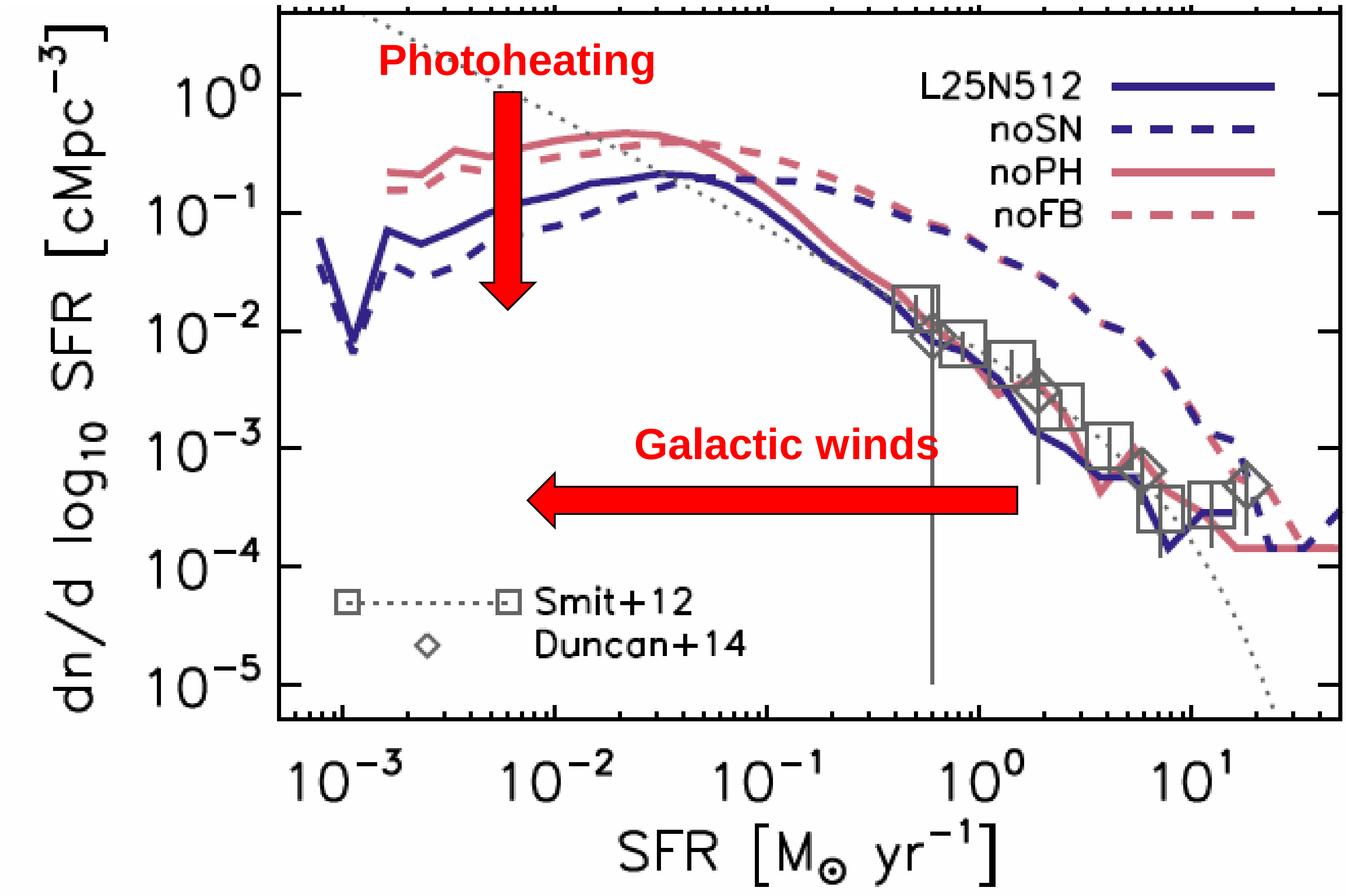
Pawlik, Rahmati, JS+ (2016)

Reionization history



Pawlik, Rahmati, JS+ (2016)

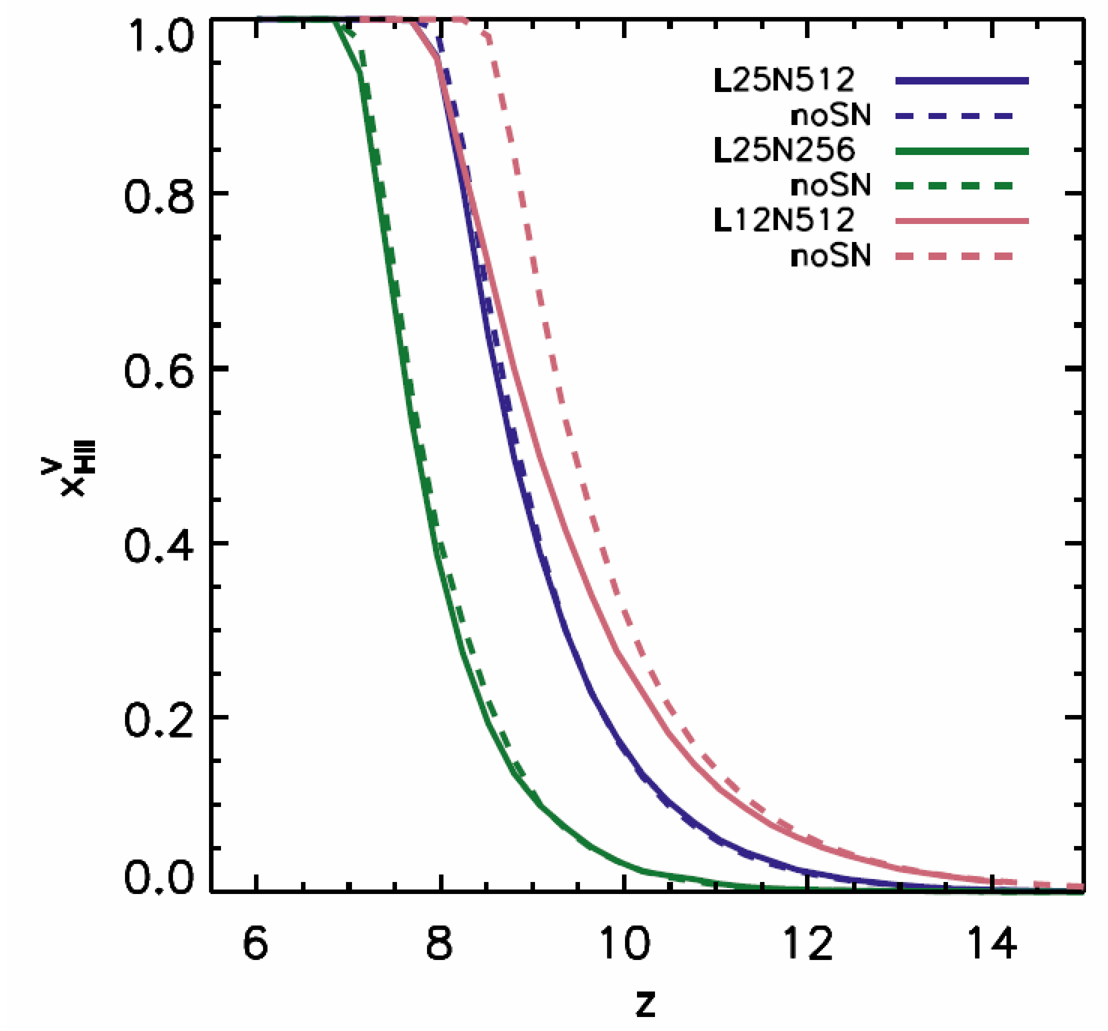
Effects of supernovae and photoheating



$z = 7$

Pawlik, JS & Dalla Vecchia (2015)

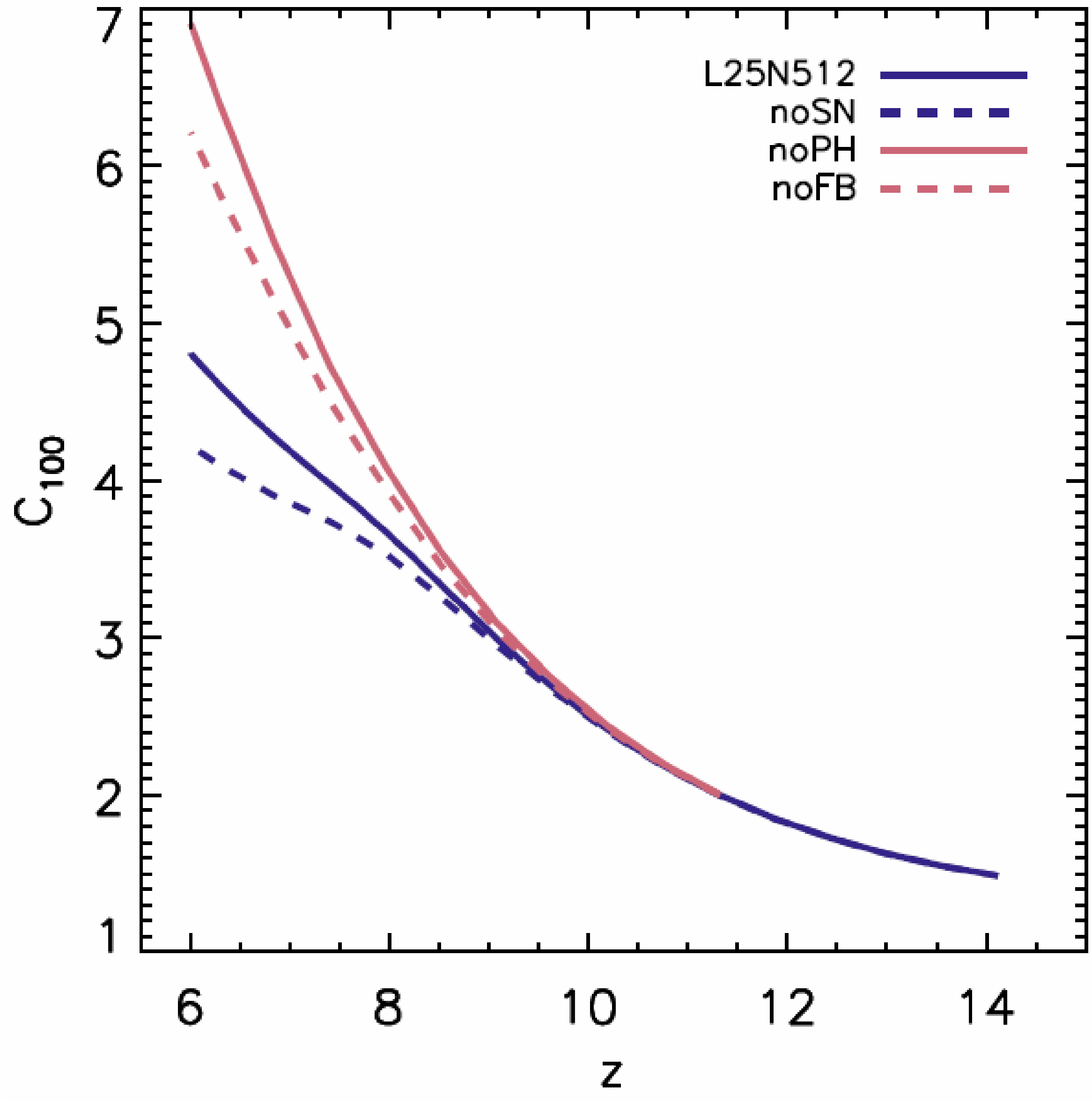
Reionisation history: Feedback and resolution



Winds reduce SFR, but increase escape fraction

Pawlik, JS & Dalla Vecchia (2015)

Clumping factor: Effect of feedback



Pawlik, JS & Dalla Vecchia (2015)

The brighter galaxies reionised the Universe

Winds of change: reionization by starburst galaxies

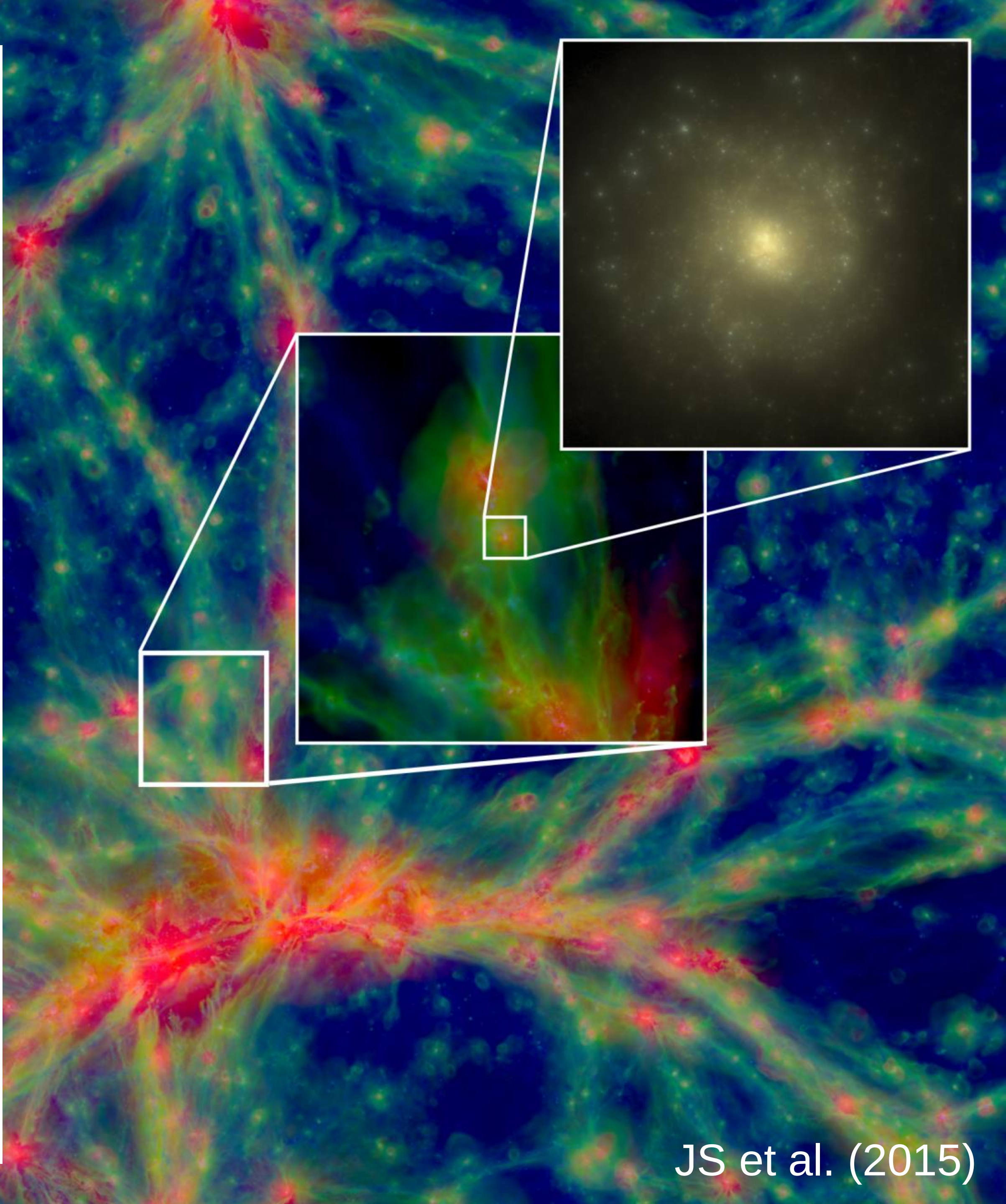
Mahavir Sharma[1]*, Tom Theuns[1], Carlos Frenk[1], Richard Bower[1], Robert Crain[2], Matthieu Schaller[1] & Joop Schaye[3]

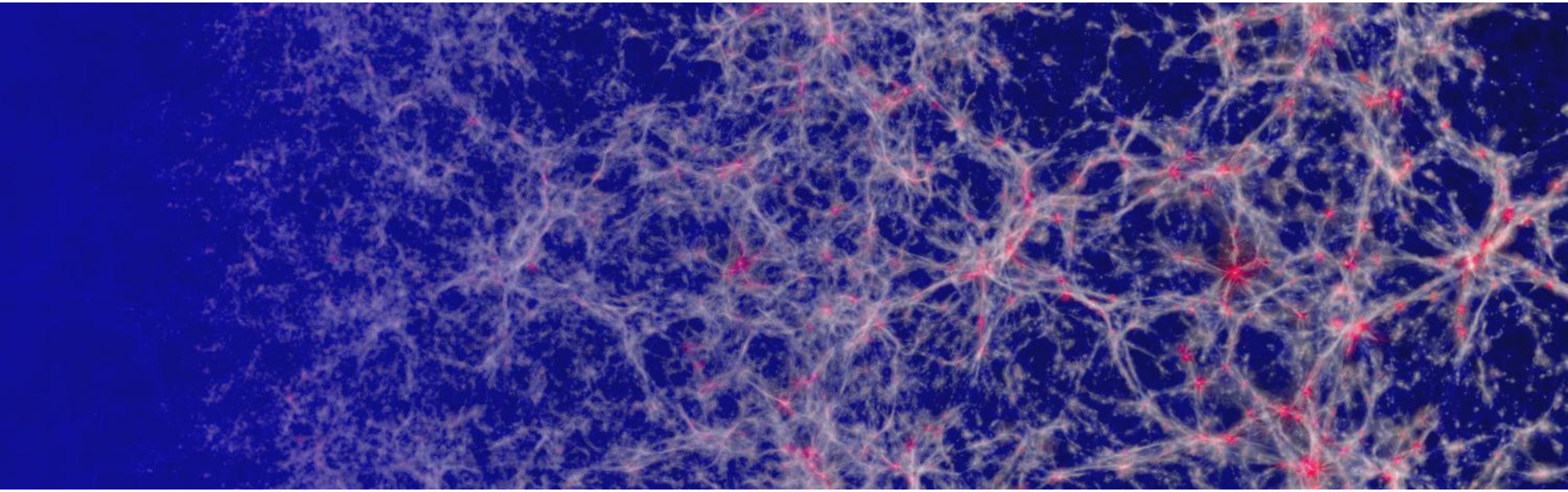
2016, MNRAS, 458, L94
2016, MNRAS subm. (arXiv: 1606.08688)

- Models that are consistent with the observed low photo-ionisation rate at $z < 6$ and the low escape fractions at $z\sim0$ require the escape fraction to increase with z (e.g. Khaire+ '16, Gnedin+ '16, Pricë+ '16, Faisst '16)
- Escape fractions should only know about local galaxy properties, not redshift
- Galactic winds open channels through which photons escape (e.g. Razoumov & Sommer-Larsen '06, Gnedin+ '08, Wise & Cen '09, Yajima+ '11, Traino"+ '15, Ma+ '15, Pawlik+ '15, '16)
- Galactic winds observed for SFR surface densities greater than $0.1\ M_\odot\ yr^{-1}\ kpc^{-2}$ (e.g. Heckman '01, '02)
- Ansatz: Escape fraction is 0 (0.2) if the *local* SFR surface density is below (above) the critical value $0.1\ M_\odot\ yr^{-1}\ kpc^{-2}$

EAGLE:

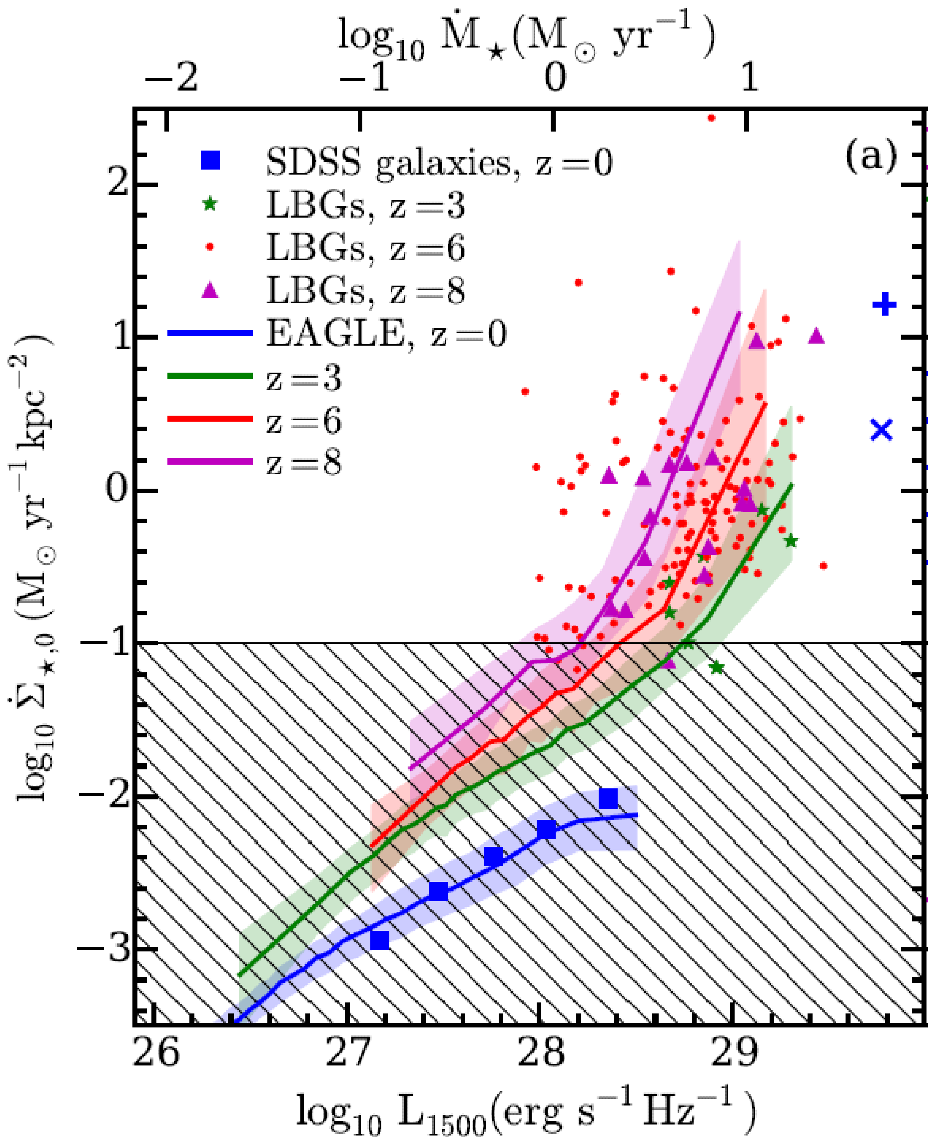
- Volumes of 25 - 100 Mpc and zooms
- Up to 7 billion particles
- Includes feedback from stars and AGN
- Winds develop naturally without predetermined mass loading or velocity
- Feedback calibrated to match z ~ 0 galaxy mass function and sizes
- Many different models, spin offs
- Galaxy data publicly available





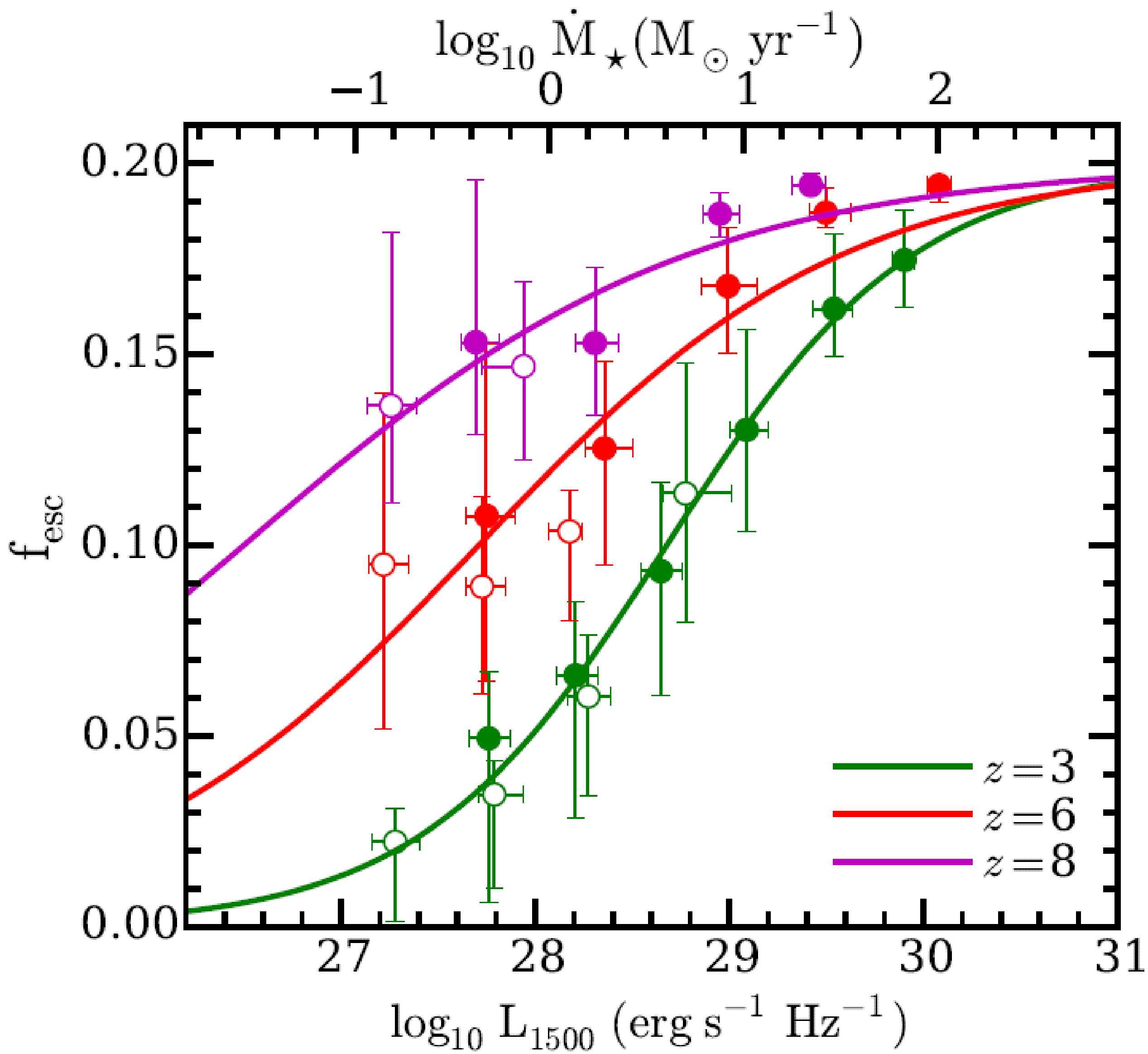
Images by Trayford/McAlpine

SFR surface density vs UV luminosity



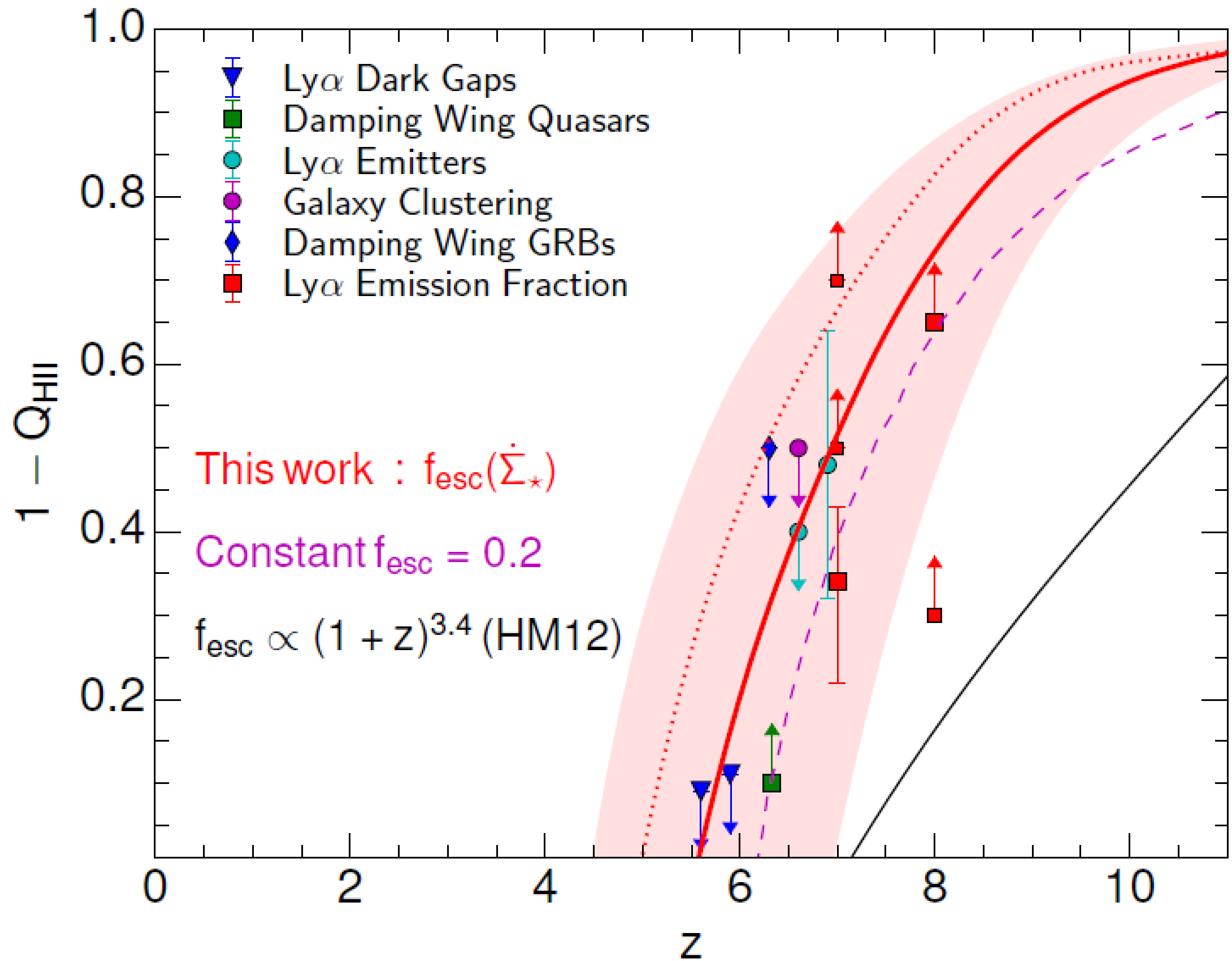
Sharma+ (2016a)

Predicted luminosity-weighted mean escape fractions



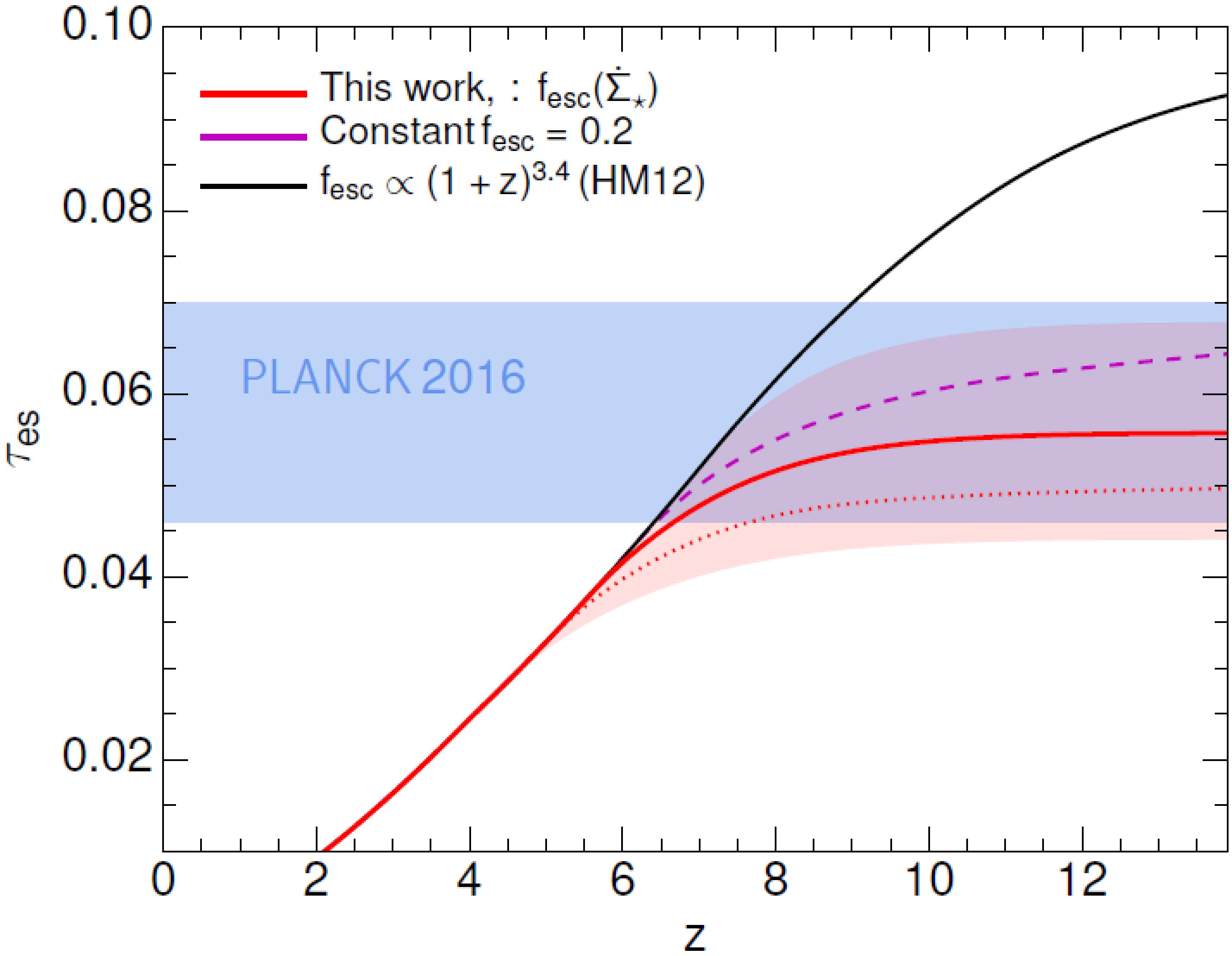
Sharma+ (2016a)

Reionisation history



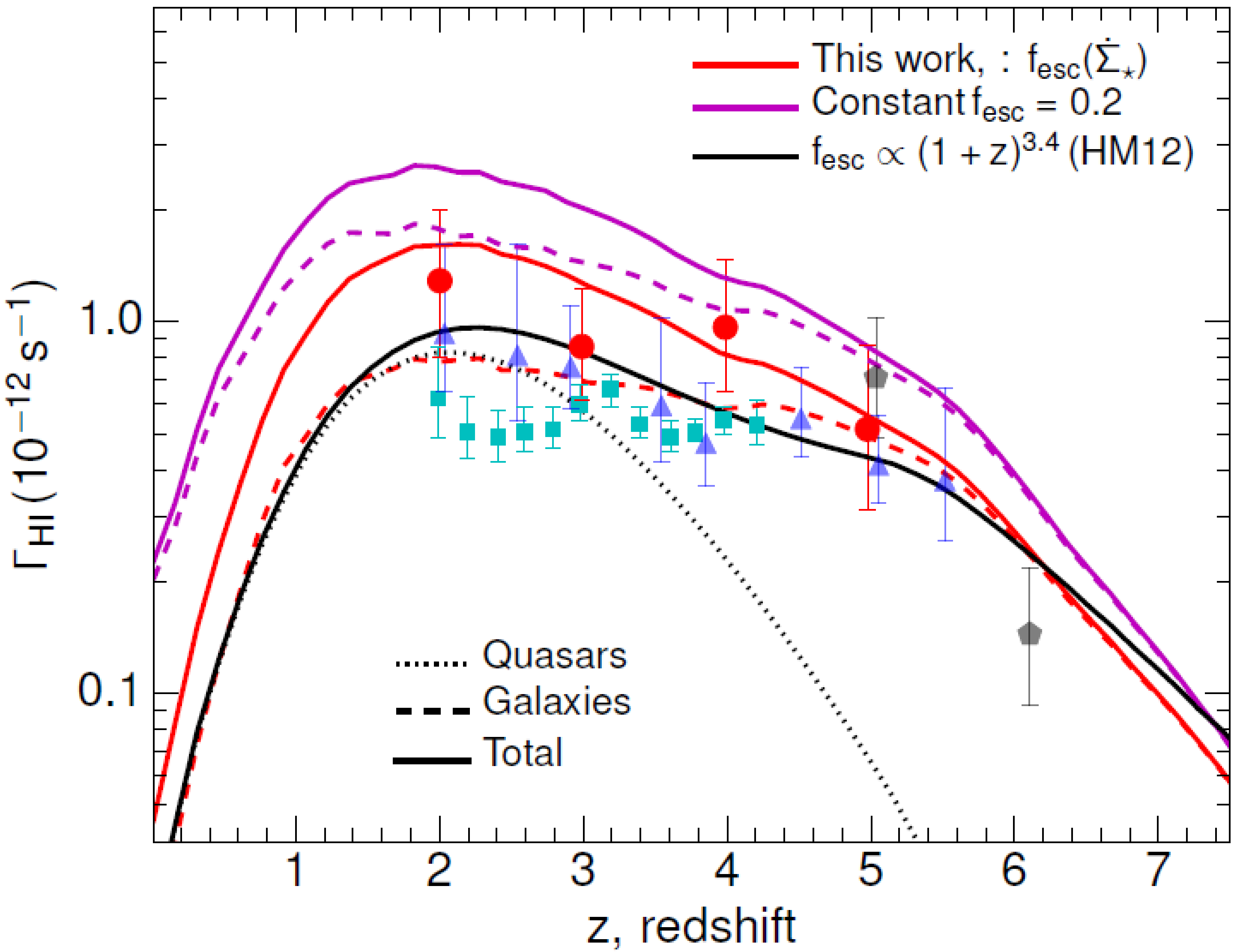
Sharma+ (2016b)

Electron scattering optical depth



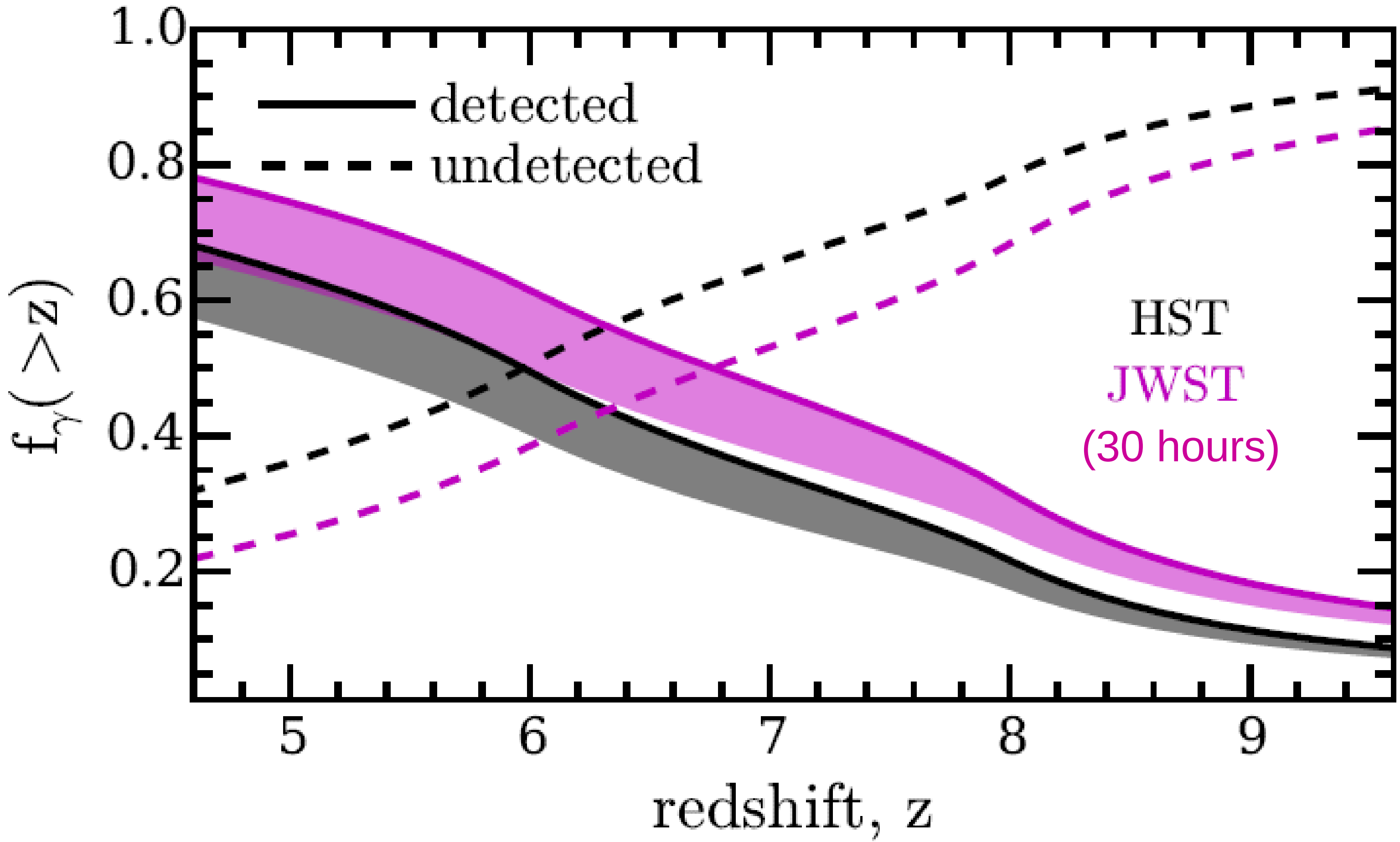
Sharma+ (2016b)

Evolution of the photo-ionisation rate



Sharma+ (2016b)

Detectable fraction of cumulative ionizing emissivity



Sharma+ (2016b)

Conclusions

- Cosmological radiative transfer simulations cannot predict the star formation history, escape fraction, and reionization history
- Need observations to calibrate stellar feedback and subgrid escape fraction (for each resolution; factor of ~2 adjustments)
- Photoheating has both negative and positive effects on reionization
- Spatially adaptive simulations are starting to capture the effects of photoheating
- Galactic winds increase the escape fraction
- Galactic winds more prominent for higher SFR surface densites, naturally results in increase of mean escape fraction with redshift, as required by observations