# Star formation and feedback at z>3

Joop Schaye (Leiden)

# Feedback from star formation

- Mechanical
  - Moves gas
  - Shock-heats gas
- Chemical
  - Boosts cooling rates
  - Catalyzes formation of H2
- Radiative:
  - Photo-dissociation of H2
  - Photo-ionization
    - Reheats the gas
    - Suppresses cooling rates
    - Catalyzes formation of H2
  - Radiation pressure

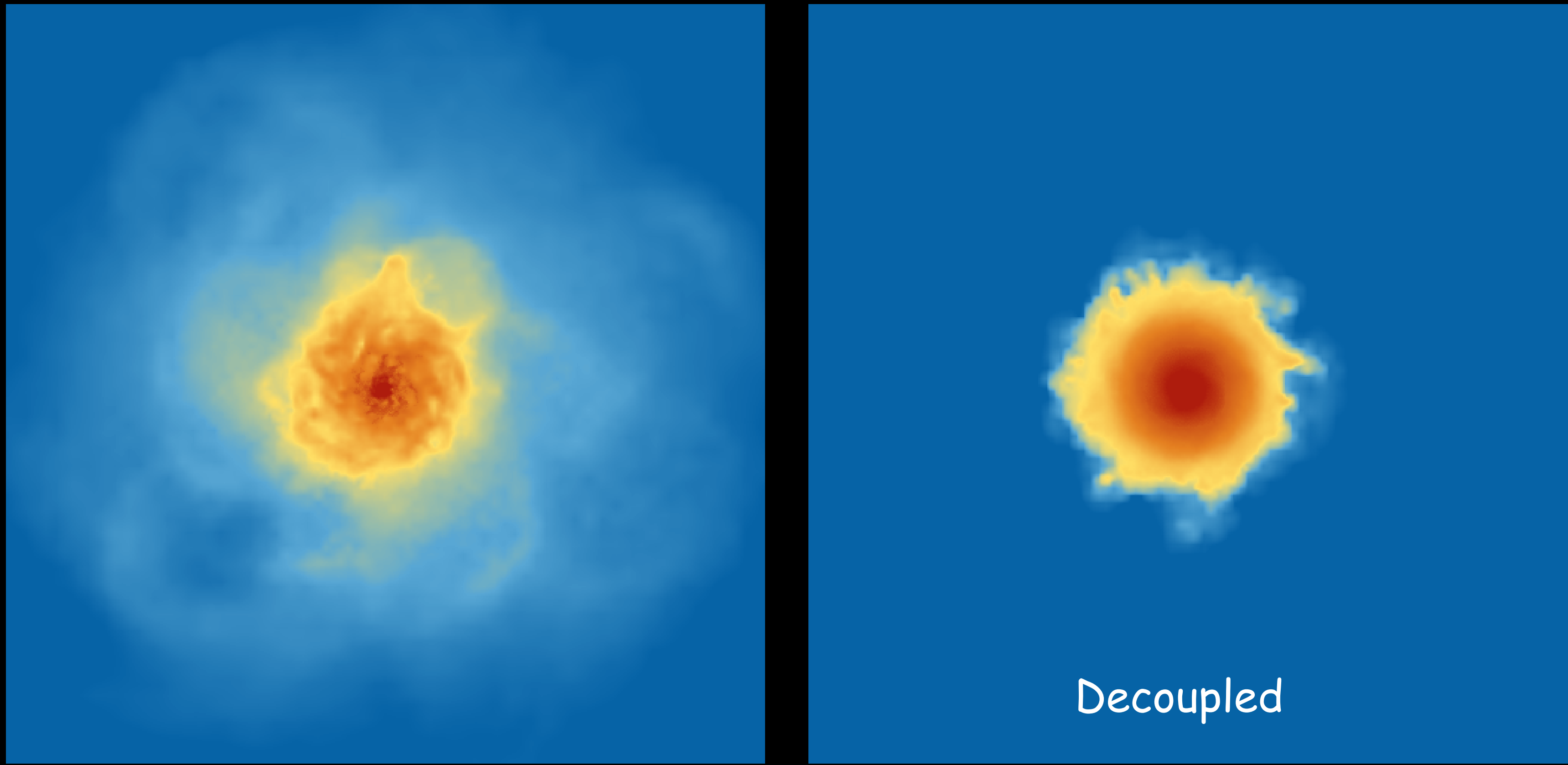
# Galactic winds in simulations

- Thermal feedback is quickly radiated away due to lack of resolution
- Solutions:
  - Kinetic feedback
  - Temporarily suppress cooling

# New kinetic winds module

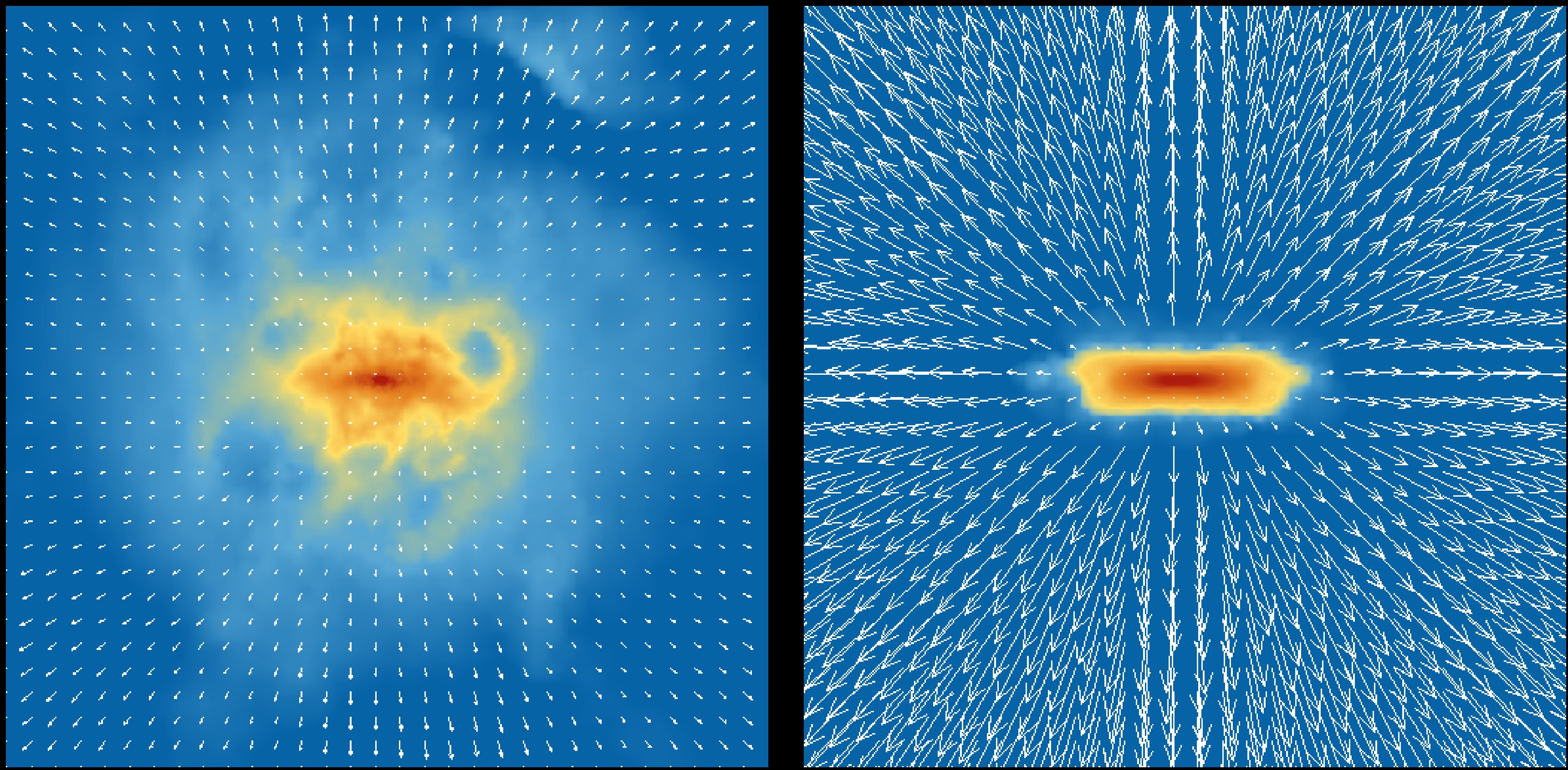
- Kinetic feedback parameters:
  - Mass loading relative to stellar mass formed (default: 2)
  - Wind velocity (default: 600 km/s)
- Differences from Gadget II:
  - Not hydrodynamically decoupled
  - Winds are local to the SF event

# 1e10 $M_\odot$, face-on, gas density



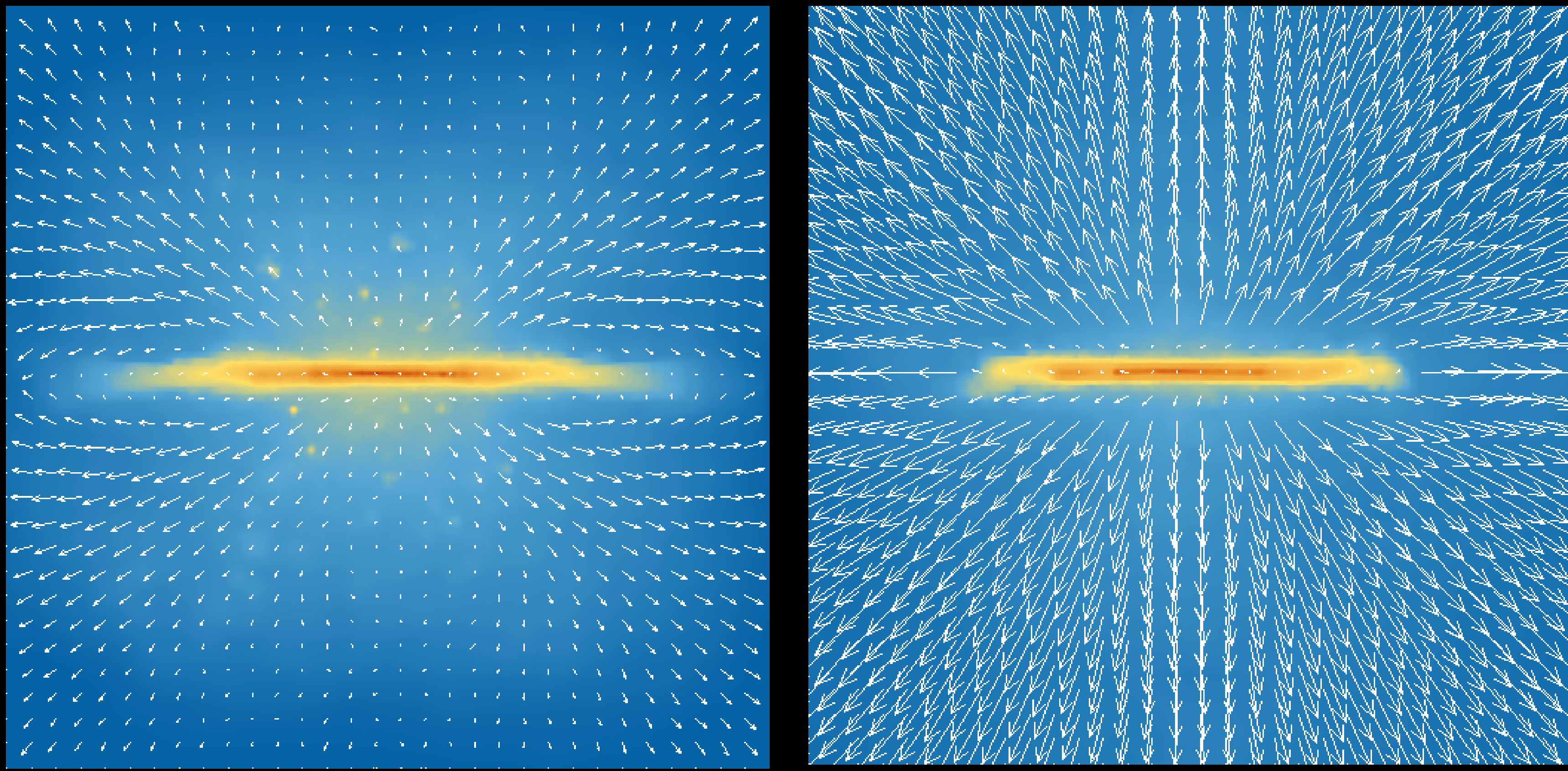

Dalla Vecchia & JS (2008)

# 1e10 $M_\odot$, edge-on, gas density



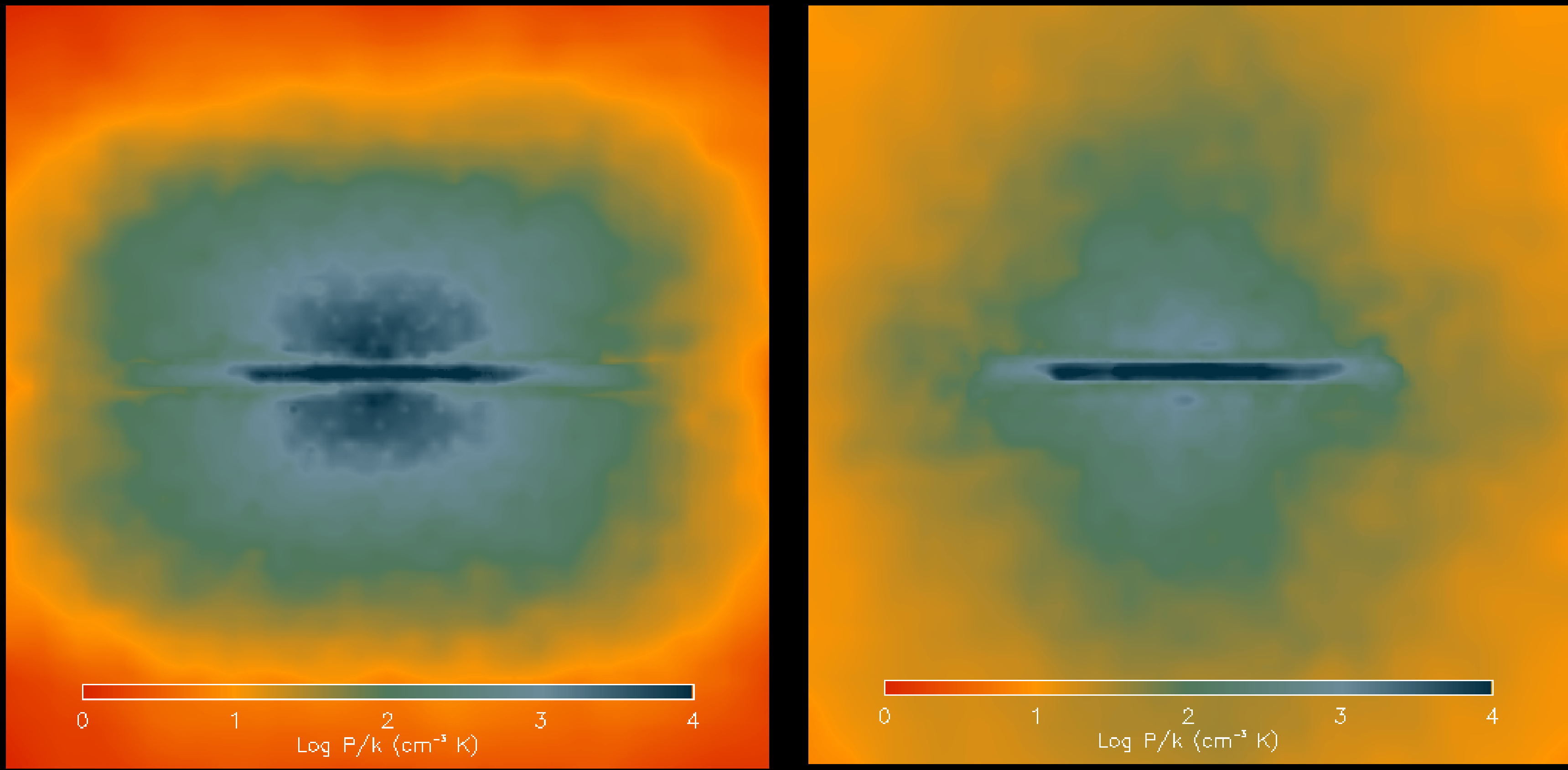
Dalla Vecchia & JS (2008)

# 1e12 M$_\odot$, edge-on, gas density



Dalla Vecchia & JS (2008)

# 1e12 $M_\odot$, edge-on, gas pressure



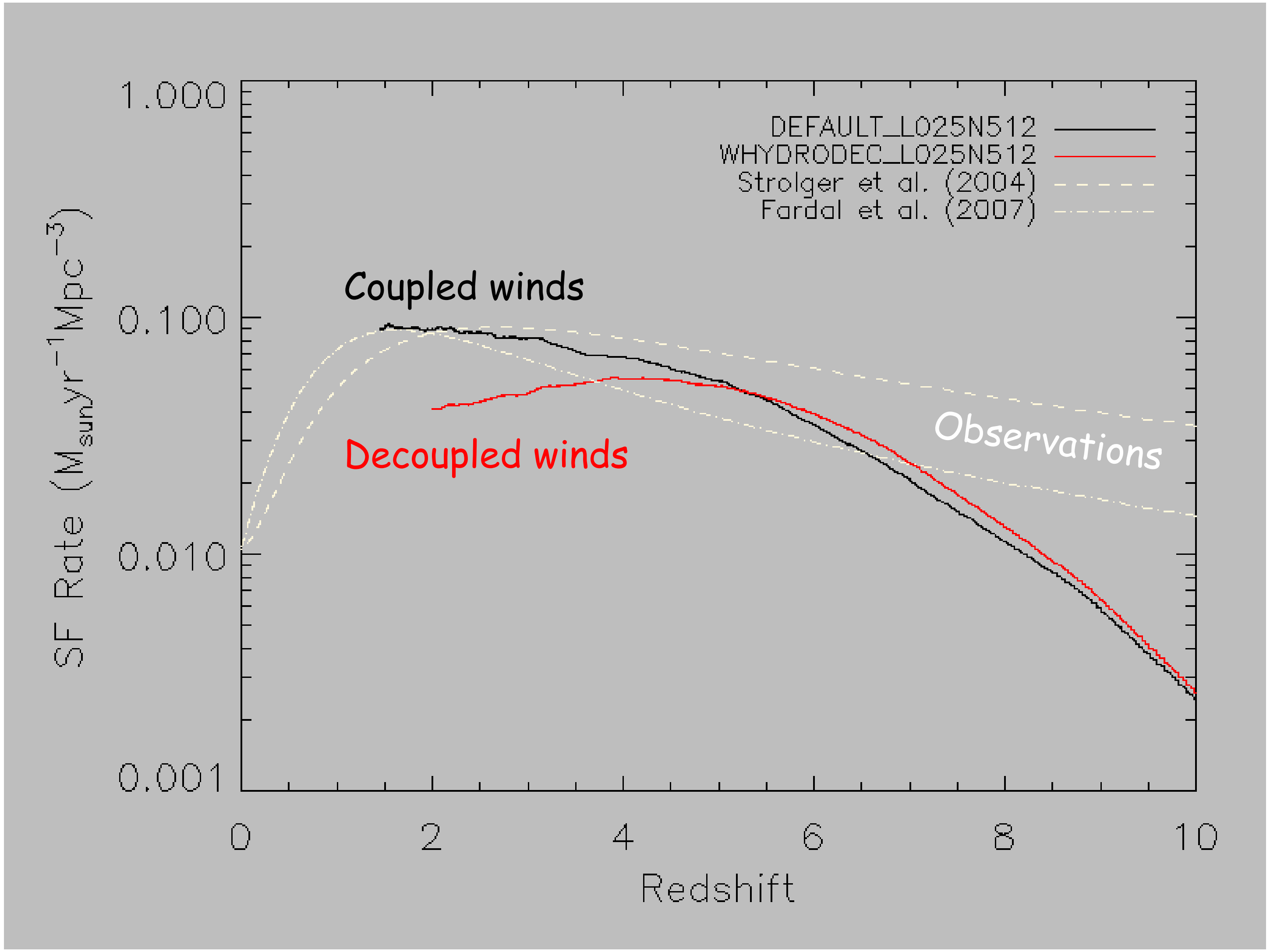

Dalla Vecchia & JS (2008)

# Conclusions 1/3 - Winds

- Hydro drag on superbubbles instrumental in shaping ISM and outflows
- Low mass galaxies:
  wind drags lots of gas along
- High mass galaxies: drag quenches wind → fountain
- Most popular existing prescription overestimates the energy in the outflow by orders of magnitude
- The details of wind implementations have grave consequences

Dalla Vecchia & Schaye, MNRAS, in press (arXiv:0801.2770)

# Cosmic SFH



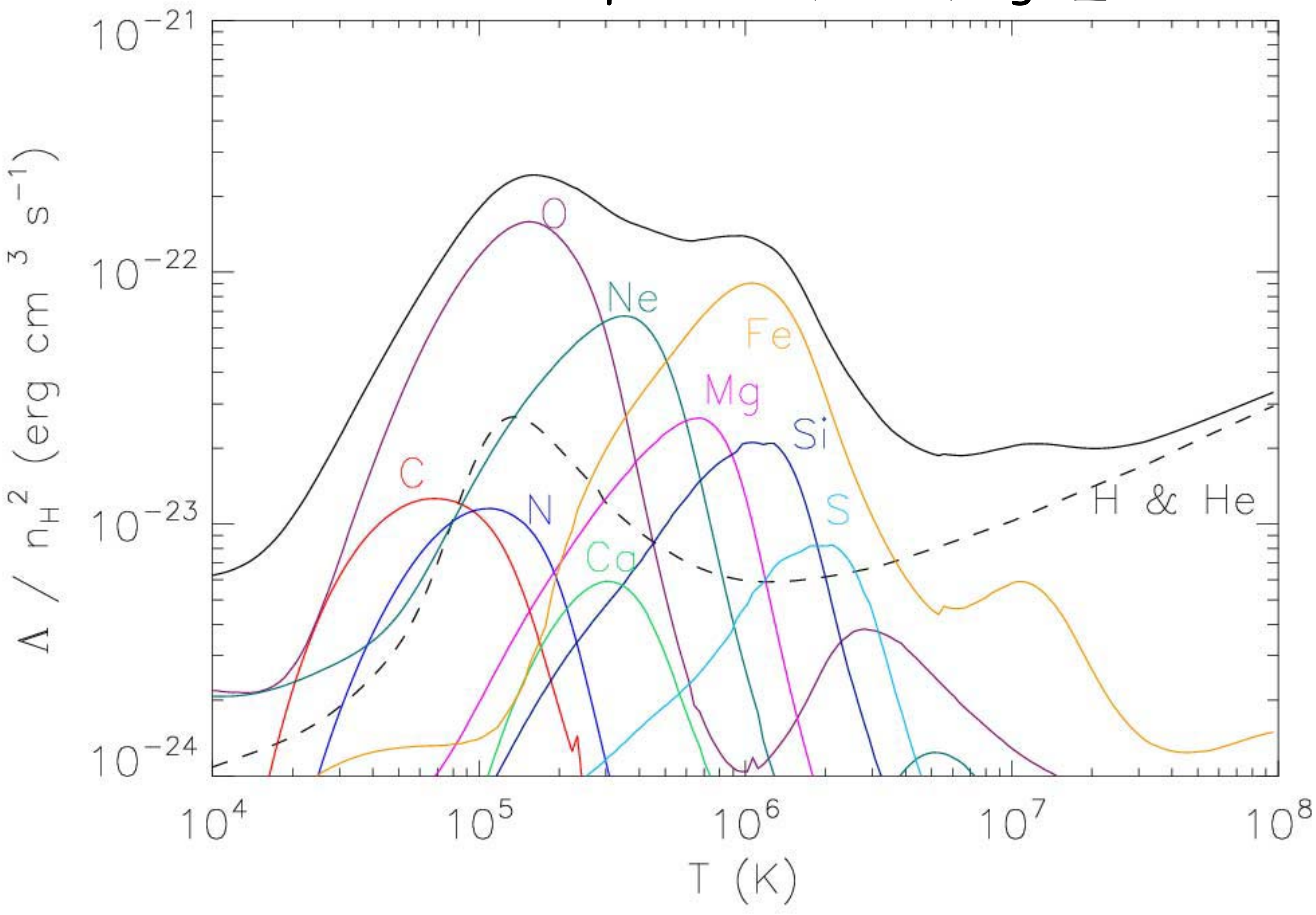
DEFAULT_L025N512
WHYDRODEC_L025N512
Strolger et al. (2004)
Fardal et al. (2007)
Coupled winds
Decoupled winds
Observations
1.000
0.100
0.010
0.001
SF Rate ($M_{sun}yr^{-1}Mpc^{-3}$)
0
2
4
6
8
10
Redshift

# Radiative cooling above 10^4 K

- Established
  - H and He cooling suppressed by photo-ionization (Efstathiou 1992)
  - Metal cooling dominates for $Z >> 10^{-2} Z_{\odot}$
  - Many elements contribute
- What is typically done
  - H and He including photo-ionization
  - Metal cooling assuming CIE and solar relative abundances

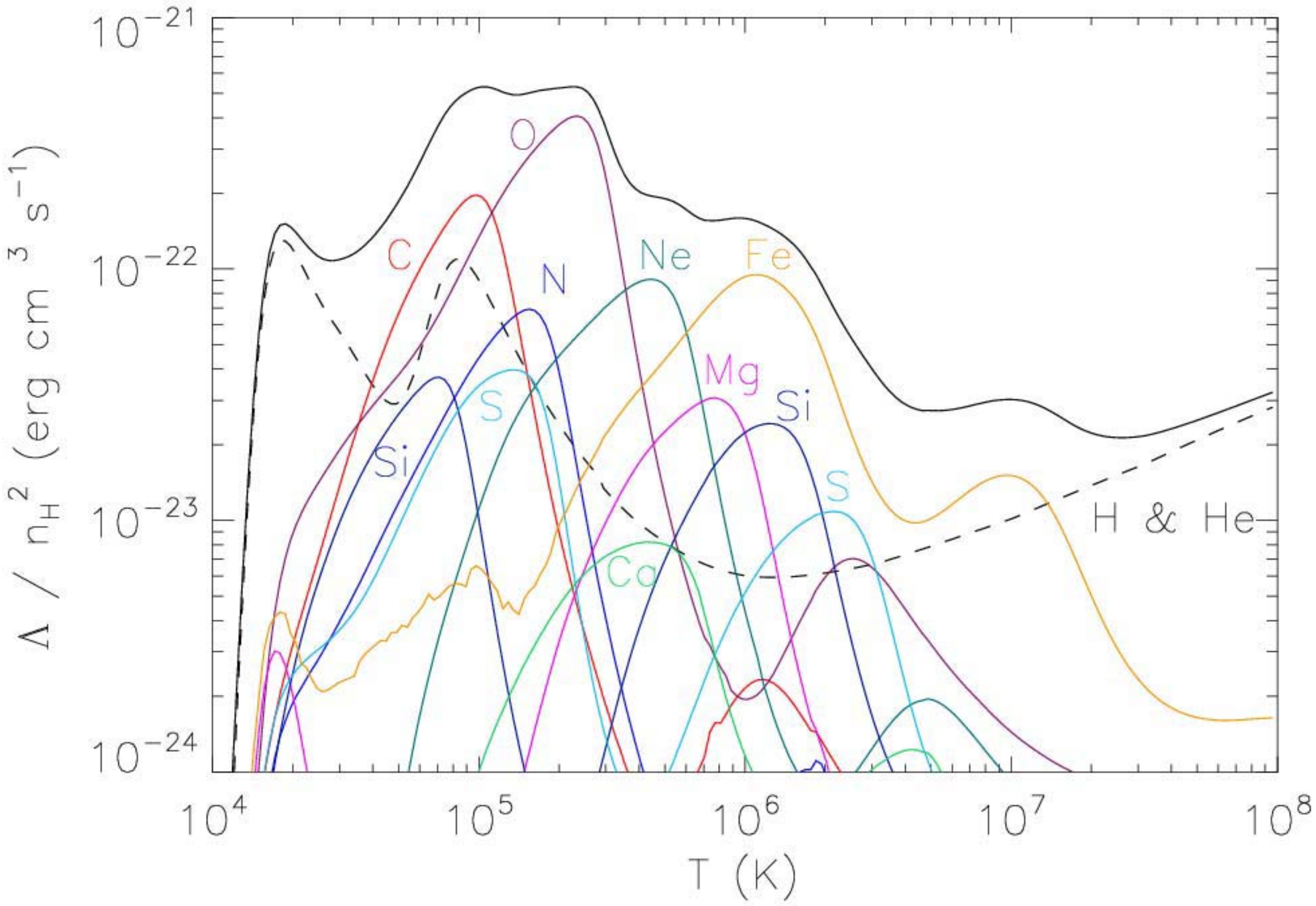
# Photo-ionization suppresses metal cooling

Photo-ionization equilibrium, z = 3, log n_H = -4




Wiersma, JS & Smith (2008)

# Video of density dependence




Wiersma, JS & Smith (2008)

# Conclusions 2/3
# Radiative cooling above 10^4 K

- Photo-ionization suppresses metal cooling → cooling rates decrease by up to an order of magnitude
- Relative abundance variations are important → cooling rates change by factors of a few
- Tables of cooling rates, element-by-element, including photo-ionization are available

Wiersma, Schaye & Smith, MNRAS, to be submitted

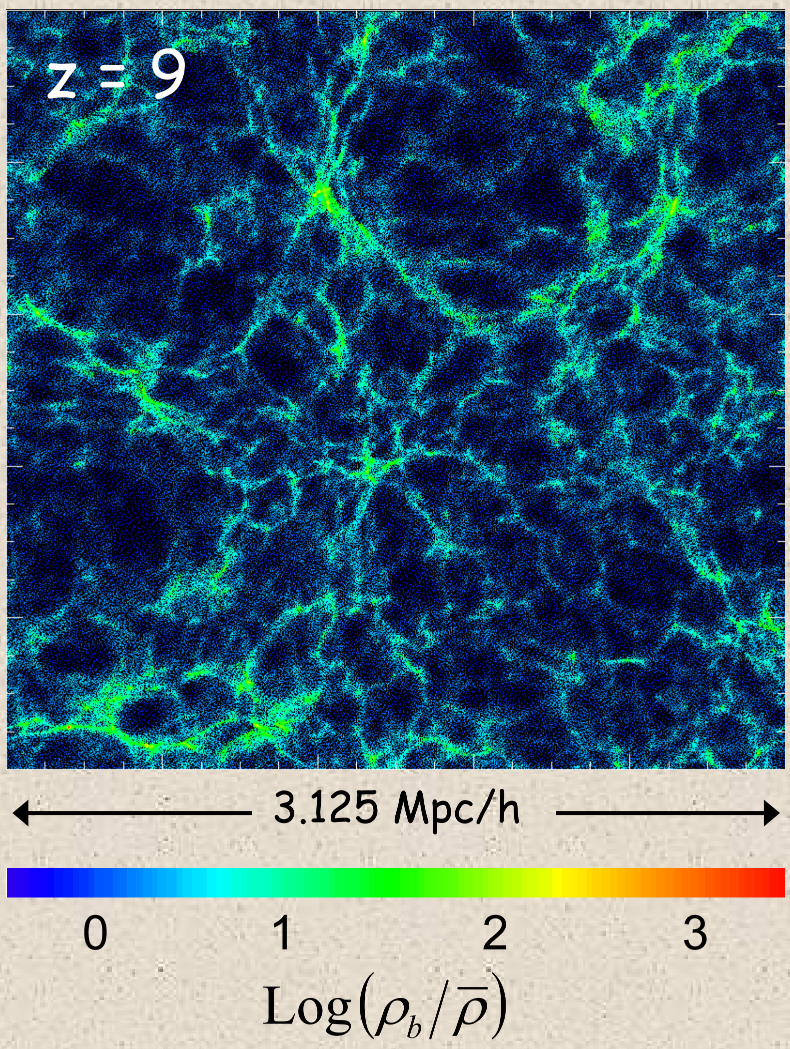
# Reheating due to photo-ionization

- Suppresses star formation
  → less ionizing photons
  → negative feedback

- Suppresses IGM clumping
  → less recombinations
  → postive feedback

# Effect of reionization heating

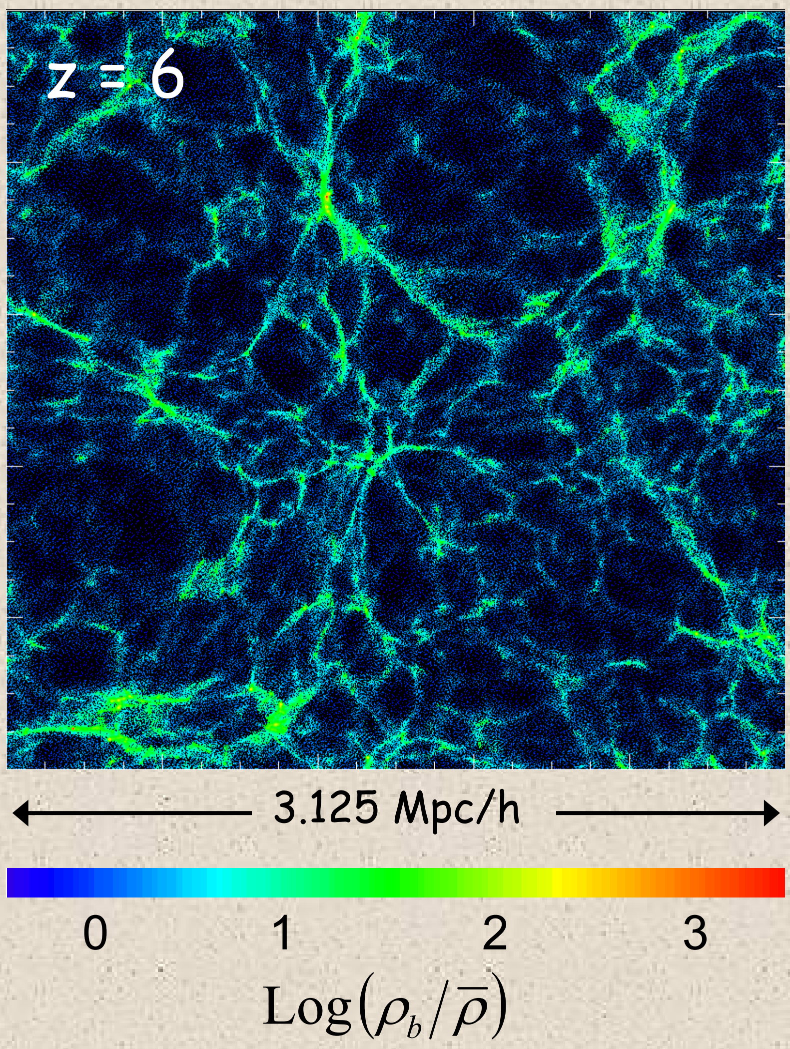
No reheating




Pawlik, JS & van Scherpenzeel (2008)

# Effect of reionization heating

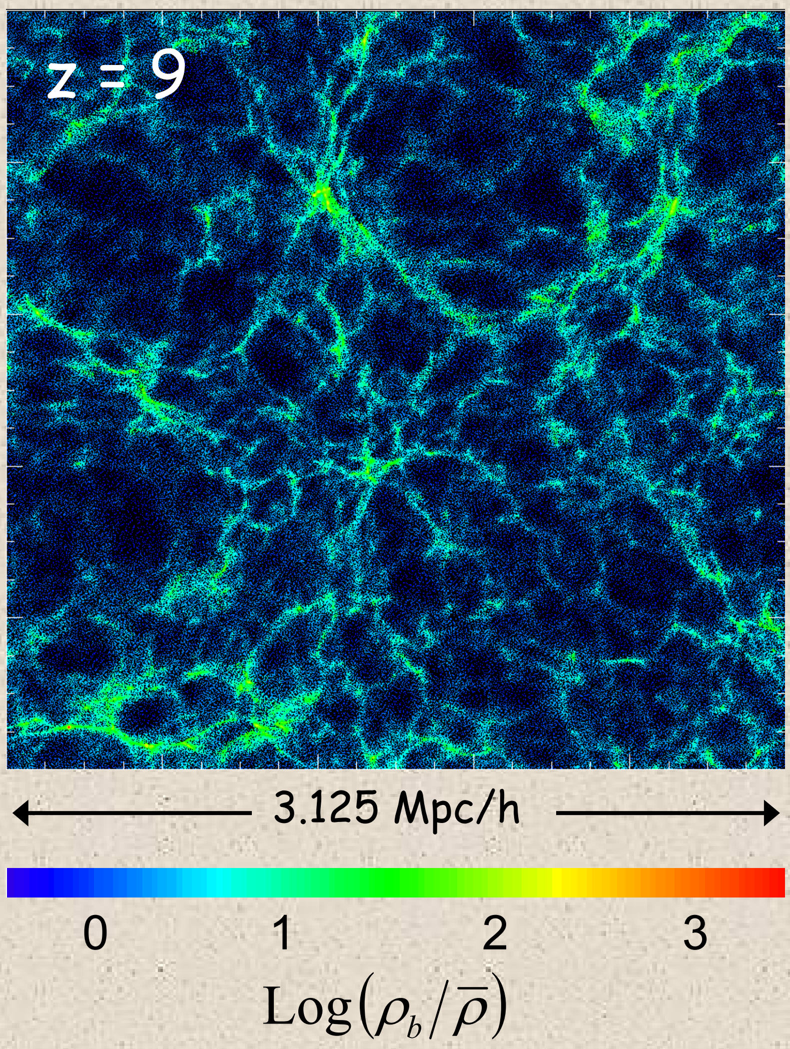
No reheating



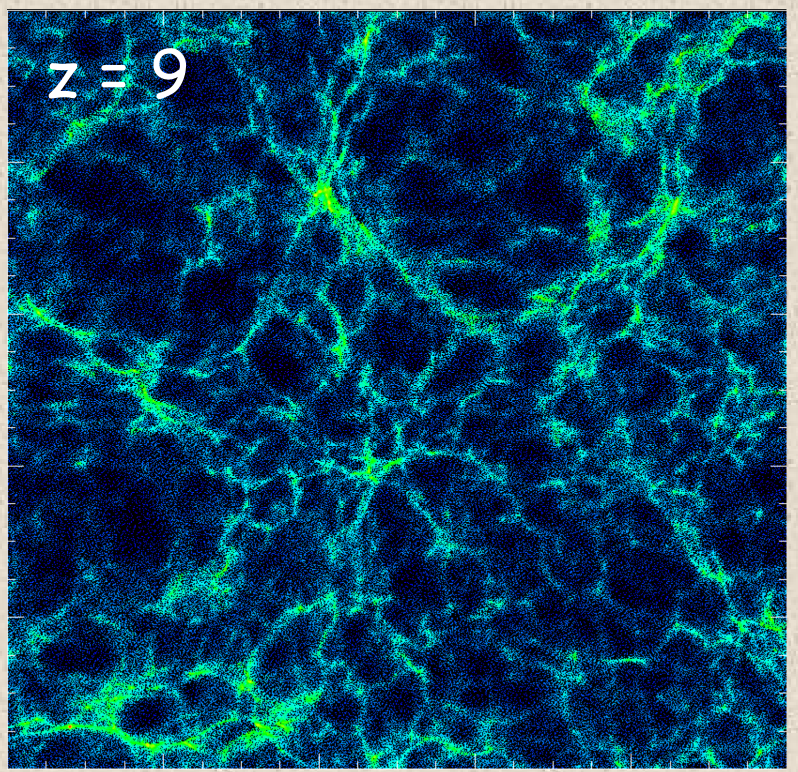

Pawlik, JS & van Scherpenzeel (2008)

# Effect of reionization heating

No reheating



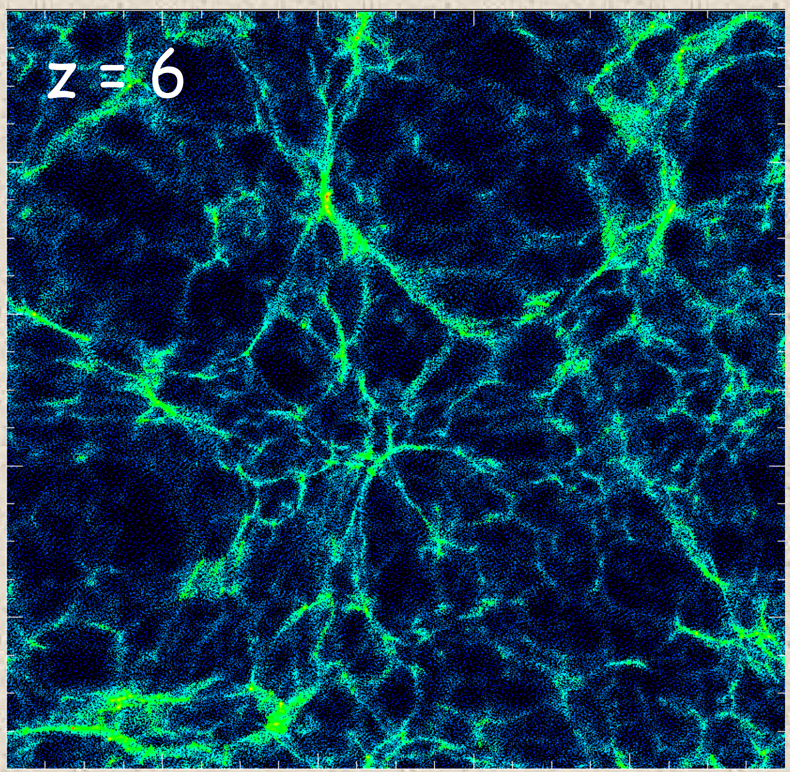

Reheating to 10^4 K at z=9



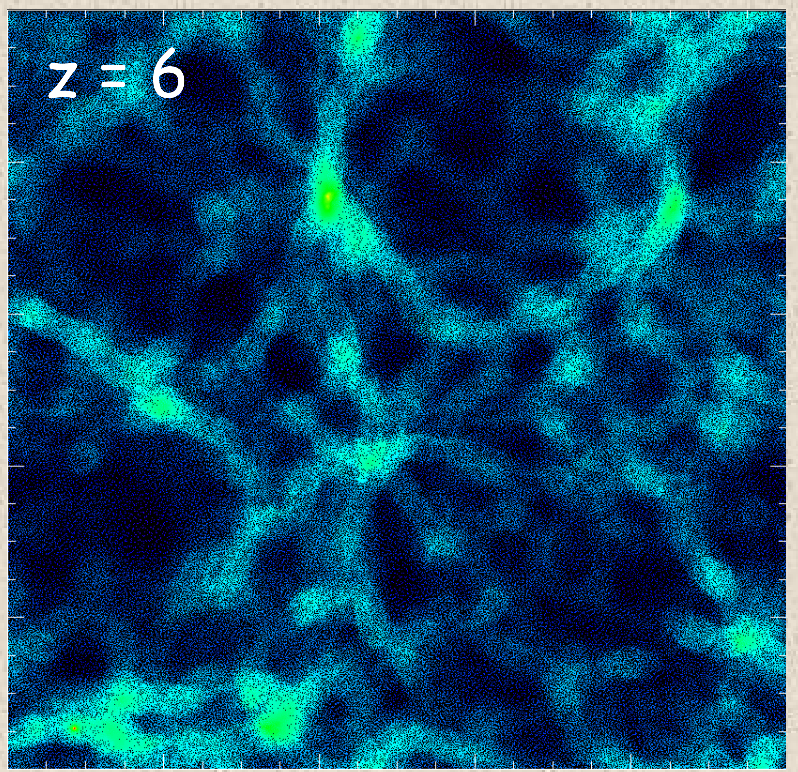

Pawlik, JS & van Scherpenzeel (2008)

# Effect of reionization heating

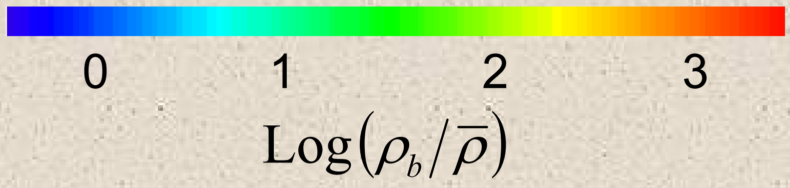
No reheating




Reheating to 10^4 K at z=9




← 3.125 Mpc/h →




Pawlik, JS & van Scherpenzeel (2008)

# Use of clumping factor

- Mean recombination rate

$$\langle \dot{n}_{\rm rec} \rangle \propto \langle \rho^2 \rangle \propto C \langle \rho \rangle^2$$

- Clumping factor

$$C \equiv \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$$

# Can observed sources keep the universe ionized?

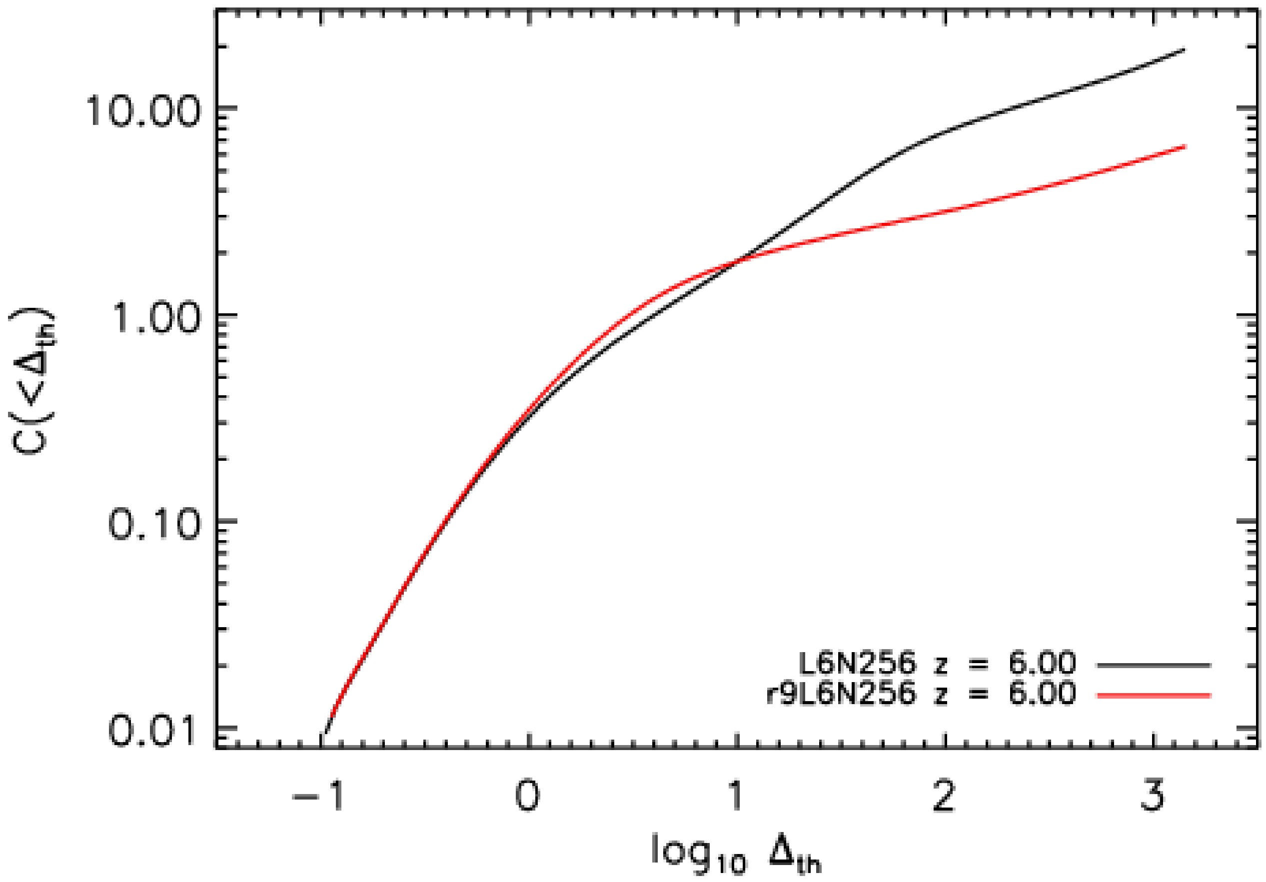
- Needed (Madau et al. 1999):

$$\dot{\rho}_* = 0.027\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3} \left(\frac{C}{30}\right) f_{\mathrm{esc}}^{-1} \left(\frac{1+z}{7}\right)^3$$

- Observed at z=6 (Bouwens et al. 2007):

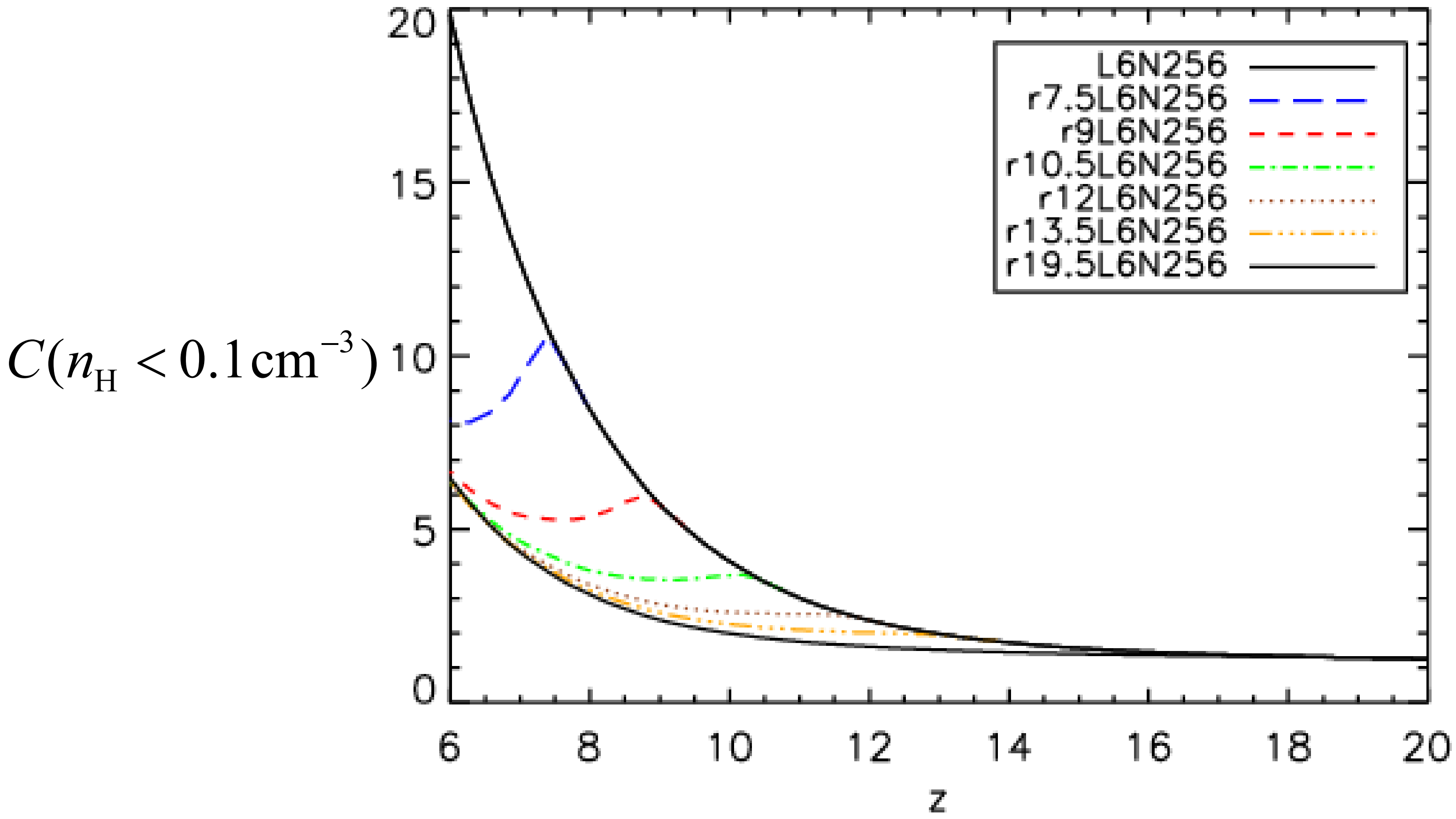
$$\dot{\rho}_* = 0.022 \pm 0.004\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}$$

# Clumping factor dependence on density




Pawlik, JS & van Scherpenzeel (2008)

# Reheating and the IGM clumping factor




Pawlik, JS & van Scherpenzeel (2008)

# Can observed sources keep the universe ionized?

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$$\dot{\rho}_* = 0.027\ \mathrm{M_\odot\ yr^{-1}\ Mpc^{-3}} \left(\frac{C}{30}\right) f_{\mathrm{esc}}^{-1} \left(\frac{1+z}{7}\right)^3$$

- Observed at z=6 (Bouwens et al. 2007):

$$\dot{\rho}_* = 0.022 \pm 0.004\ \mathrm{M_\odot\ yr^{-1}\ Mpc^{-3}}$$

- Needed if reheating at z > 9 (Pawlik et al. 2008):

$$\dot{\rho}_* = 0.005\ \mathrm{M_\odot\ yr^{-1}\ Mpc^{-3}} \left(\frac{C}{6}\right) f_{\mathrm{esc}}^{-1} \left(\frac{1+z}{7}\right)^3$$

# Conclusions 3/3 - Reheating

- Reheating reduces the mean recombination rate by at least a factor 5 → Strong positive feedback
- Reheating removes the tension between the observed and required SFRs at z=6

Pawlik, Schaye, & van Scherpenzeel, MNRAS, to be submitted