Effects of Radiative Feedback on Reionization and the Local Universe

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Kavli IPMU ACP Seminar

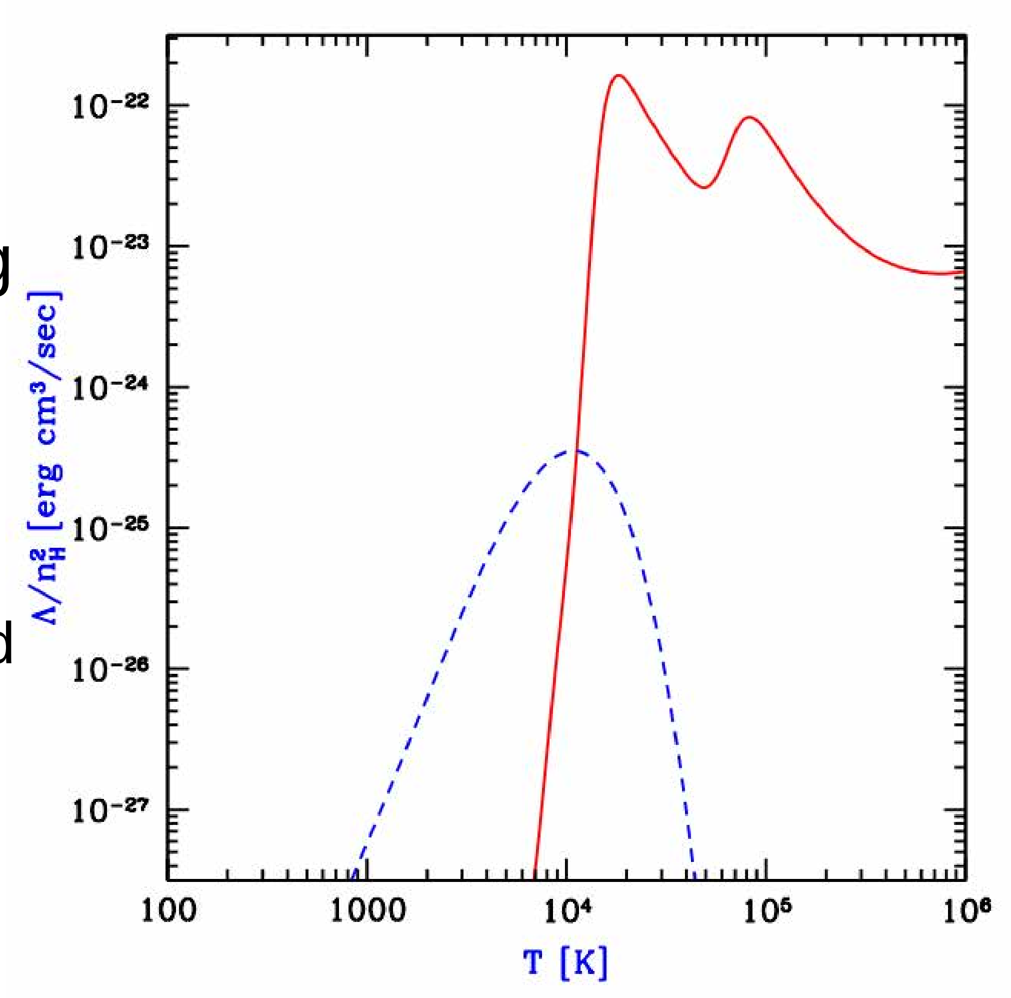
November 1, 2012

Outline

- Introduction
- Ionizing Efficiency of First Galaxies
  - Star Formation Efficiency
  - Escape Fraction
  - Suppression of star formation by photoionization
  - Minimal Reionization Model
- Reionization and the Local Universe
  - “Missing Satellites” Problem
  - Satellite Abundance and Reionization Epoch
  - Environmental Dependence
- Summary

Reionization: The Standard Picture

- Reionization driven by ionizing radiation produced by **stars**
- First stars (Pop III) forming in minihalos were likely massive and efficient producers of ionizing radiation at z~15-30
- Pop III stars must have polluted IGM as **minihalos** ($M<10^8$ $M_\odot$) merged into larger **atomic cooling halos** ($M>10^8$ $M_\odot$)
- Eventually **Pop II star forming galaxies** dominate as reionization **ends at z~6**



Barkana & Loeb (2001)

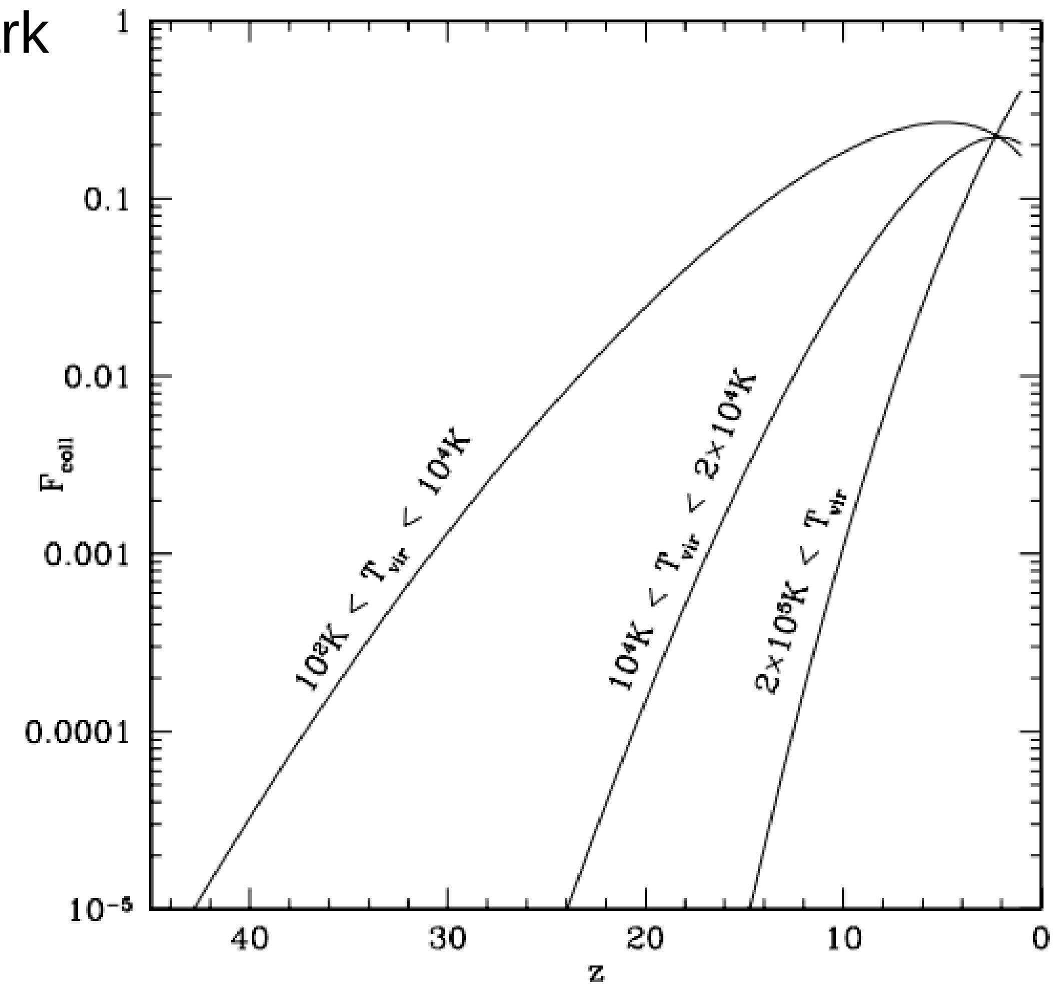
Reionization: The Standard Picture

- Ionization is driven by exponential increase in dark matter halo **collapsed fraction**

$$F_{\mathrm{coll,II}}(z) \equiv \frac{1}{\rho_0} \int_{M_{\mathrm{II}}}^{M_{\mathrm{Ia}}} dM \left(\frac{dn}{dM}\right) M$$

$$F_{\mathrm{coll,Ia}}(z) \equiv \frac{1}{\rho_0} \int_{M_{\mathrm{Ia}}}^{M_{\mathrm{Ib}}} dM \left(\frac{dn}{dM}\right) M$$

$$F_{\mathrm{coll,Ib}}(z) \equiv \frac{1}{\rho_0} \int_{M_{\mathrm{Ib}}}^{\infty} dM \left(\frac{dn}{dM}\right) M$$



Haiman & Holder (2003)

Complications

- Star formation efficiency vs. halo mass & environment (e.g. mergers vs. quiescent star formation)
- Escape fraction of ionizing radiation vs. halo mass & environment
- Effects of radiative feedback both internal and external
- Metal enrichment
- Evolving IMF
- Radiative transfer in the IGM
  - Clumping
  - Photoevaporation
  - Absorption systems
- Role of X-ray sources (e.g. binaries and quasars)
- Observations give global constraints (e.g. WMAP-tau), only probe brightest galaxies (LBGs and LAEs), or probe ionization state only at relatively late times (Lyman-alpha forest, $z<6$)

Complications

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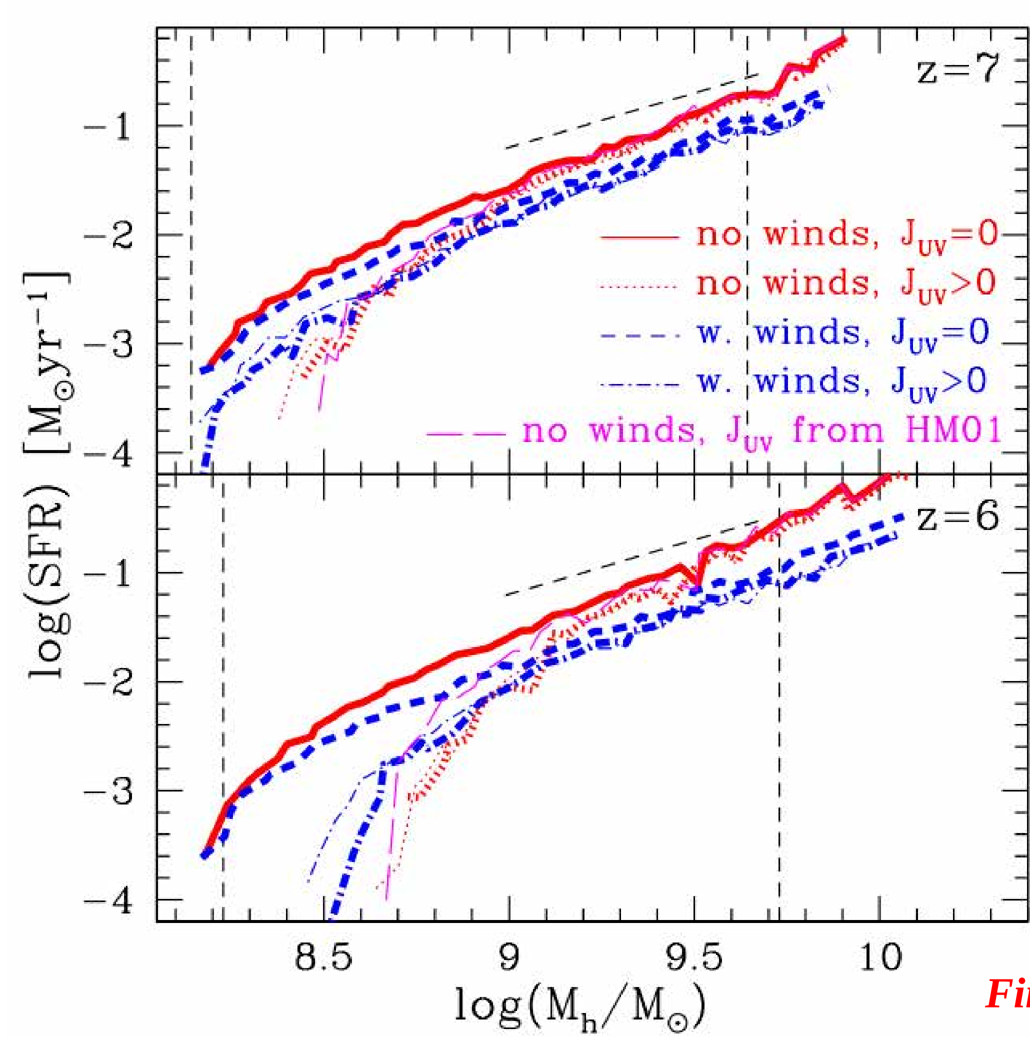
Star Formation Efficiency of Early Galaxies

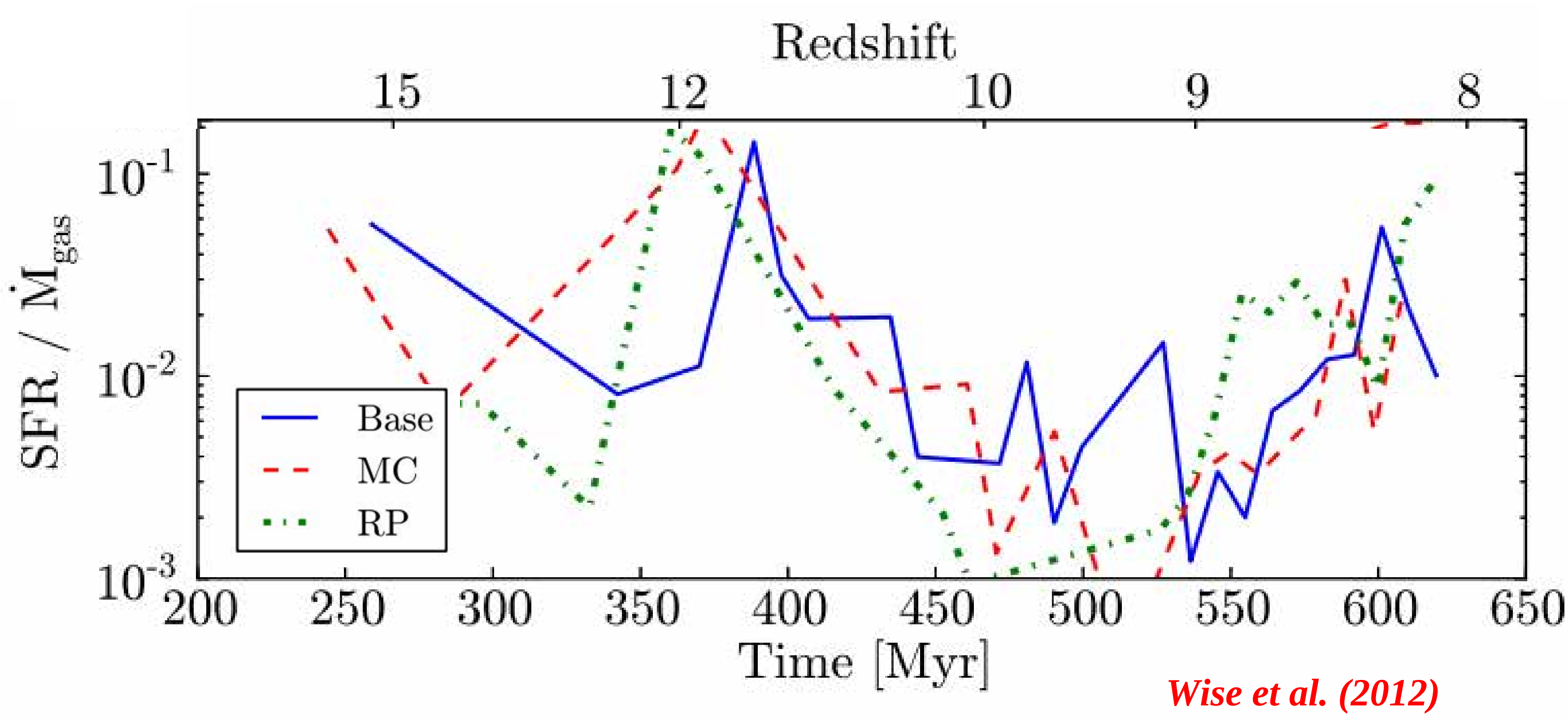
- Key parameter in predicting ionizing production rate for a given background cosmology
- Largely dependent on theoretical predictions (e.g. hydrodynamical simulations) due to extreme faintness
- Subject to several important physical effects:
  - Energy injection from supernovae and ionization heating
  - Metal enrichment history of the gas

Star Formation Efficiency of Early Galaxies



Finlator et al. (2011)

Star Formation Efficiency of Early Galaxies



Wise et al. (2012)

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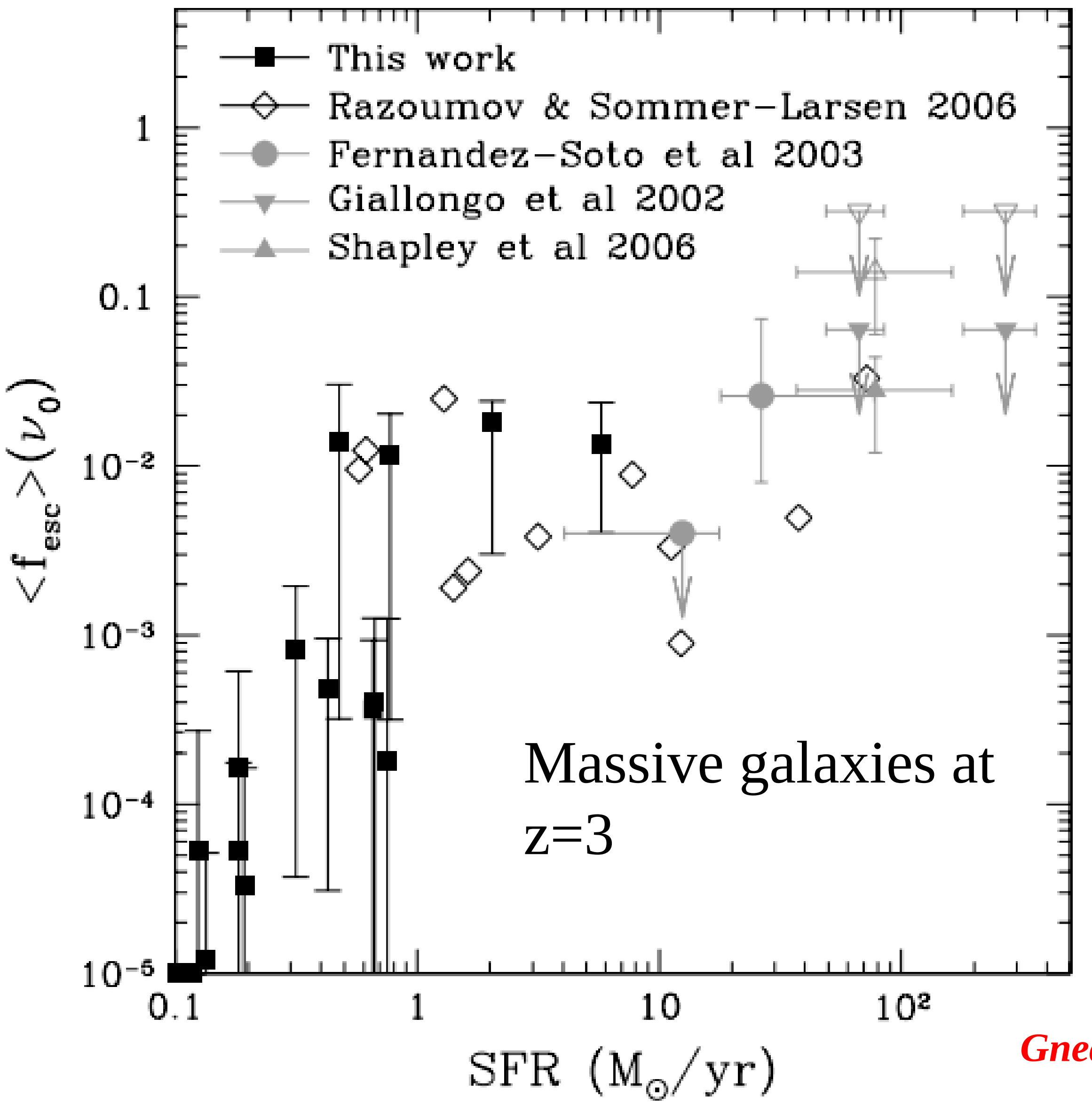
Ionizing Escape Fraction

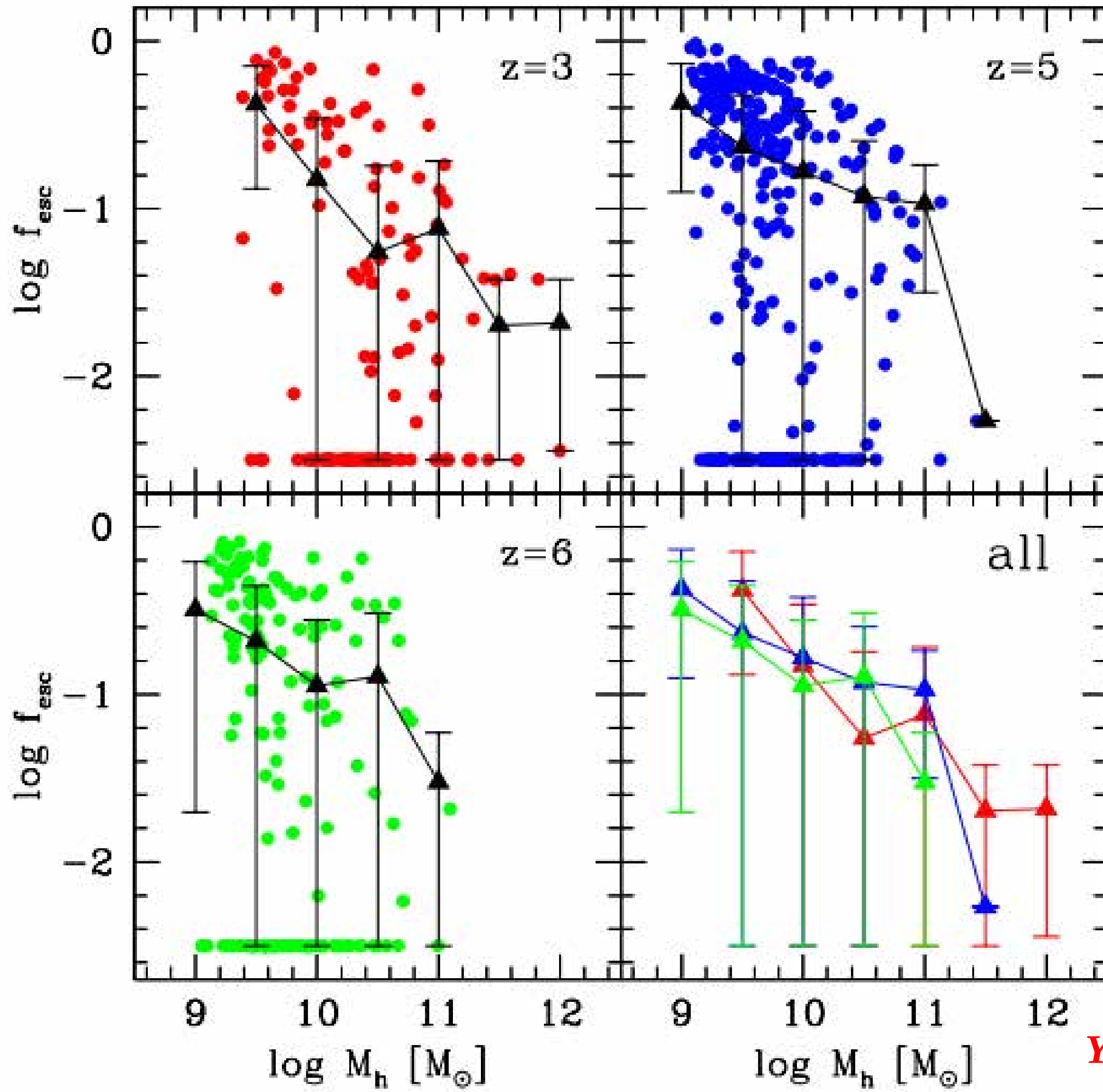
- Typically found to be low observationally -- less than ~5-10% at z<6 (e.g. Boutsia et al. 2011)
- Dependent on geometric effects -- whether stars can carve out “channels” of low-density gas out of which ionizing radiation can escape
- Simulations point to an increasing escape fraction with decreasing halo mass (Gnedin et al. 2008; Wise & Cen 2011; Yajima et al. 2011)

Ionizing Escape Fraction



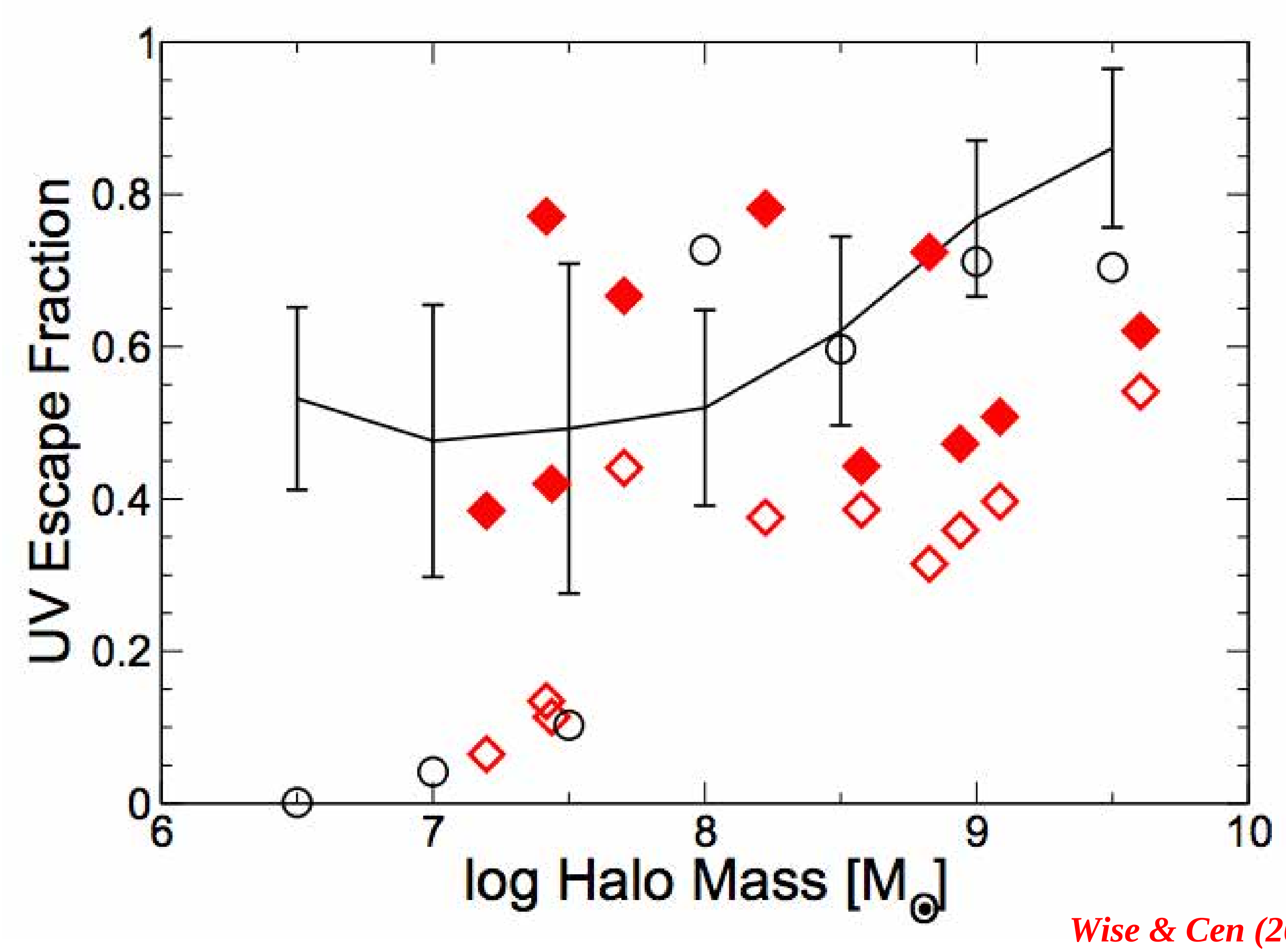
Gnedin et al. (2008)

Ionizing Escape Fraction



Yajima et al. (2011)

Ionizing Escape Fraction



Wise & Cen (2009)

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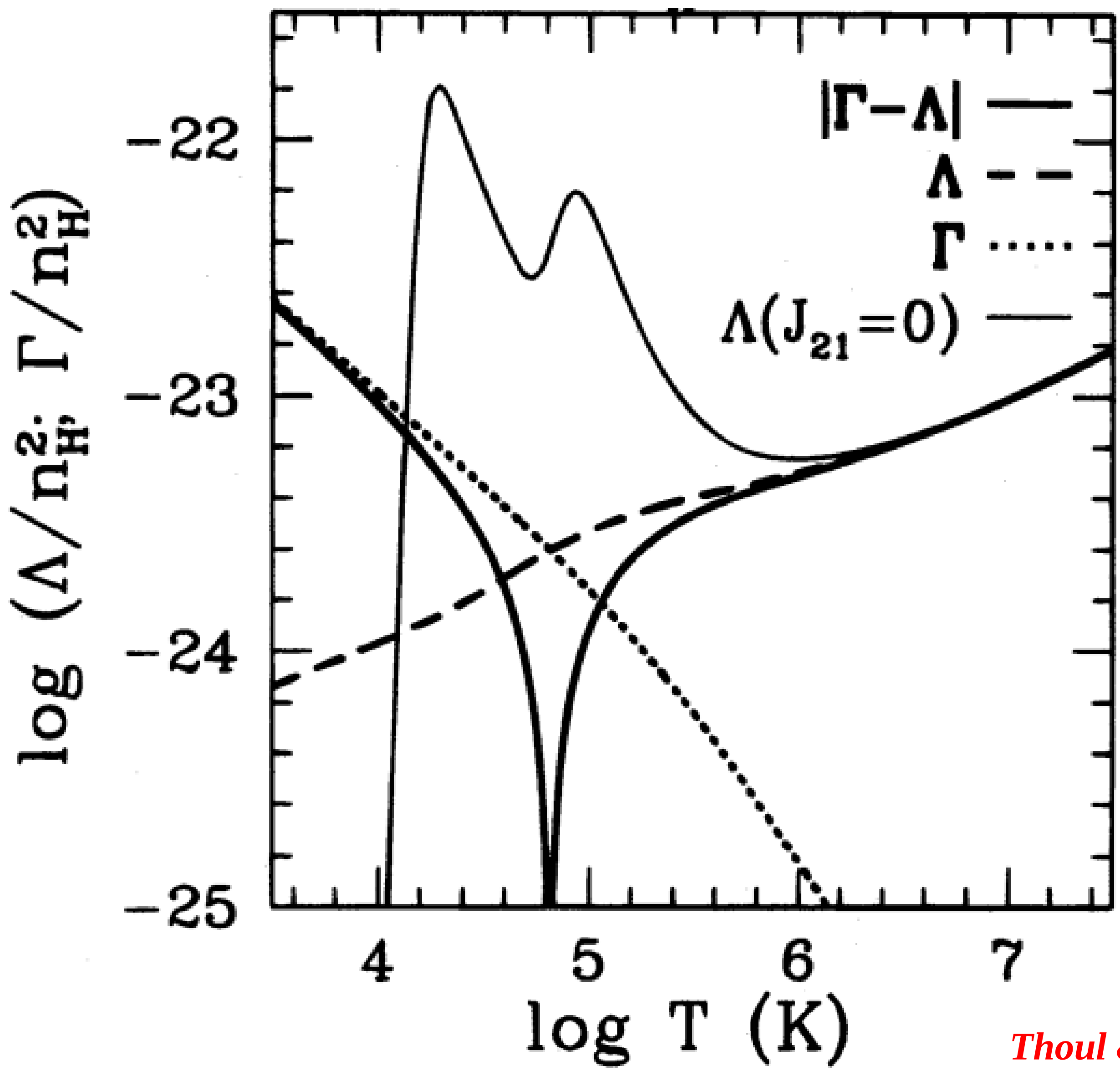
Photoionization Heating

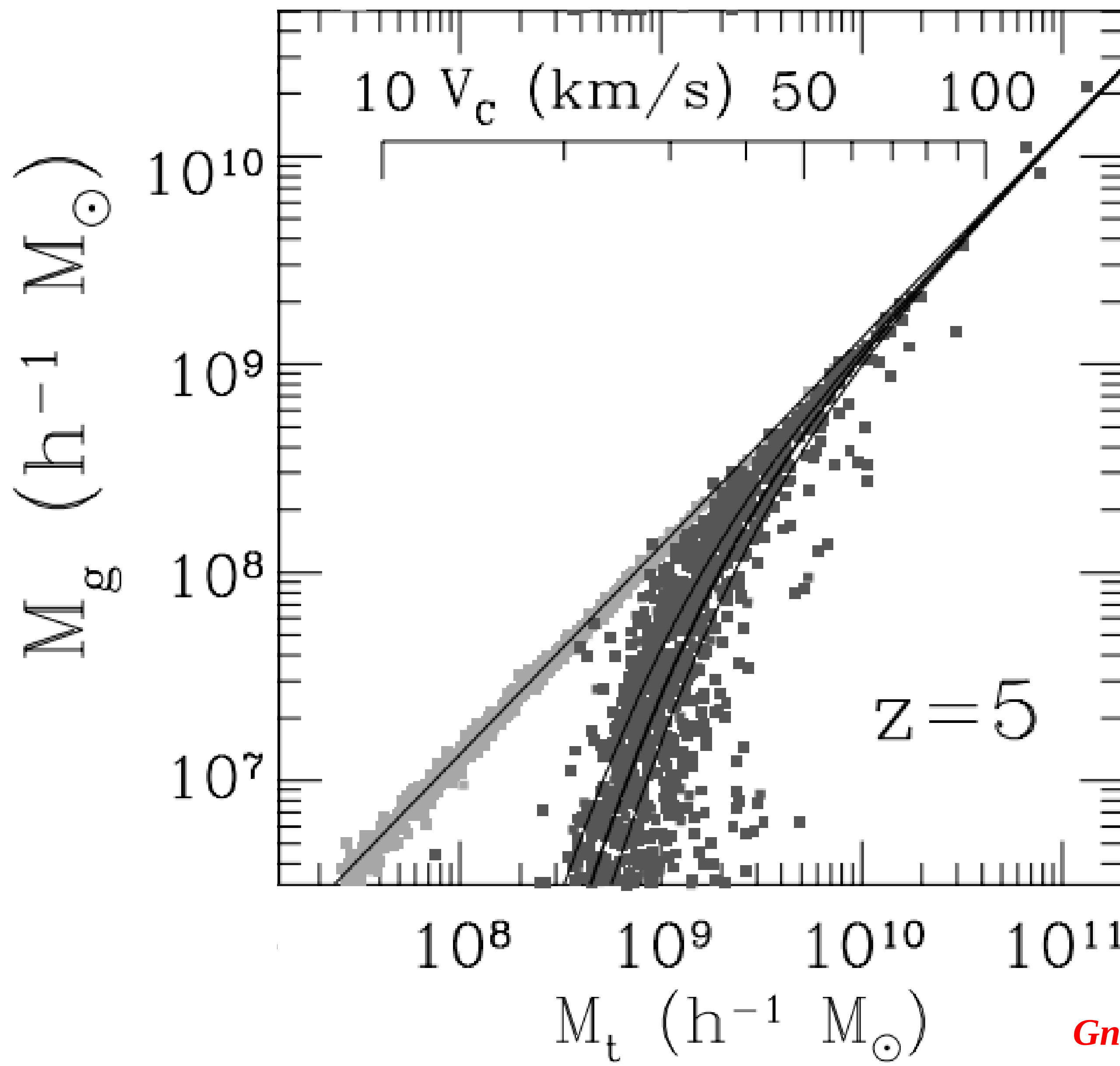
- Whether or not a dark matter halo can host star formation can depend on whether it is exposed to ionizing radiation
- Low mass halos do not have sufficiently deep gravitational potentials to overcome the pressure of ionized gas
- Suppression of star formation in low mass halos expected to be strongly inhomogeneous during reionization, due to the patchy build-up of the photoionizing UV background

Photoionization Heating



Thoul & Weinberg (1996)

Photoionization Heating



Gnedin (2000)

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Minimal Reionization Model

(Alvarez, Finlator & Trenti 2012)

- We set out to find simplest reionization model that adheres to major current observational constraints:
  - WMAP electron scattering optical depth ~0.09
  - Gunn-Peterson trough in high-z QSOs
  - Low escape fraction for high-mass galaxies observed at z<6
  - UV Luminosity function of galaxies at z ~ 6-8 (e.g. Trenti et al 2010; Bouwens et al. 2011)
  - Ionizing emissivity from Lyα forest and Lyman-limit system mean free path (Bolton & Haehnelt 2008; Songaila & Cowie 2010)

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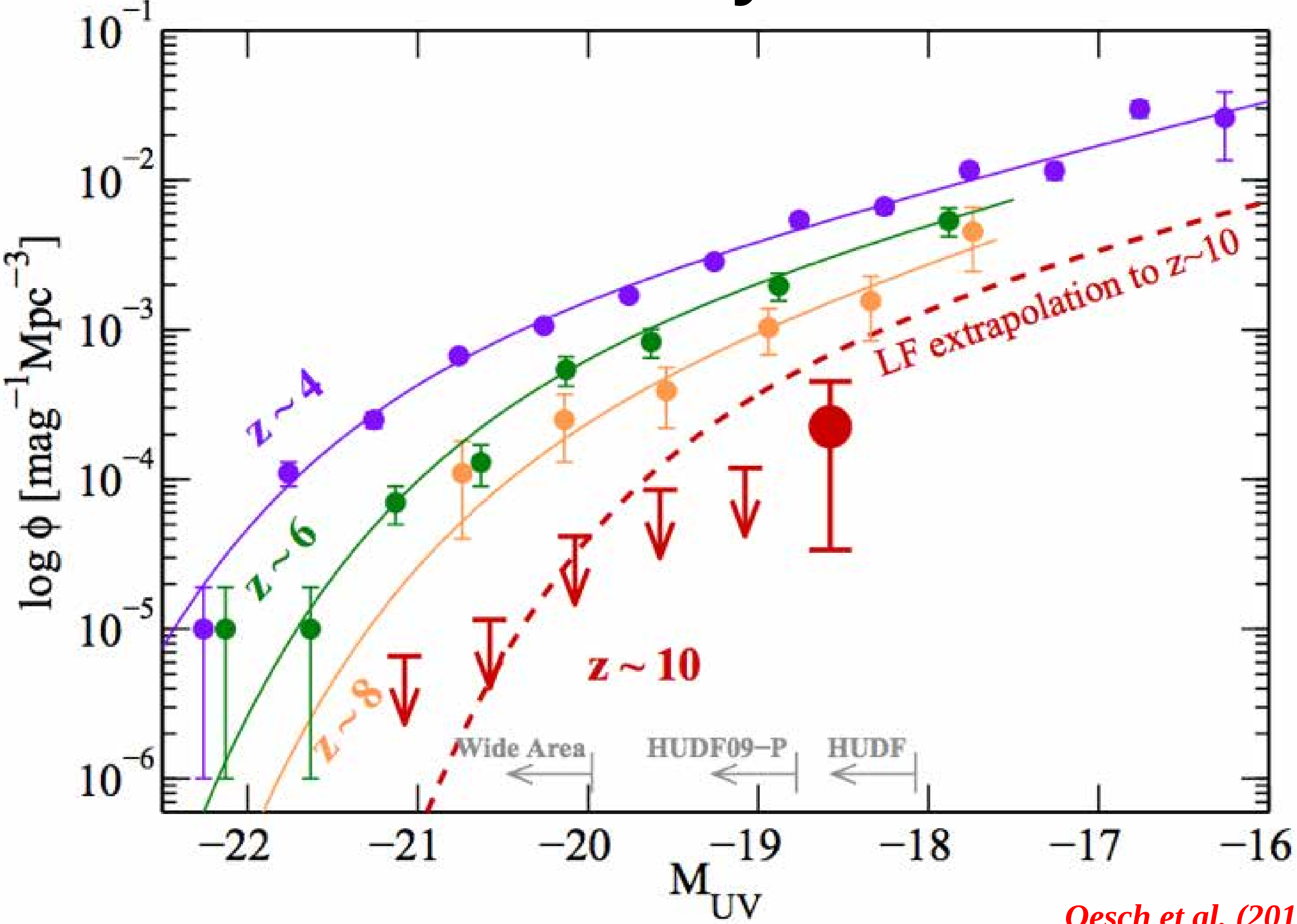
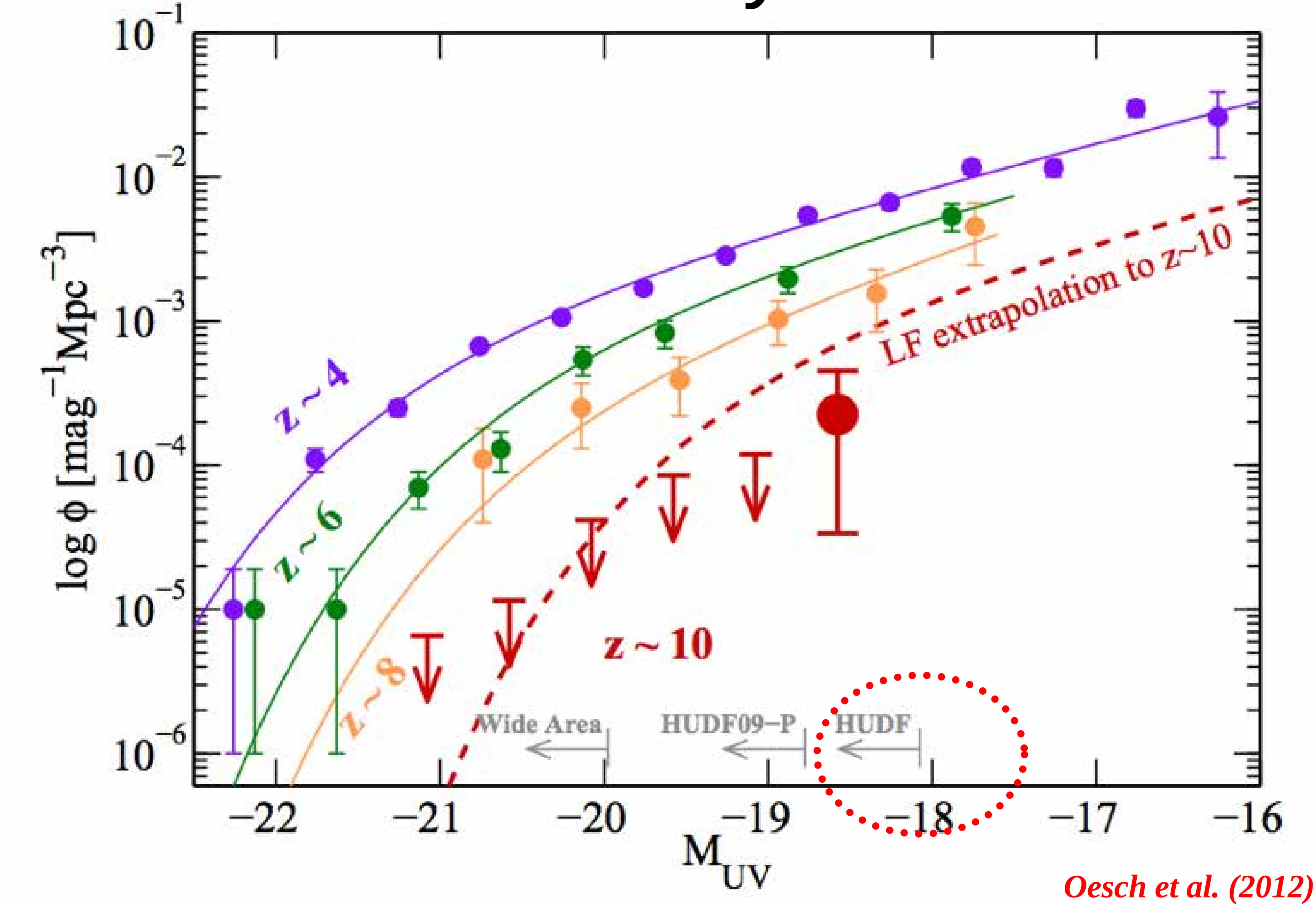
UV Luminosity Function



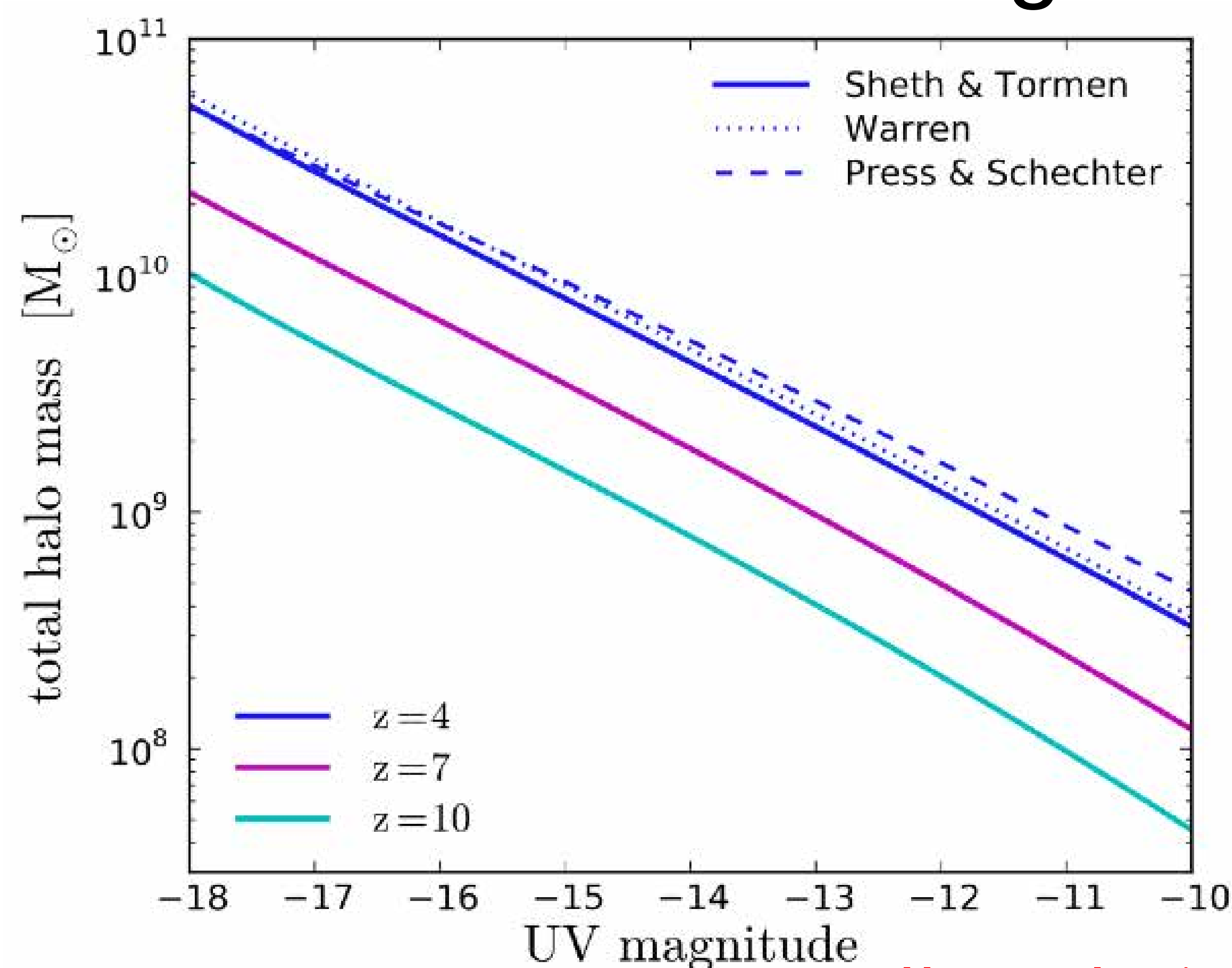
Oesch et al. (2012)

UV Luminosity Function



Oesch et al. (2012)

Abundance Matching



Kuhlen & Faucher-Giguere (2012)

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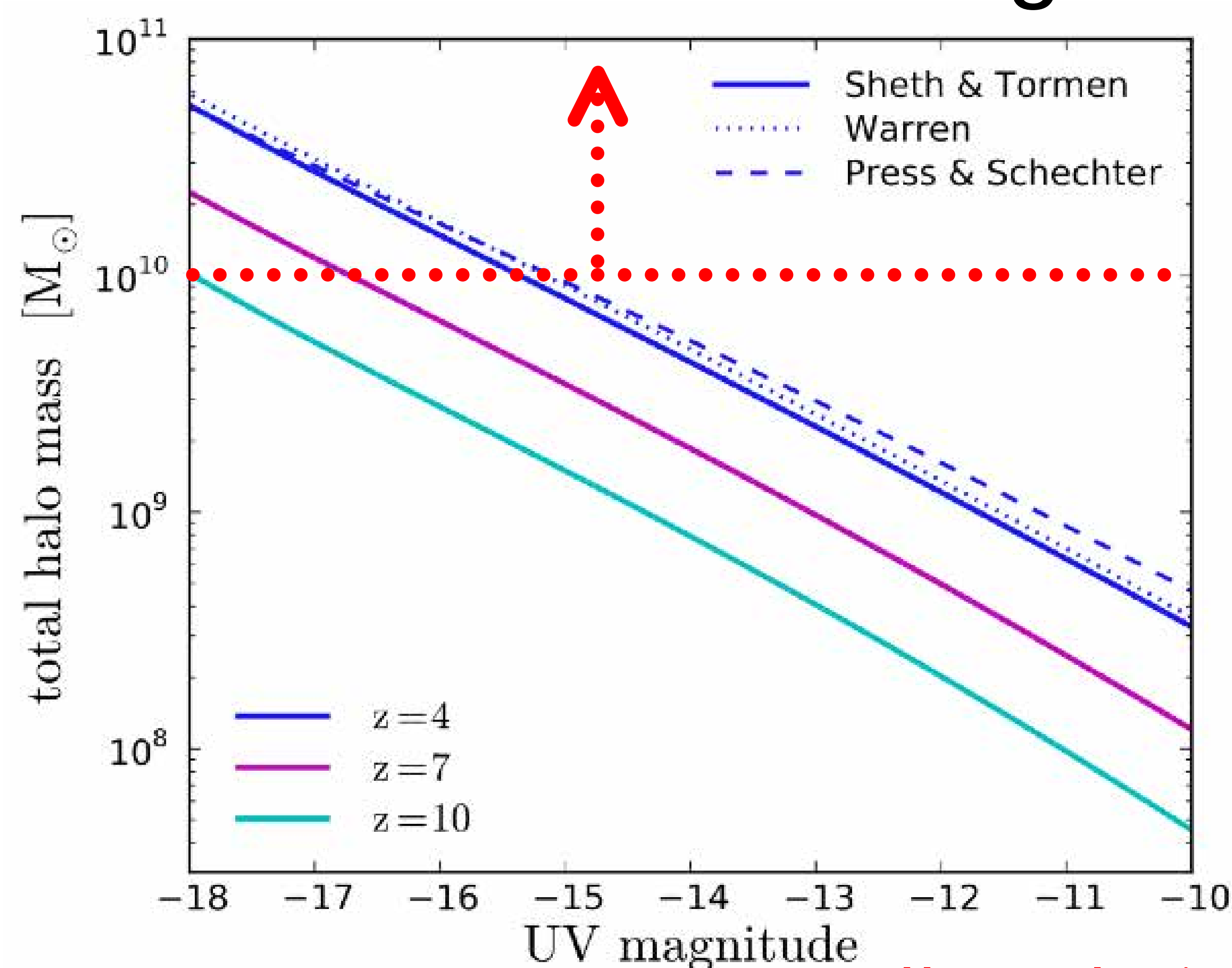

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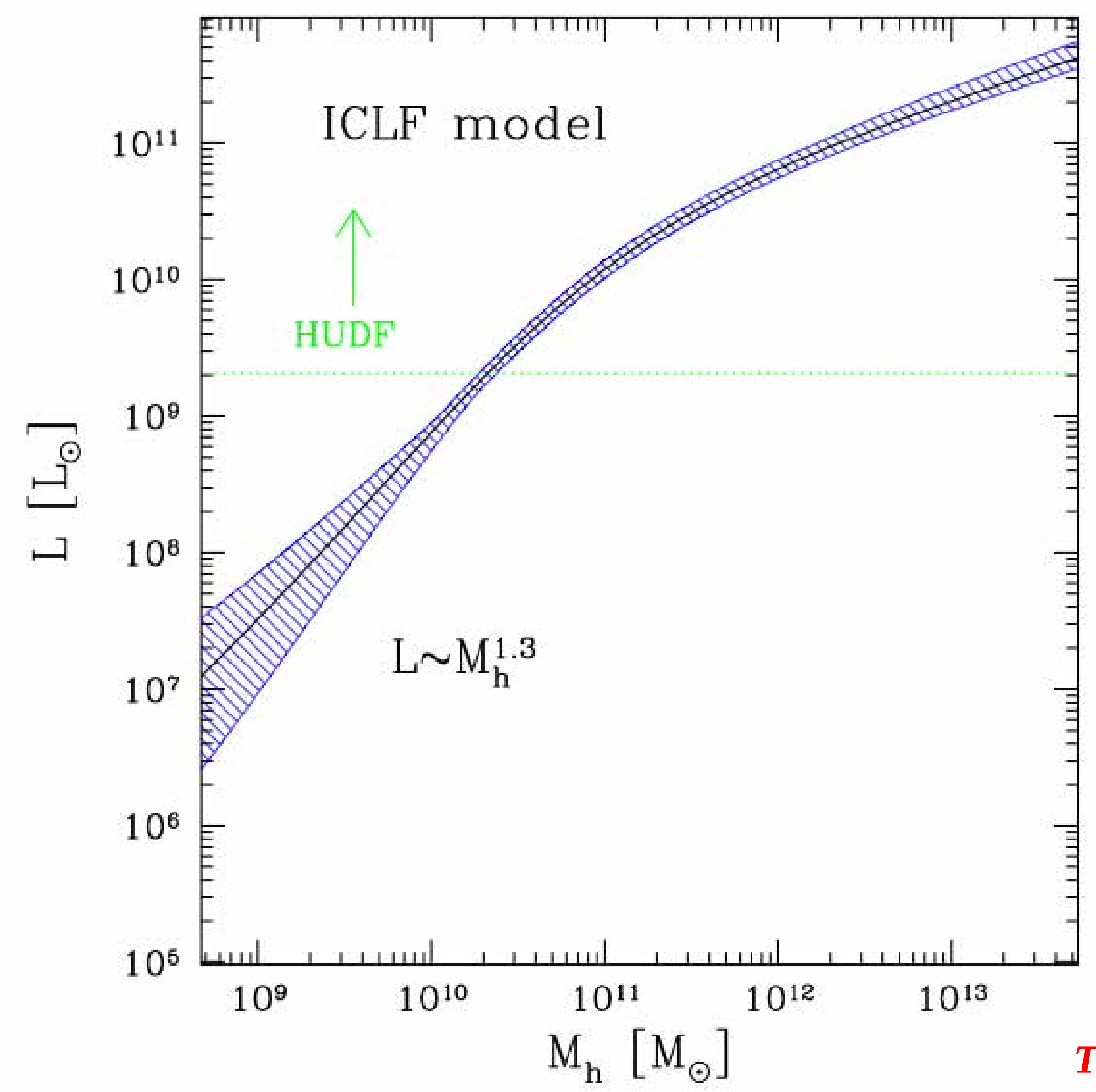
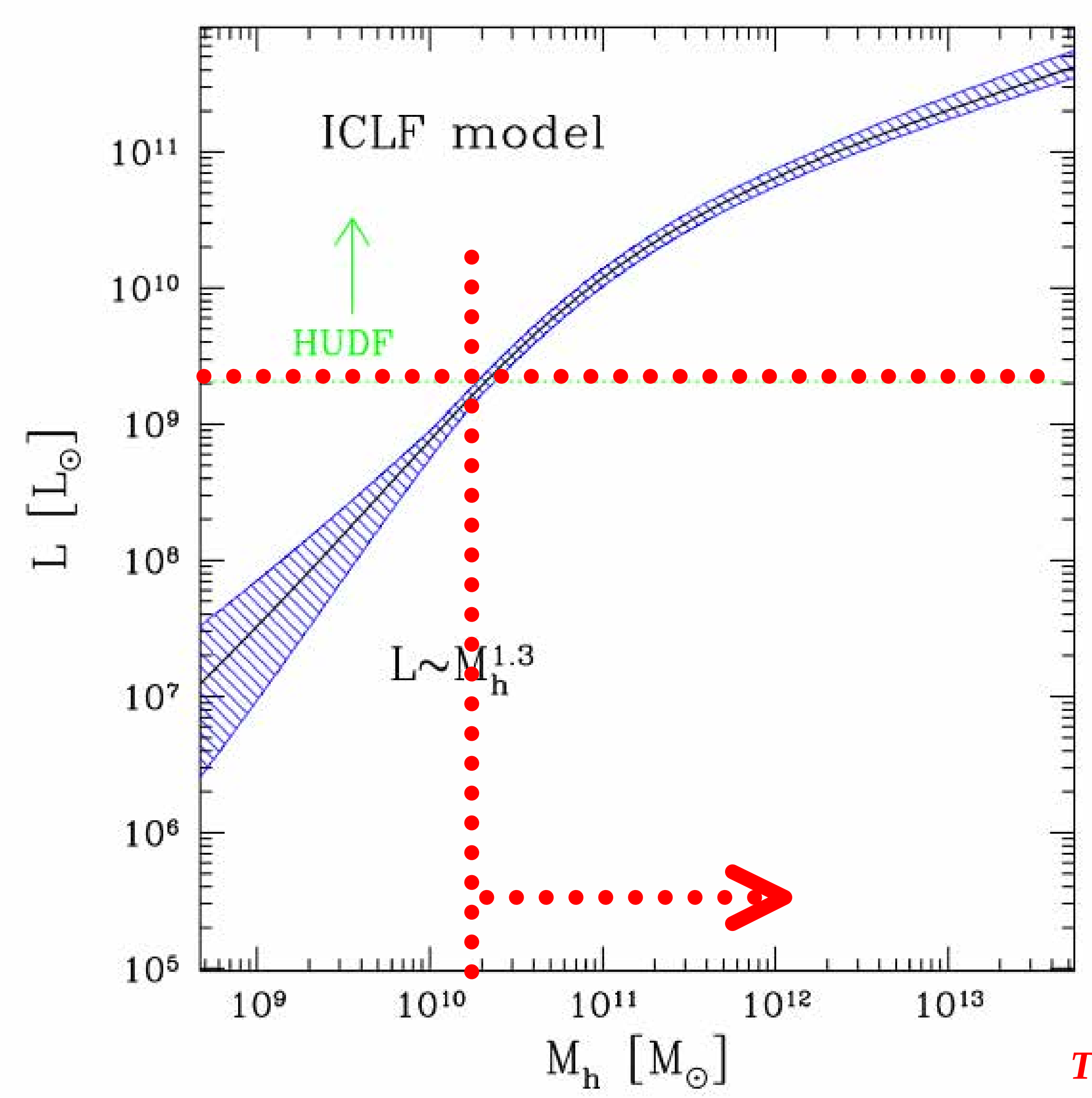


Trenti et al. (2010)

Abundance Matching



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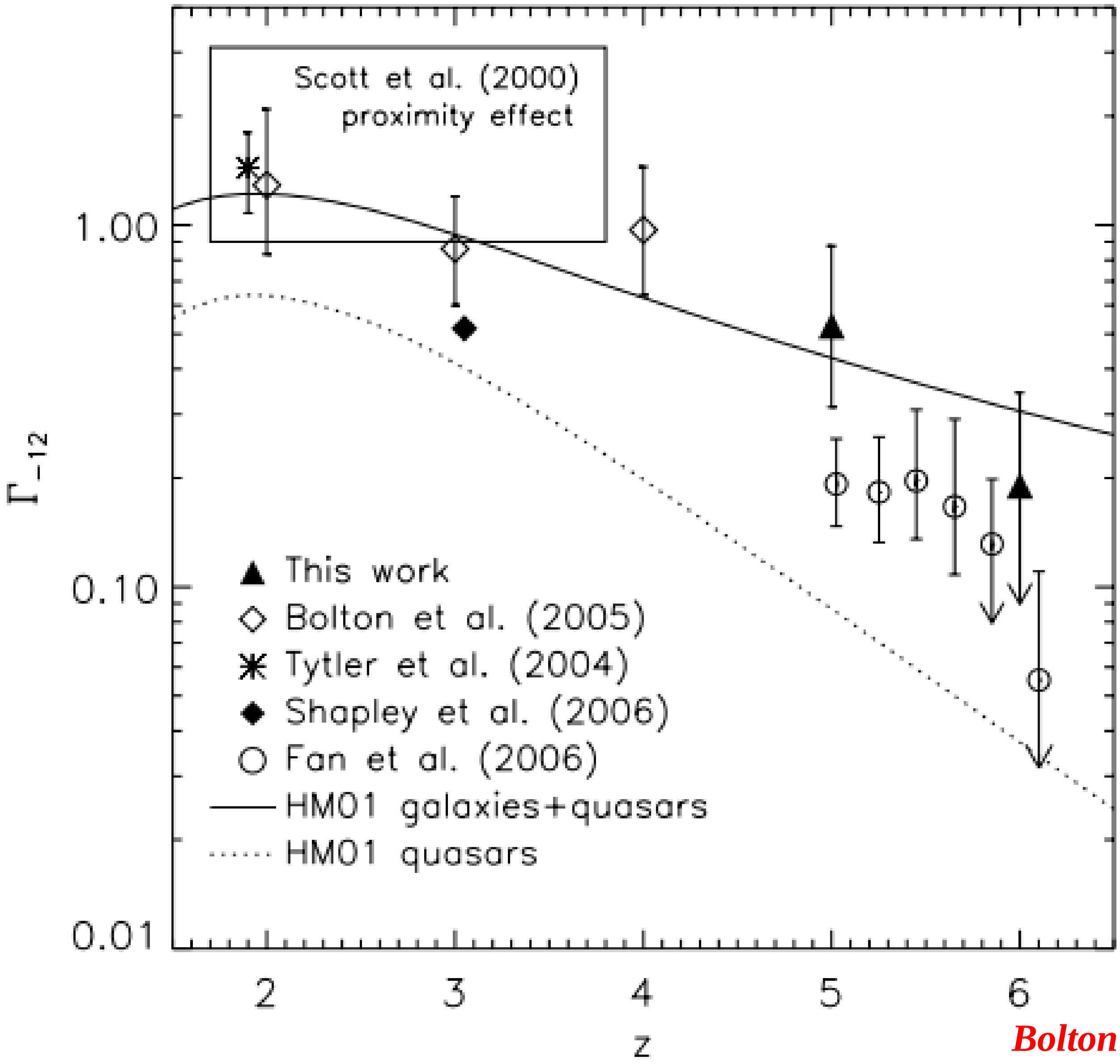
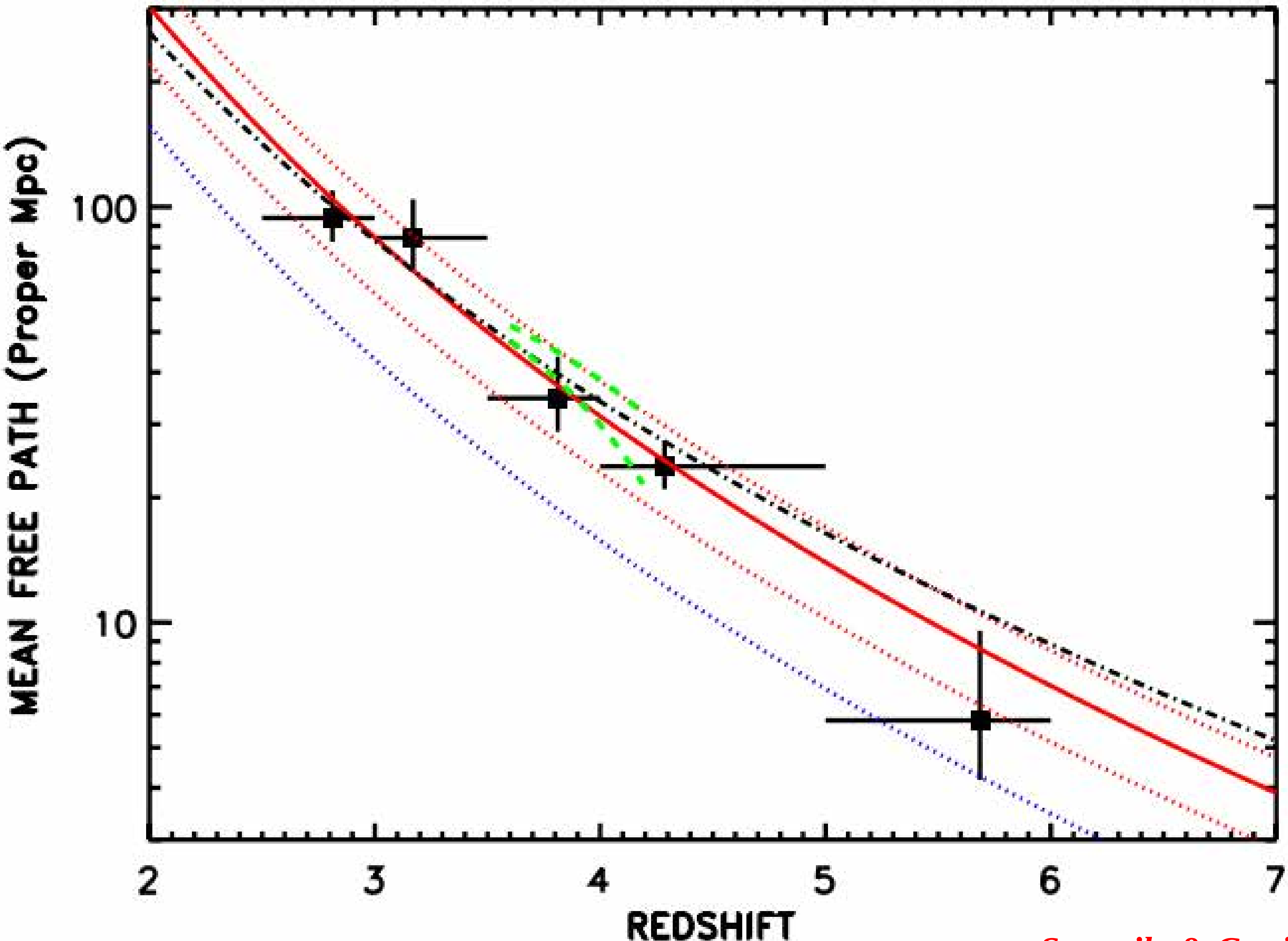
Emissivity from Lyα Forest



Bolton & Haehnelt (2007)

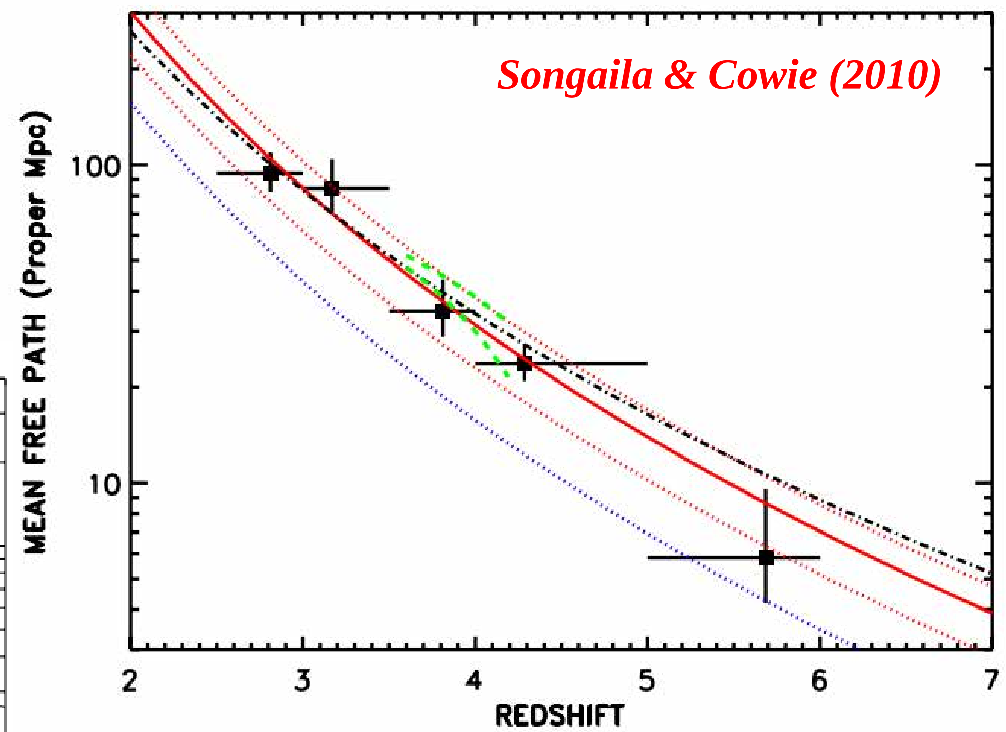
Emissivity from Lyα Forest

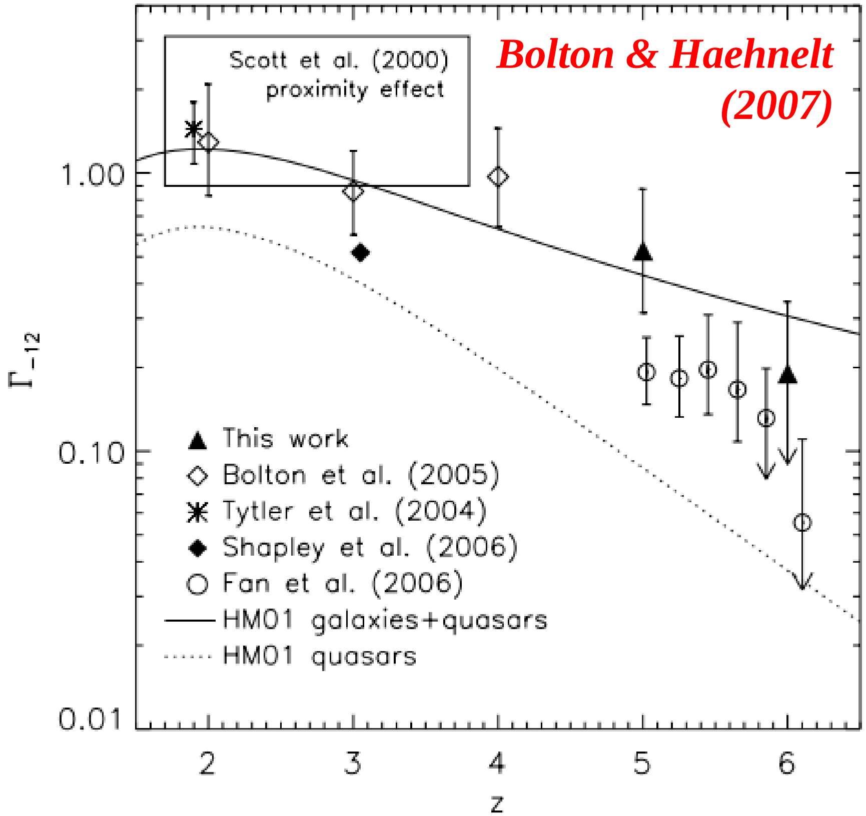


Songaila & Cowie (2010)

Emissivity from Lyα Forest

Flux and mean free path measurements can be combined to obtain ionizing photon emissivity





$$\dot{n}_\gamma \propto \frac{\Gamma_{-12}}{\lambda_{\rm mfp}}$$

Minimal Reionization Model

$$\dot{x} = \frac{\dot{n}_\gamma}{n_0} - \frac{x}{\langle t_{\rm rec} \rangle}$$

$$\dot{n}_\gamma = f_{\rm esc,1} f_\gamma \dot{\rho}_{*,1} + f_{\rm esc,2} f_\gamma \dot{\rho}_{*,2}$$

$$\dot{\rho}_* = \rho_0 \frac{\Omega_b}{\Omega_m} \left[(1-x)\epsilon_{*,1} \dot{f}_1 + \epsilon_{*,2} \dot{f}_2 \right]$$

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Use standard clumping factor of ~3 at z=6, declining to high redshift (e.g. Pawlik et al. 2011)

$$-x)\epsilon_{*,1}\dot{f}_1 + \epsilon_{*,2}\dot{f}_2]$$

Minimal Reionization Model

$$\dot{x} = \frac{\dot{n}_\gamma}{n_0} - \frac{x}{\langle t_{\rm rec} \rangle}$$

$$\dot{n}_\gamma = f_{\rm esc,1} f_\gamma \dot{\rho}_{*,1} + f_{\rm esc,2} f_\gamma \dot{\rho}_{*,2}$$

Motivated by simulations, we use a two-component model, with two different escape fractions for low and high mass halos. High-mass halo escape fraction is fixed to be 0.05, while low-mass halo escape fraction was varied so as to obtain $\tau_{\rm es} = 0.086$

Minimal Reionization Model

$$\dot{x} = \frac{\dot{n}_\gamma}{n_0} - \frac{x}{\langle t_{\rm rec} \rangle}$$

$$\dot{n}_\gamma = f_{\rm esc,1} f_\gamma \dot{\rho}_{*,1} + f_{\rm esc,2} f_\gamma \dot{\rho}_{*,2}$$

$$M_1 = 10^8 M_\odot \qquad f_{\rm esc,1} = 0.8$$

$$M_2 = 2 \times 10^9 M_\odot \qquad f_{\rm esc,2} = 0.05$$

Minimal Reionization Model

$$\dot{x} = \frac{\dot{n}_\gamma}{n_0} - \frac{x}{\langle t_{\rm rec} \rangle}$$

We include the effect of suppression of low-mass halos by only allowing star formation to occur in halos with mass $M_1 < M_h < M_2$ if located in neutral regions, assuming they are distributed uniformly in space

$$\dot{\rho}_* = \rho_0 \frac{\Omega_b}{\Omega_m} \left[(1-x)\epsilon_{*,1}\dot{f}_1 + \epsilon_{*,2}\dot{f}_2 \right]$$

Minimal Reionization Model

$$\dot{x} = \frac{\dot{n}_\gamma}{n_0} - \frac{x}{\langle t_{\rm rec} \rangle}$$

Star formation efficiency fixed to be same in both halo mass ranges - low mass halos no more efficient at forming stars. Ionizing photon per stellar mass obtained using Salpeter IMF with [Fe/H] = -2

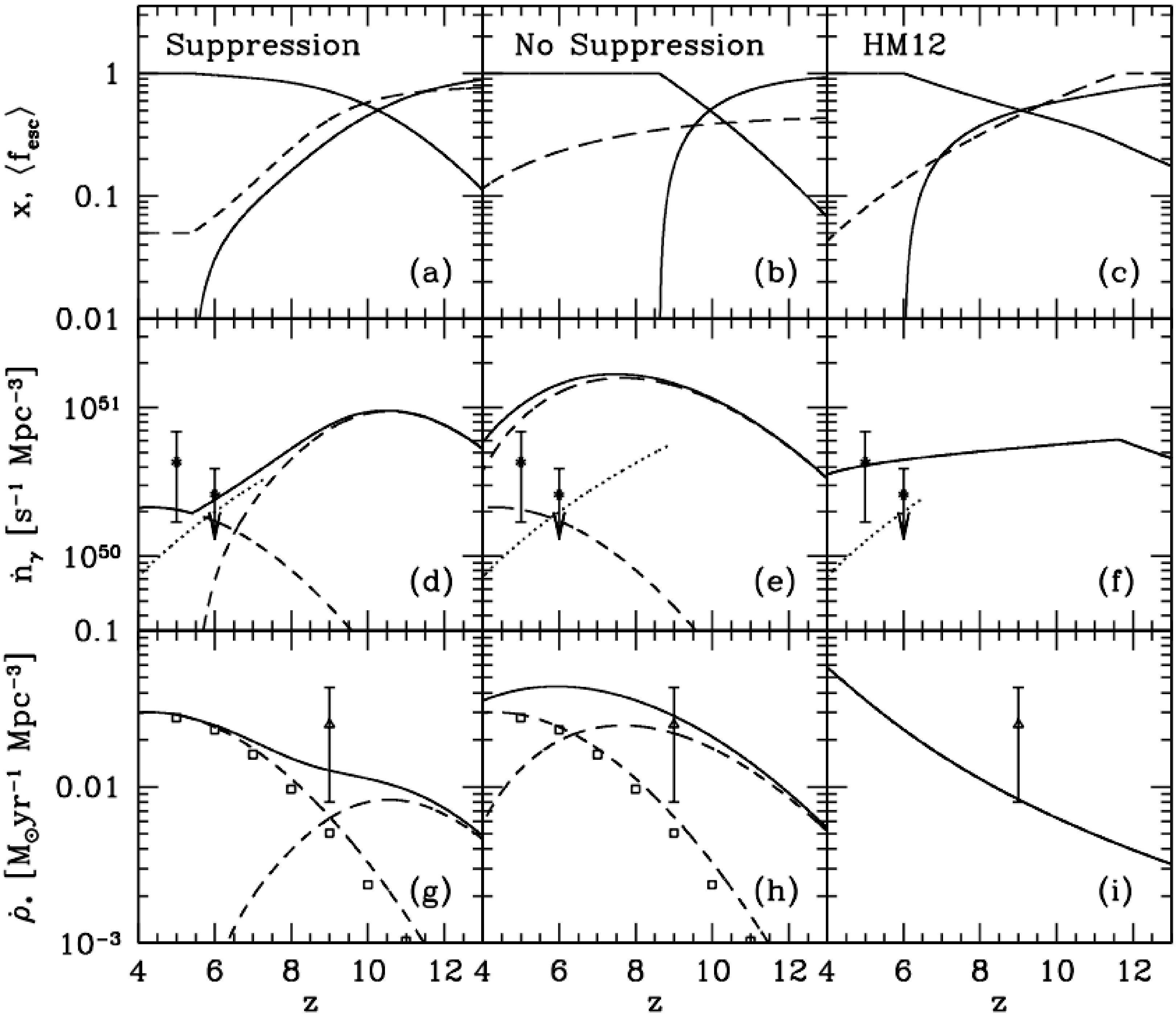
$$\dot{\rho}_* = \rho_0 \frac{\Omega_b}{\Omega_m} \left[(1-x)\epsilon_{*,1}\dot{f}_1 + \epsilon_{*,2}\dot{f}_2 \right]$$

Minimal Reionization Model

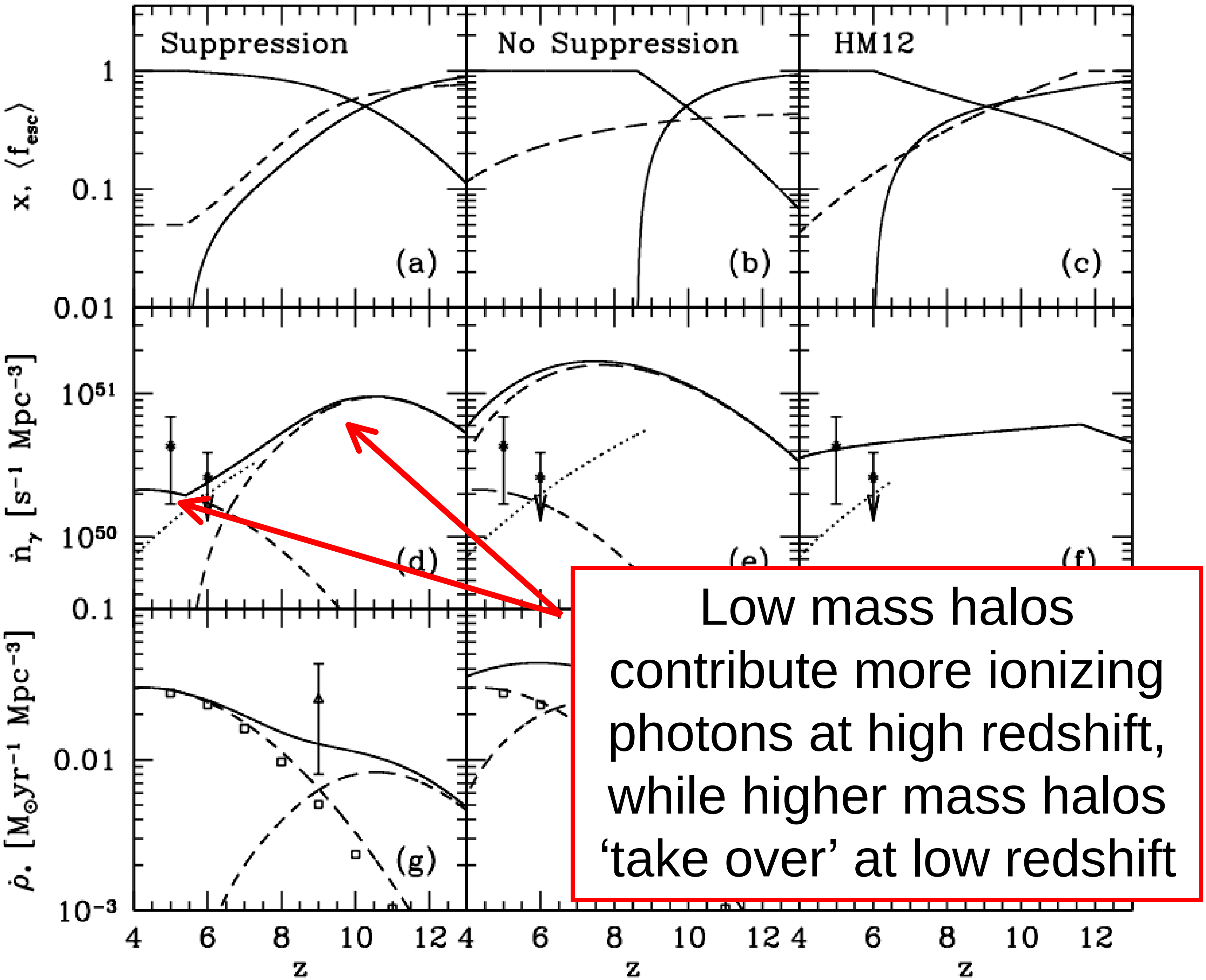
$$\dot{x} = \frac{\dot{n}_\gamma}{n_0} - \frac{x}{\langle t_{\rm rec} \rangle}$$

$$\boxed{\begin{array}{ll} M_1 = 10^8 M_\odot & \\ & \epsilon_{*,1} = \epsilon_{*,2} = 0.03 \\ M_2 = 2 \times 10^9 M_\odot & \end{array}}$$

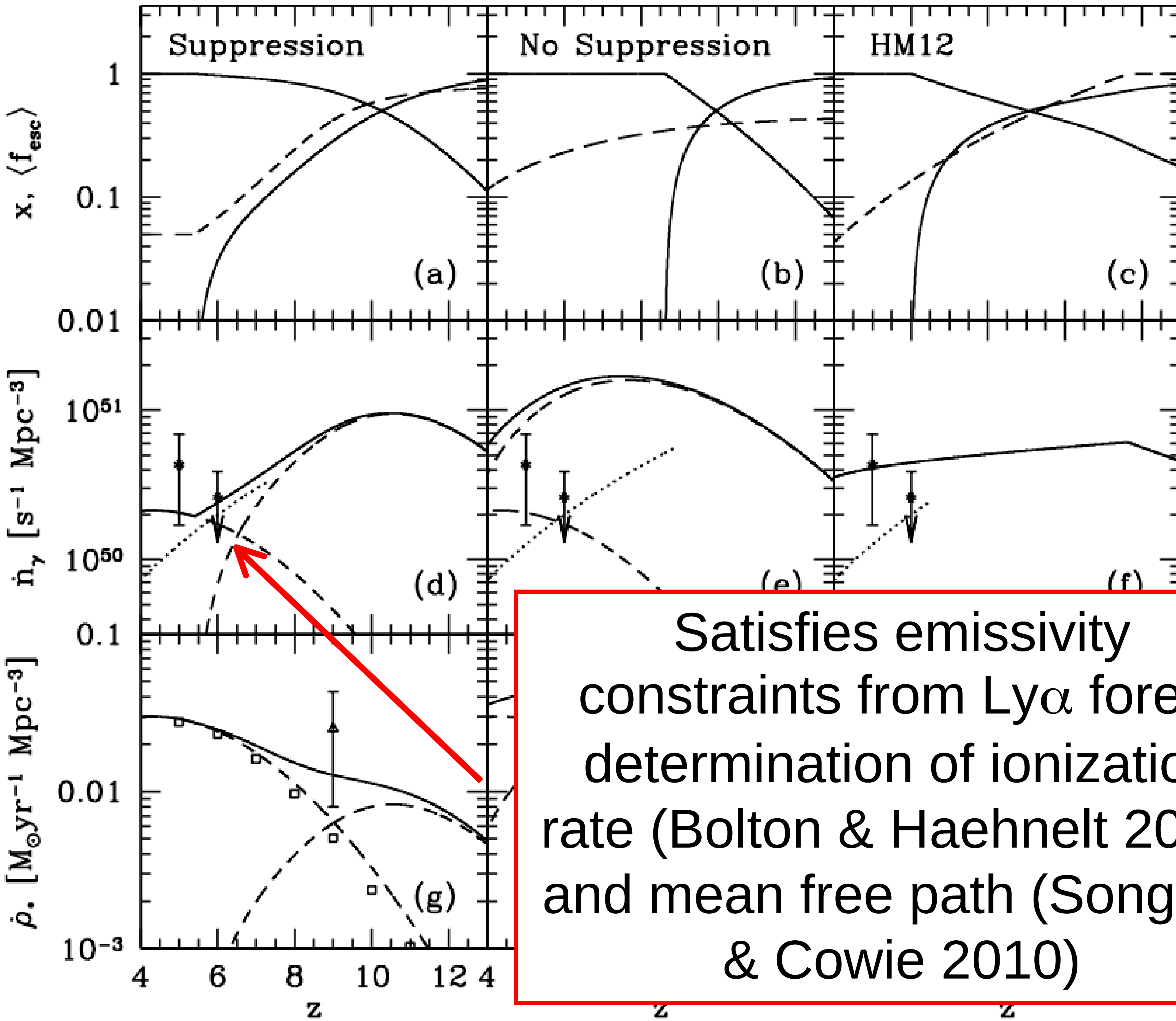
$$\dot{\rho}_* = \rho_0 \frac{\Omega_b}{\Omega_m} \left[(1-x)\epsilon_{*,1} \dot{f}_1 + \epsilon_{*,2} \dot{f}_2 \right]$$



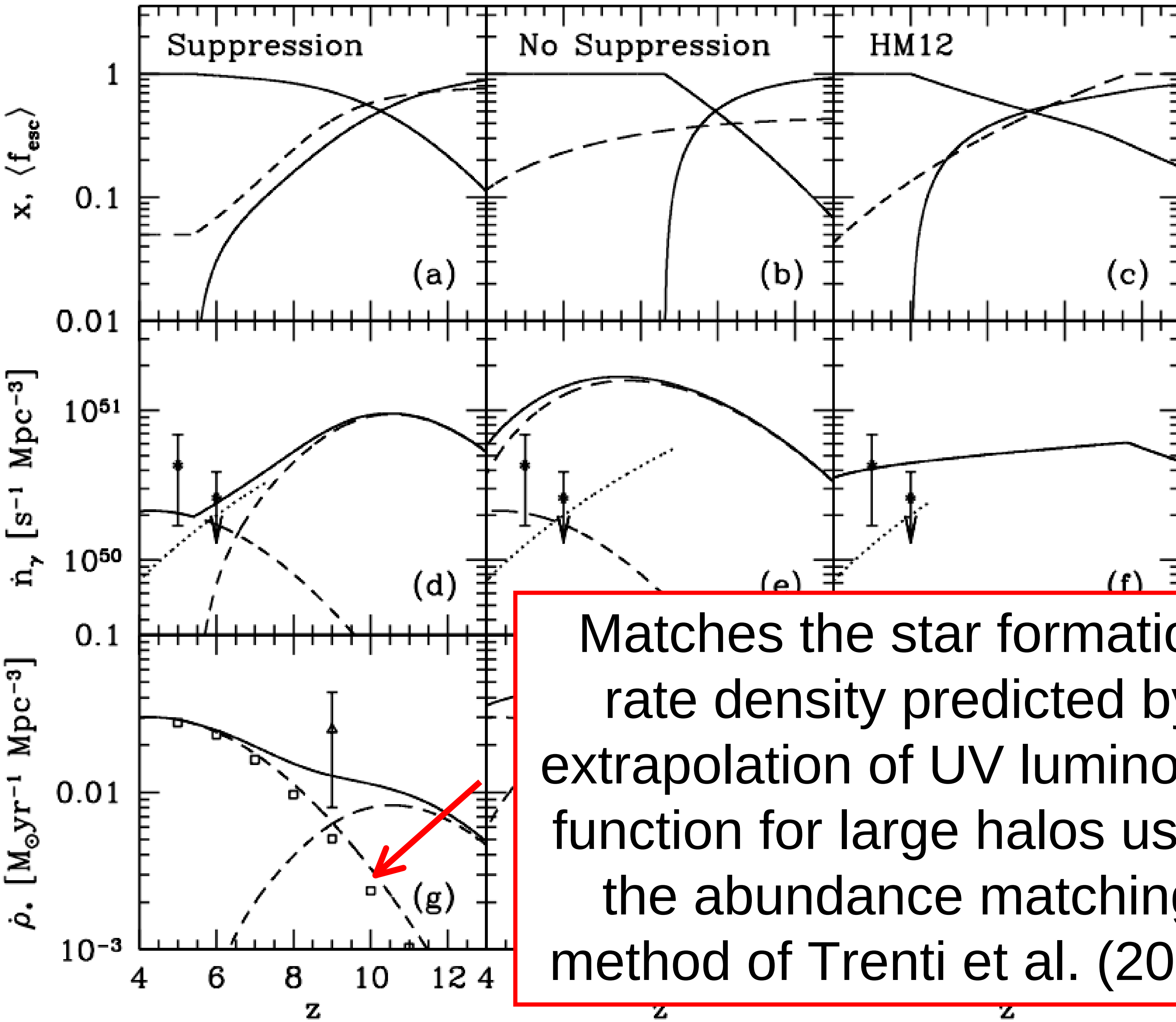
Suppression
No Suppression
HM12
x, ⟨f_esc⟩
1
0.1
0.01
(a)
(b)
(c)
ṅ_γ [s^-1 Mpc^-3]
10^51
10^50
(d)
(e)
(f)
ρ̇_* [M_⊙ yr^-1 Mpc^-3]
0.1
0.01
10^-3
(g)
(h)
(i)
4 6 8 10 12
z



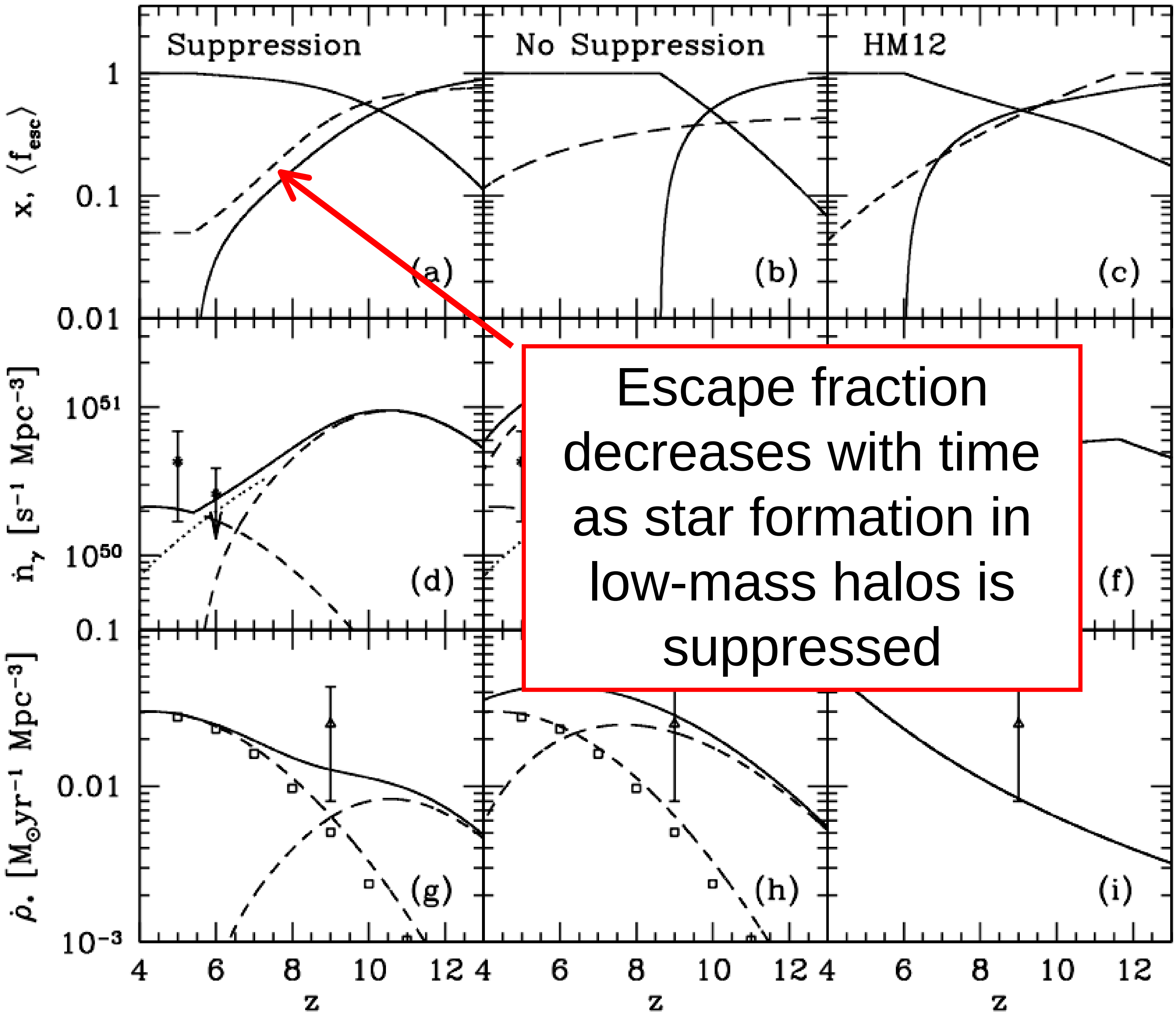
Suppression
No Suppression
HM12
x, ⟨f_esc⟩
ṅ_γ [s^-1 Mpc^-3]
ρ̇_* [M_⊙ yr^-1 Mpc^-3]
z
(a)
(b)
(c)
(d)
(e)
(f)
(g)
Low mass halos contribute more ionizing photons at high redshift, while higher mass halos ‘take over’ at low redshift

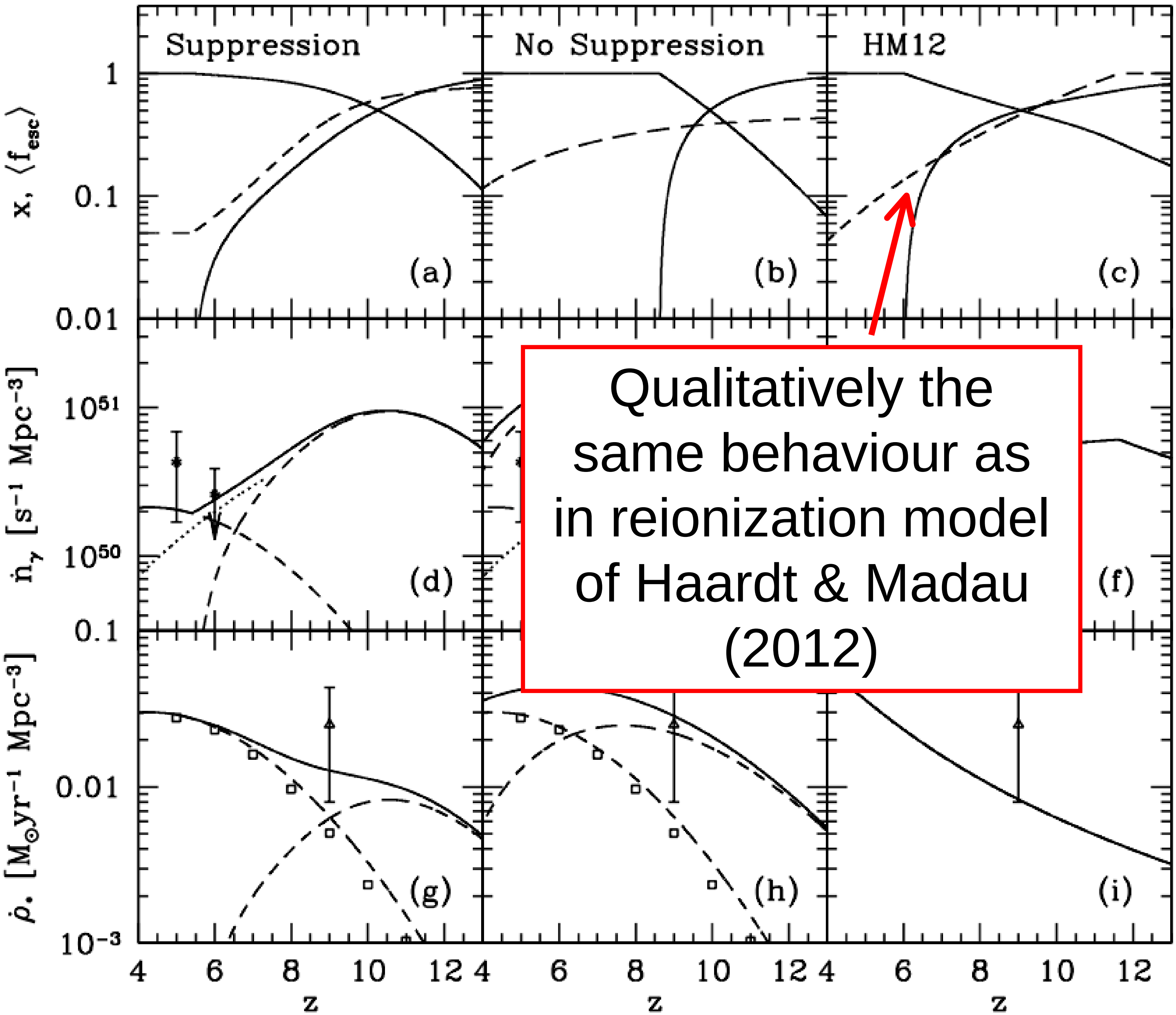


Satisfies emissivity constraints from Lyα forest determination of ionization rate (Bolton & Haehnelt 2007) and mean free path (Songaila & Cowie 2010)



Matches the star formation rate density predicted by extrapolation of UV luminosity function for large halos using the abundance matching method of Trenti et al. (2010)


Suppression
No Suppression
HM12
x, ⟨f_esc⟩
1
0.1
0.01
(a)
(b)
(c)
ṅ_γ [s⁻¹ Mpc⁻³]
10^51
10^50
(d)
(f)
0.1
ρ̇* [M⊙yr⁻¹ Mpc⁻³]
0.01
10⁻³
(g)
(h)
(i)
4 6 8 10 12
z
Escape fraction decreases with time as star formation in low-mass halos is suppressed



Suppression
No Suppression
HM12
x, ⟨f_esc⟩
ṅ_γ [s^-1 Mpc^-3]
ρ̇_* [M_⊙ yr^-1 Mpc^-3]
1
0.1
0.01
10^51
10^50
0.1
0.01
10^-3
(a)
(b)
(c)
(d)
(f)
(g)
(h)
(i)
4
6
8
10
12
z
Qualitatively the same behaviour as in reionization model of Haardt & Madau (2012)

Summary

- Our model matches
  - Relatively low emissivity of ionizing photons at end of reionization
  - Relatively high Thomson scattering optical depth of ~0.09 reported by WMAP
  - Rapid decline in star formation rate density in high mass halos towards high redshift predicted from abundance matching LBGs
- No need to invoke Pop III stars or star formation in minihalos -- we use standard Salpeter IMF and Pop II metallicity and only atomic cooling halos
- Rapid increase in escape fraction required by Haardt & Madau (2012) and Kuhlen & Faucher-Giguere (2012) naturally explained by suppression of star formation in low-mass halos possesing high escape fractions

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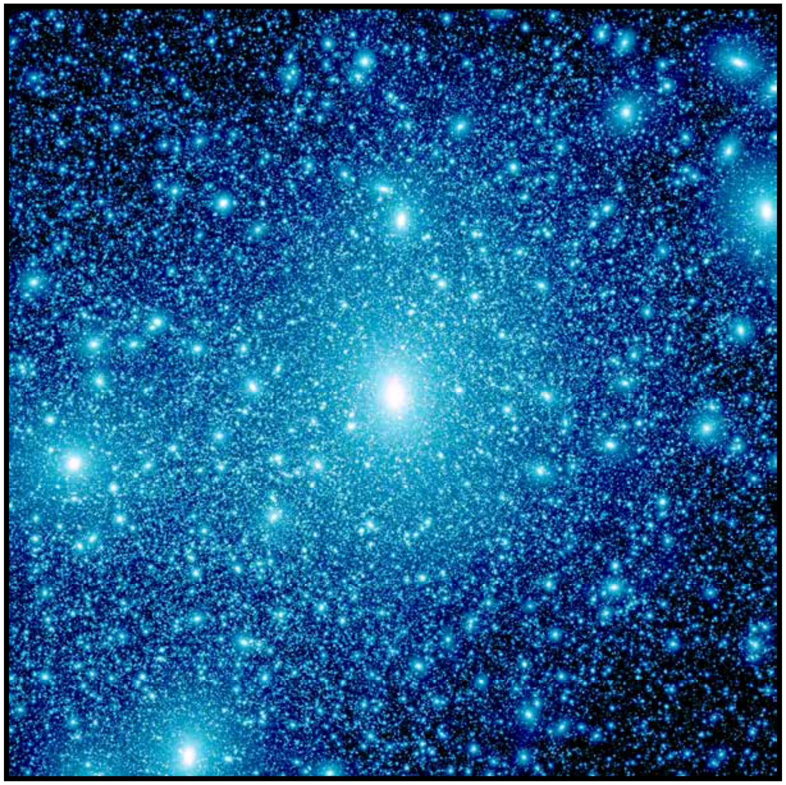
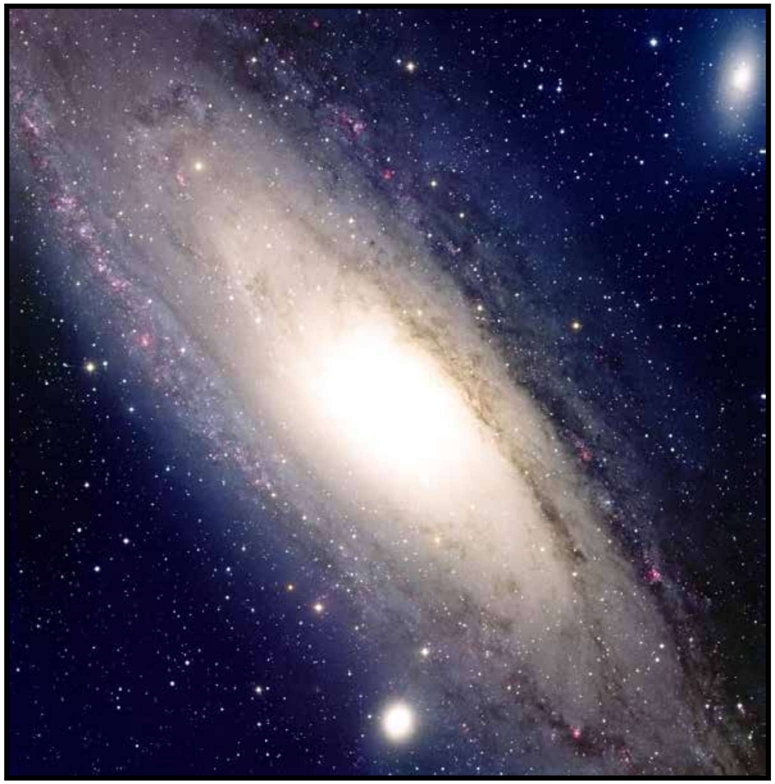
Reionization and the Local Universe

MA, Busha, Wechsler & Abel (2009)
Busha, MA, Wechsler, Abel, & Strigari (2010)
Li, MA, Wecshler & Abel (2012)



Ben Moore



NOAO

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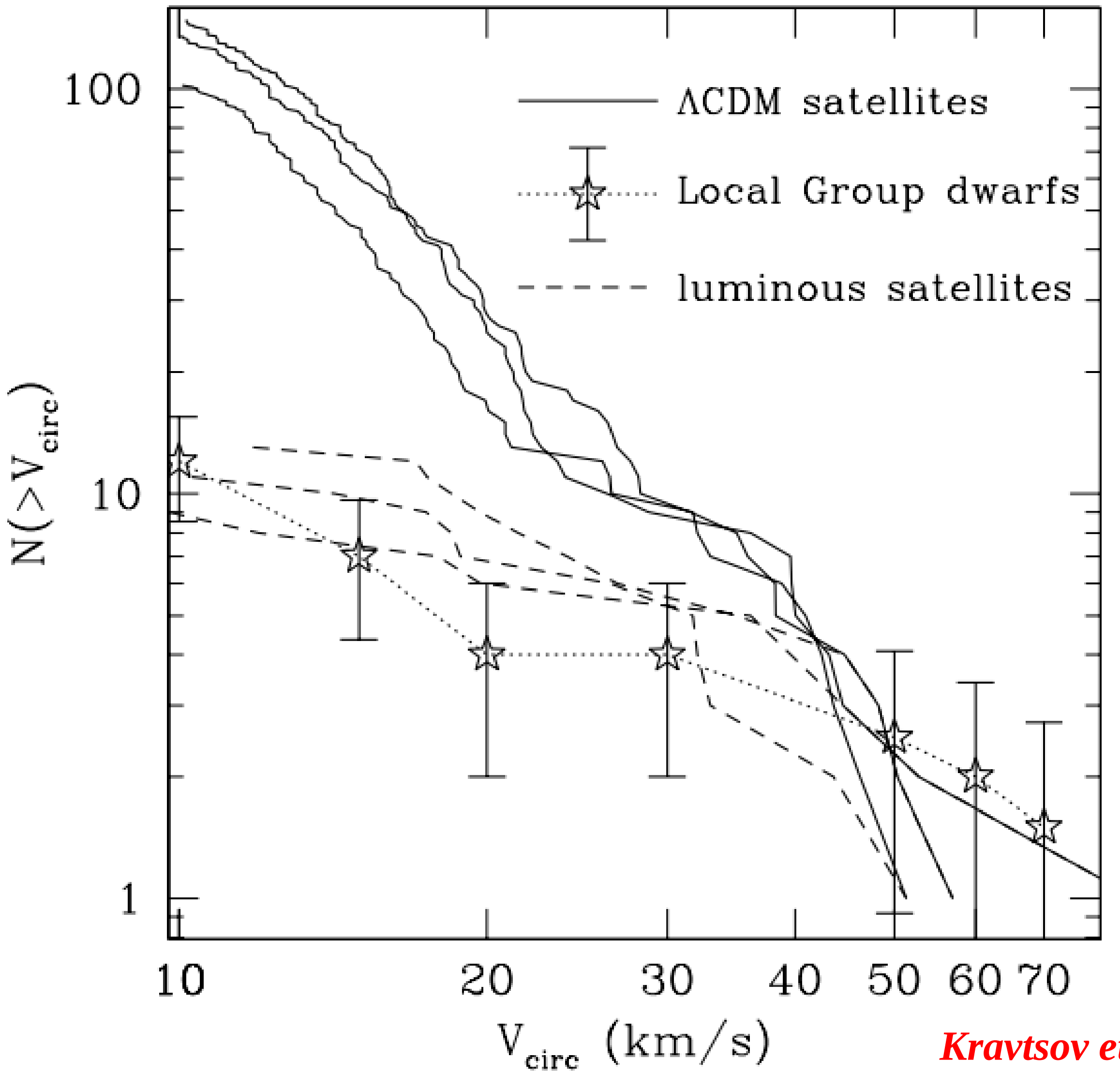
Missing Satellites "Problem"

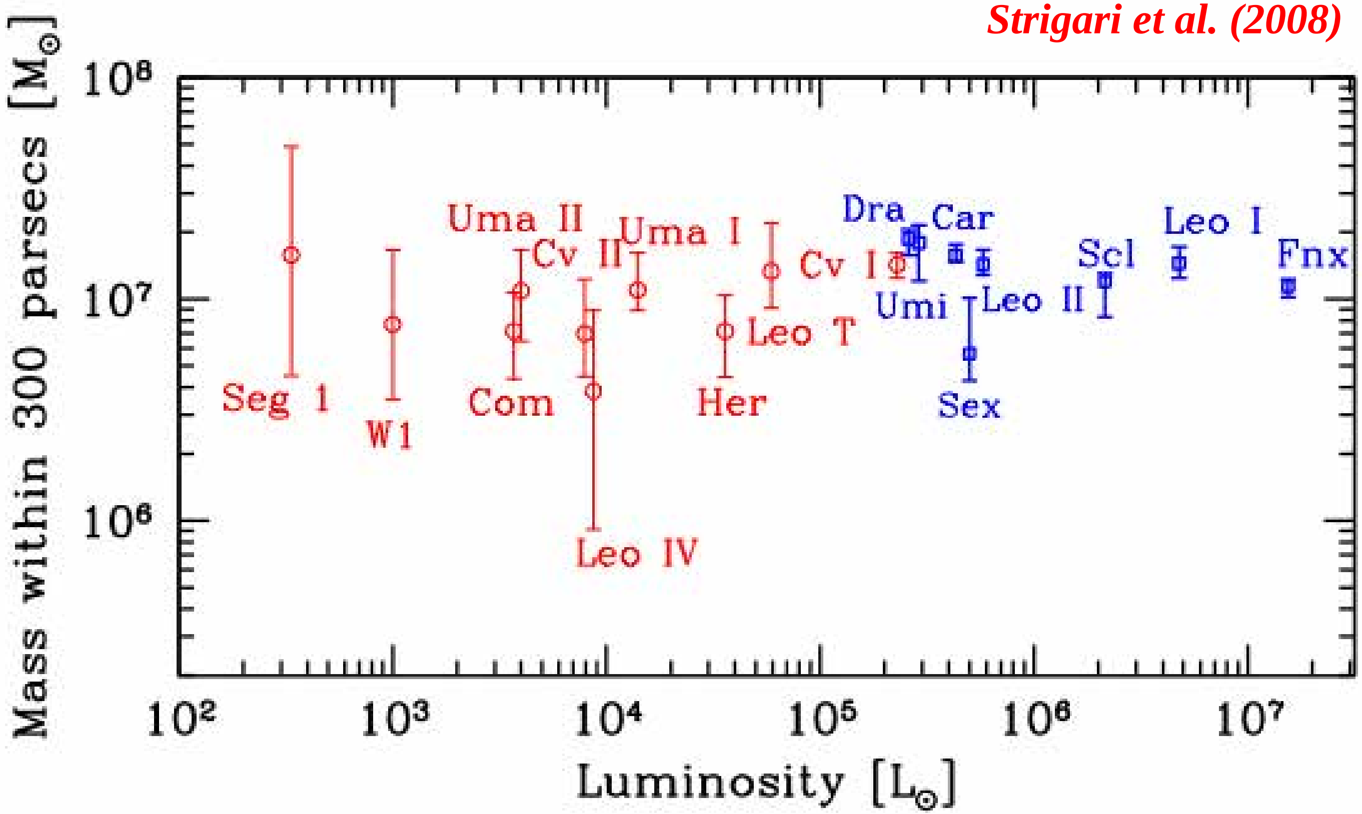


Kravtsov et al. (2004)

Missing Satellites "Problem"

- **Below a given mass, some satellite halos of the local group have been inhibited from forming long-lived stars**
- **Many more of these satellite halos are predicted to form in CDM than are actually observed**

Strigari et al. (2008)



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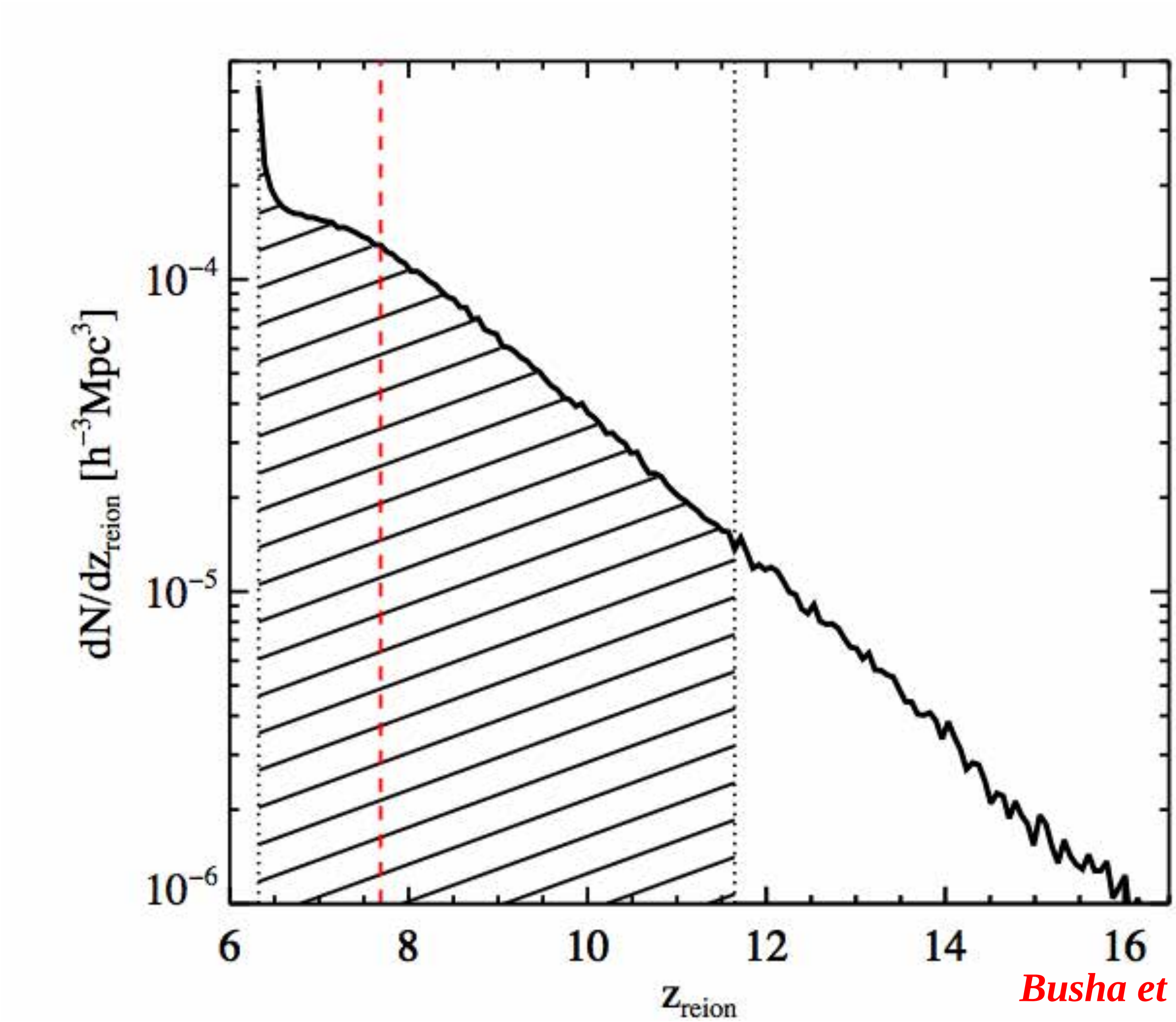
Satellite Abundance and Reionization History

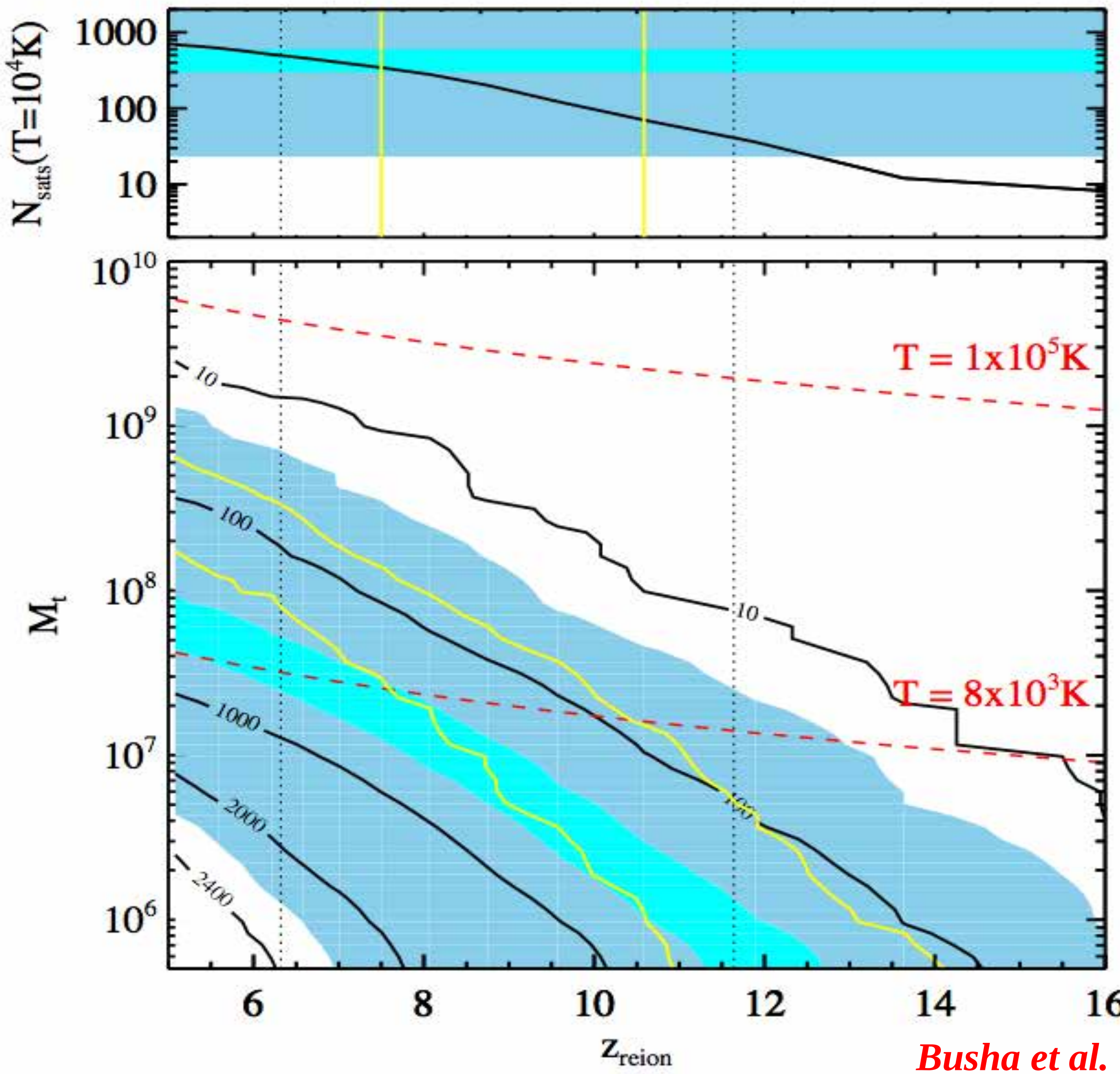
- Milky Way mass halos could have been reionized at $12 < z < 6$, even for a given global reionization history
- We used publicly available Via Lactea 2 data to track ~ 6,000 subhalos back to the reionization epoch
- We then assumed a given reionization epoch z_{reion} and assumed star formation was shut off if halos were below a mass M_{thresh}

Satellite Abundance and Reionization History



Busha et al. (2010)

Results

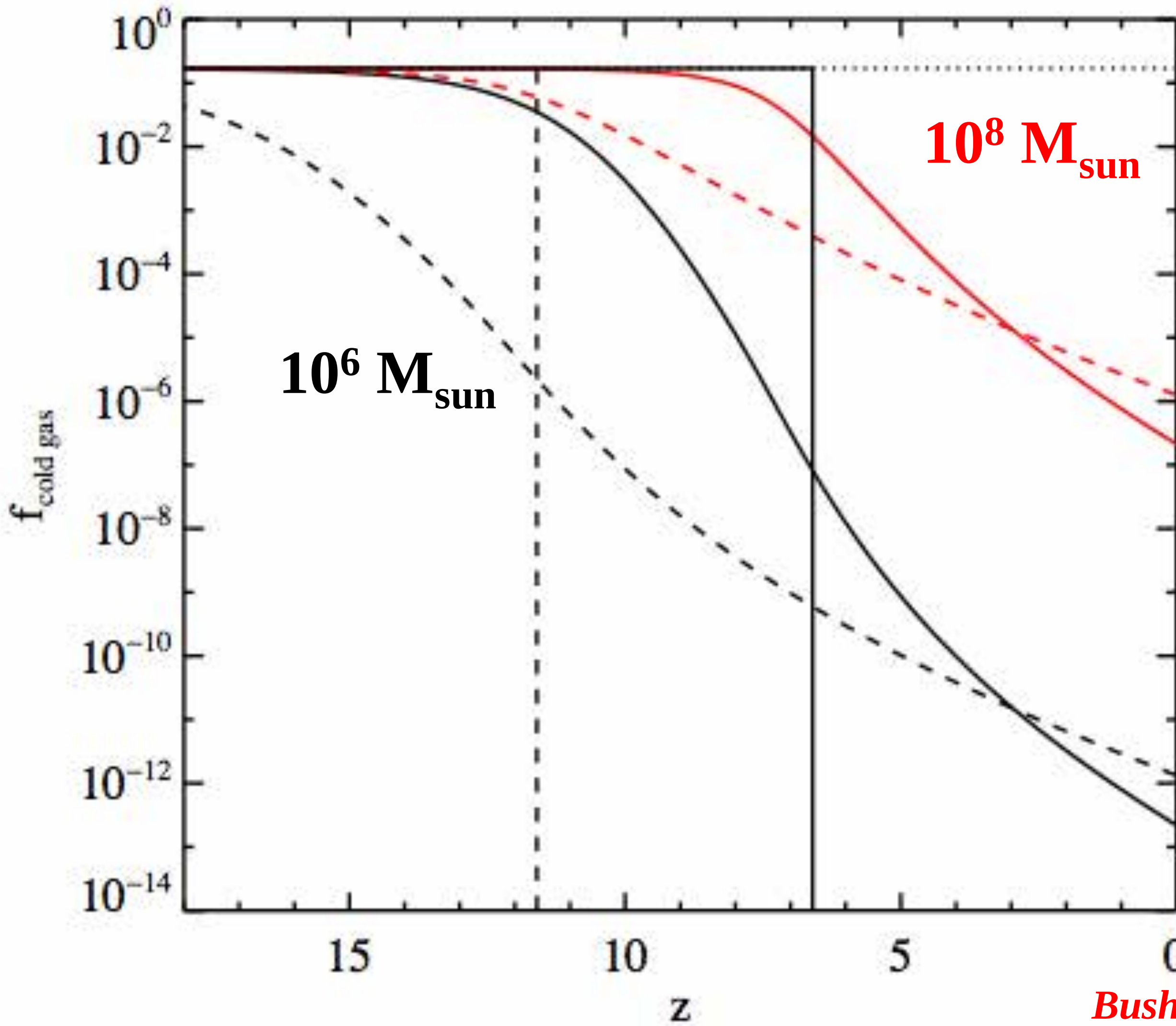


Busha et al. (2010)

Results

- Strong dependence on z_{reion} is at odds with previous results (i.e. Somerville 2002; Kravtsov et al. 2004)
- They used very smooth dependence of star formation rate by applying f_{gas} from Gnedin (2000)
- However, that was measurement of **total** gas fraction, including hot gas
- In reality, such gas in low mass halos is completely ionized and cannot form stars

$$f_{\mathrm{gas}}(M, z) = \frac{f_{\mathrm{baryon}}}{[1 + 0.26 M_f(z)/M]^3}$$



Busha et al. (2010)

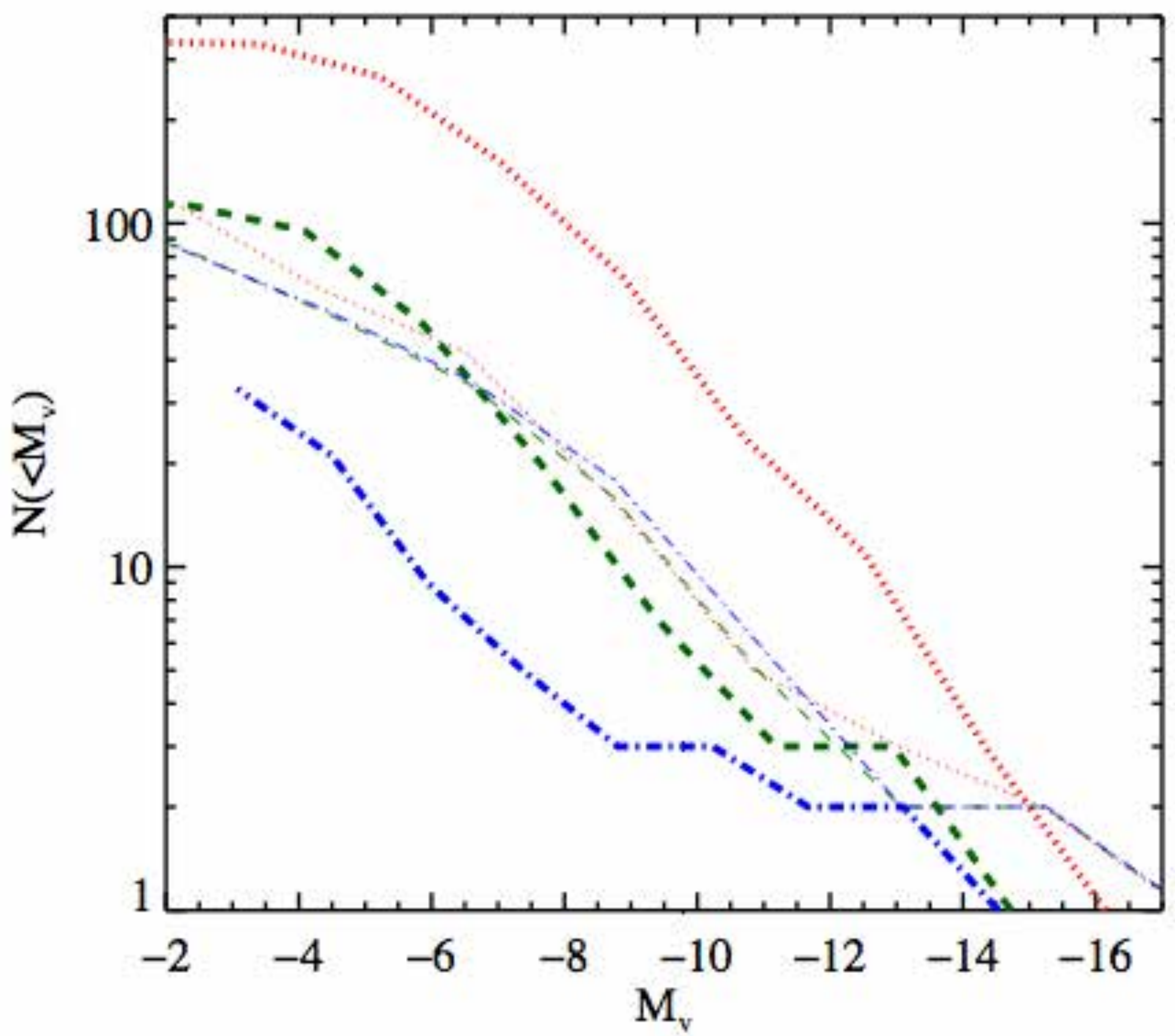
Results

- To show this, we used star formation rate

$$SFR = \begin{cases} \epsilon \left(f_{coldgas} \frac{M_{DM}}{1\,\mathrm{M}_\odot} \right)^{\alpha} & \text{if } M_{DM} > M_{\mathrm{t}},\ z > z_{\mathrm{reion}} \\ 0 & \text{otherwise} \end{cases}$$

for a model with gradual and instantaneous suppression of star formation and tracked stellar luminosity using Bruzual & Charlot (2003) stellar population synthesis code with lowest possible metallicity

Results



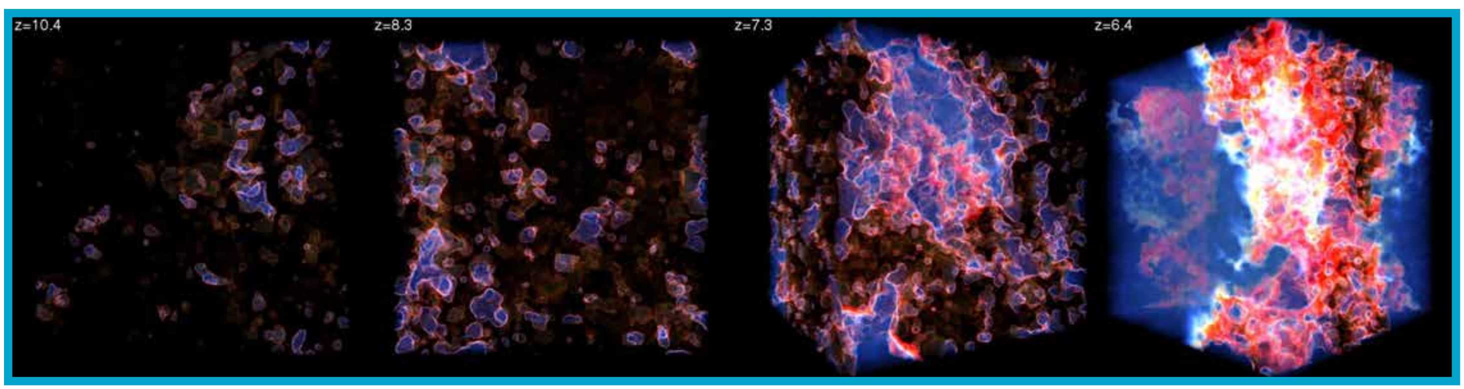
Busha et al. (2010)

Outline

- Introduction
- Ionizing Efficiency of First Galaxies
  - Star Formation Efficiency
  - Escape Fraction
  - Suppression of star formation by photoionization
  - Minimal reionization model
- Reionization and the Local Universe
  - “Missing Satellites” Problem
  - Satellite Abundance and Reionization Epoch
  - Environmental Dependence
- Summary

Fast Reionization Simulations

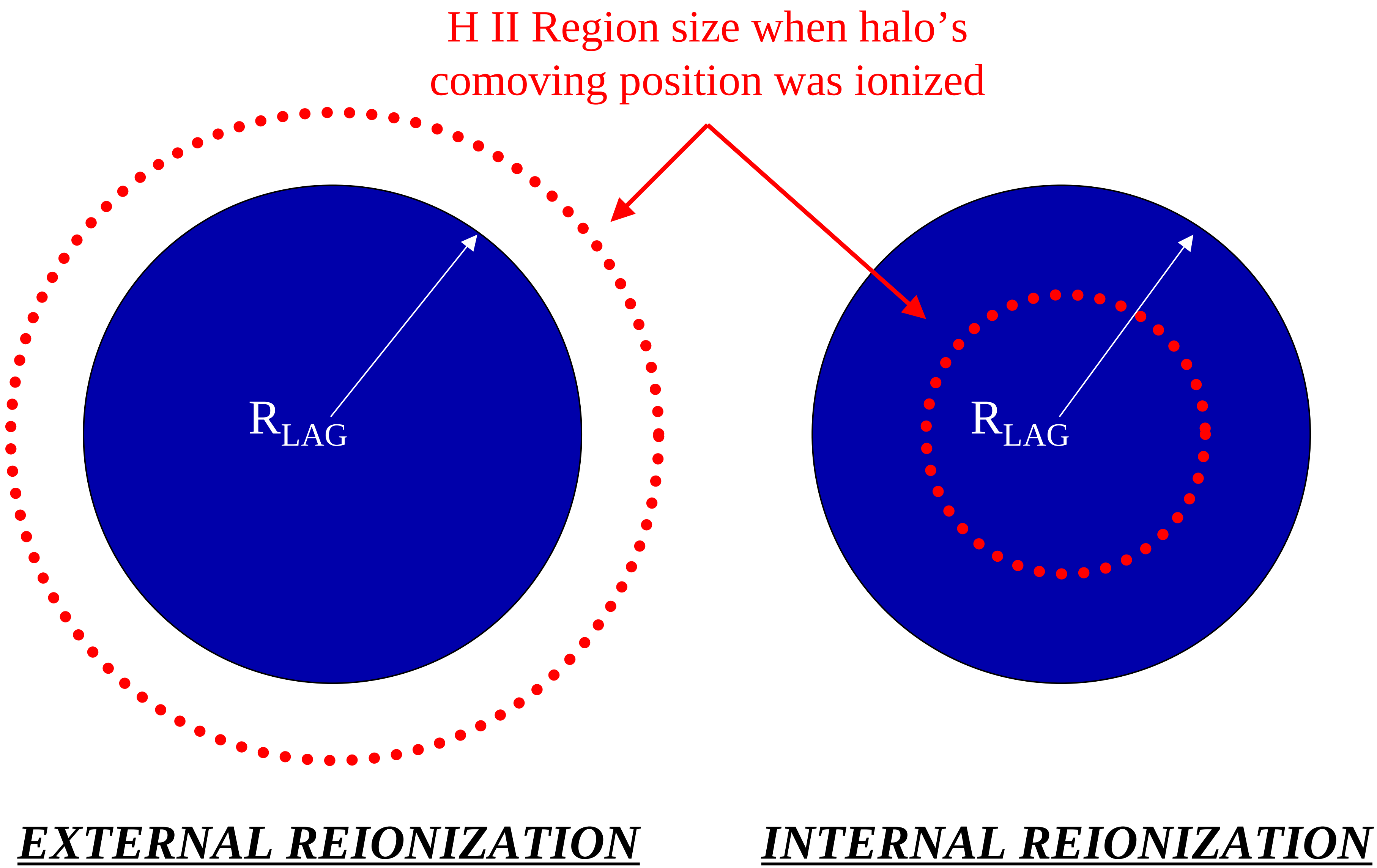
- A technique for producing 3D evolving ionization field without doing radiative transfer
- Based on Furlanetto, Zaldarriaga, & Hernquist (2004) model
- Only requires linear Gaussian random density field as is usually produced for cosmological N-body simulations
- Smooth around each point and calculate collapsed fraction according to $$f_{\rm coll}(t) = {\rm erfc}\left[\frac{\delta_c(t) - \delta_m}{\sqrt{2\left[\sigma^2_{\rm min} - \sigma^2(m)\right]}}\right]$$
- Point is ionized if $\zeta f_{\rm coll} > 1$ is met for **any** smoothing scale



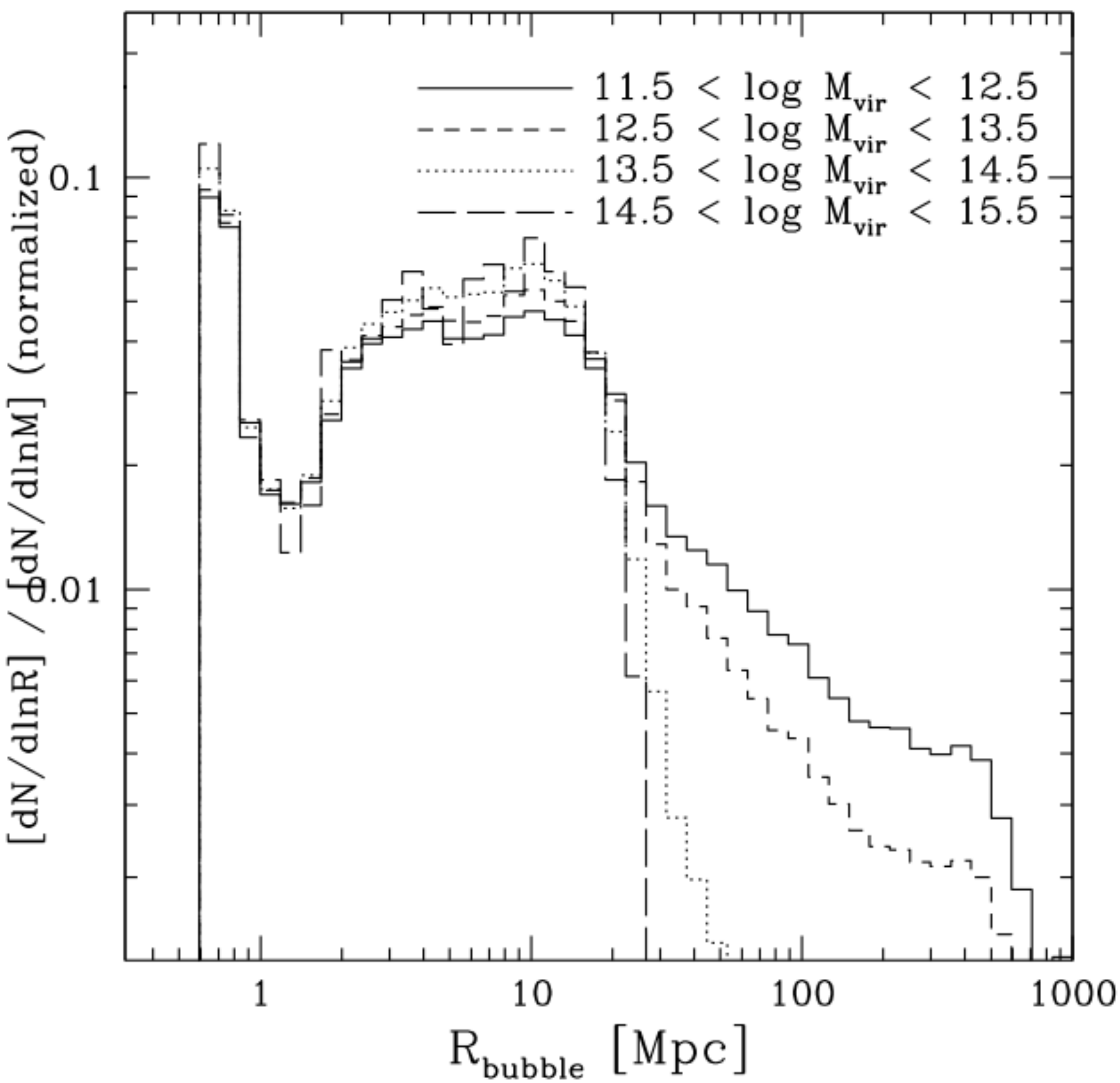
Coupling N-body and Reionization Simulations

- Couple reionization and N-body simulations in
  - 1 Gpc/h box with 1120^3 particles (Alvarez et al. 2009)
  - 420 Mpc/h box with 1400^3 particles (Li et al. 2012)
- Halos identified at z=0
- For each halo, we trace back all the particles to find the redshift at which they were reionized
- This method allows easy determination of the size of the region that reionized a given point and the reionization history of every halo in the volume

$M_{\mathrm{HALO}}=(4\pi\rho_0 R^3_{\mathrm{LAG}})/3$ $\quad$ R_{LAG} is radius of halo mass at mean density

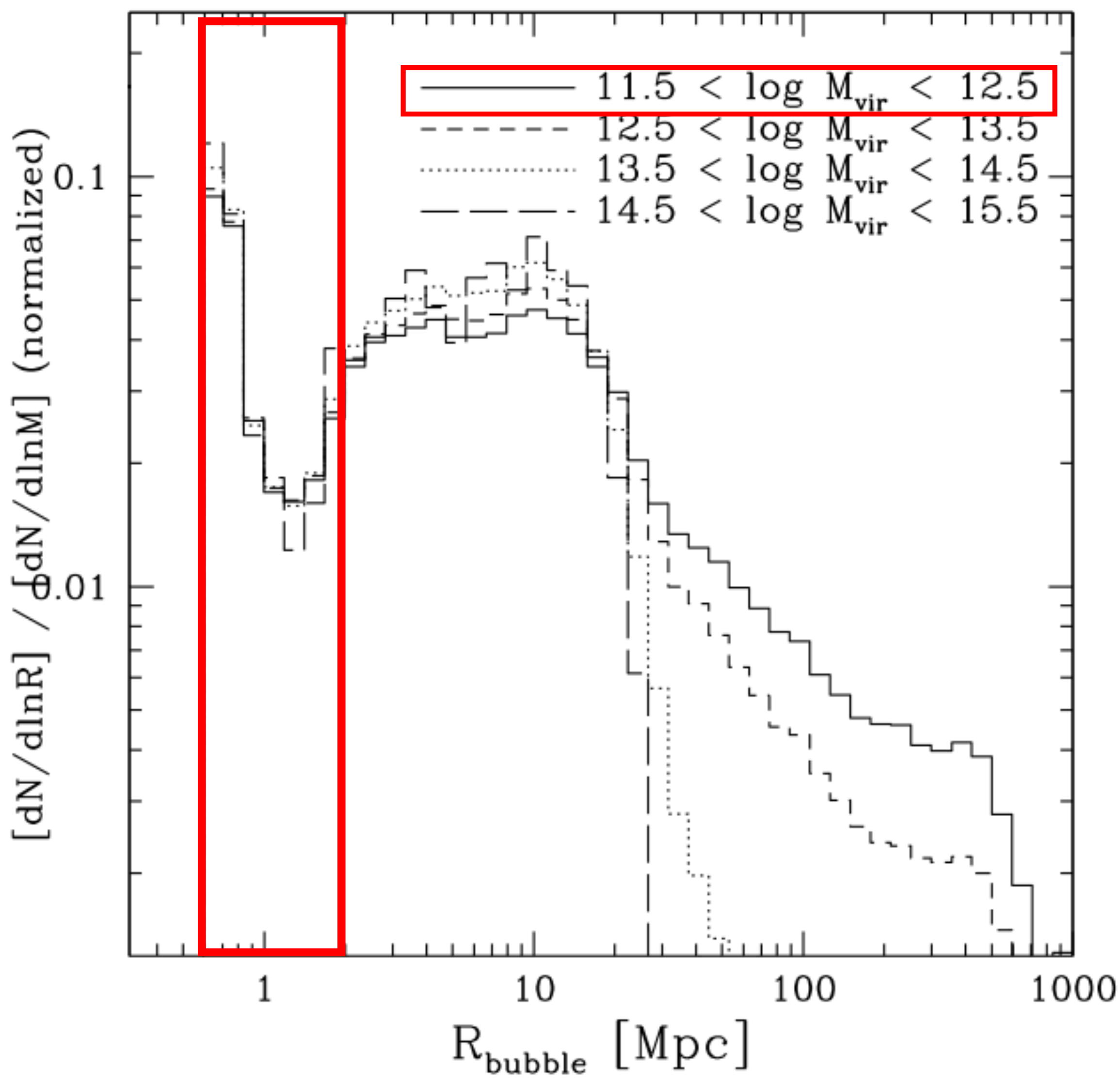


Bubble size distribution



Alvarez et al. (2009)

Bubble size distribution



Alvarez et al. (2009)

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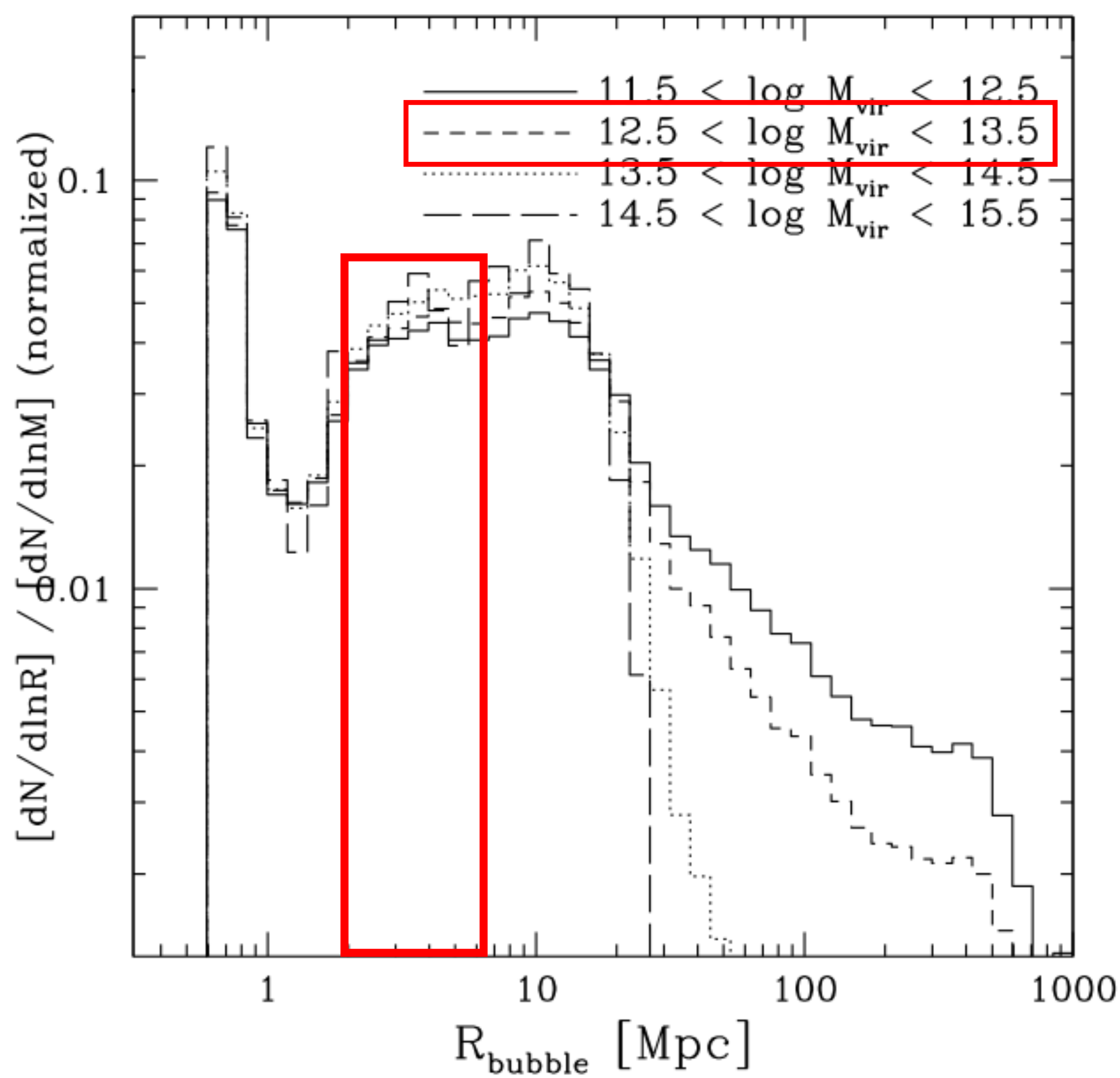

Alvarez et al. (2009)

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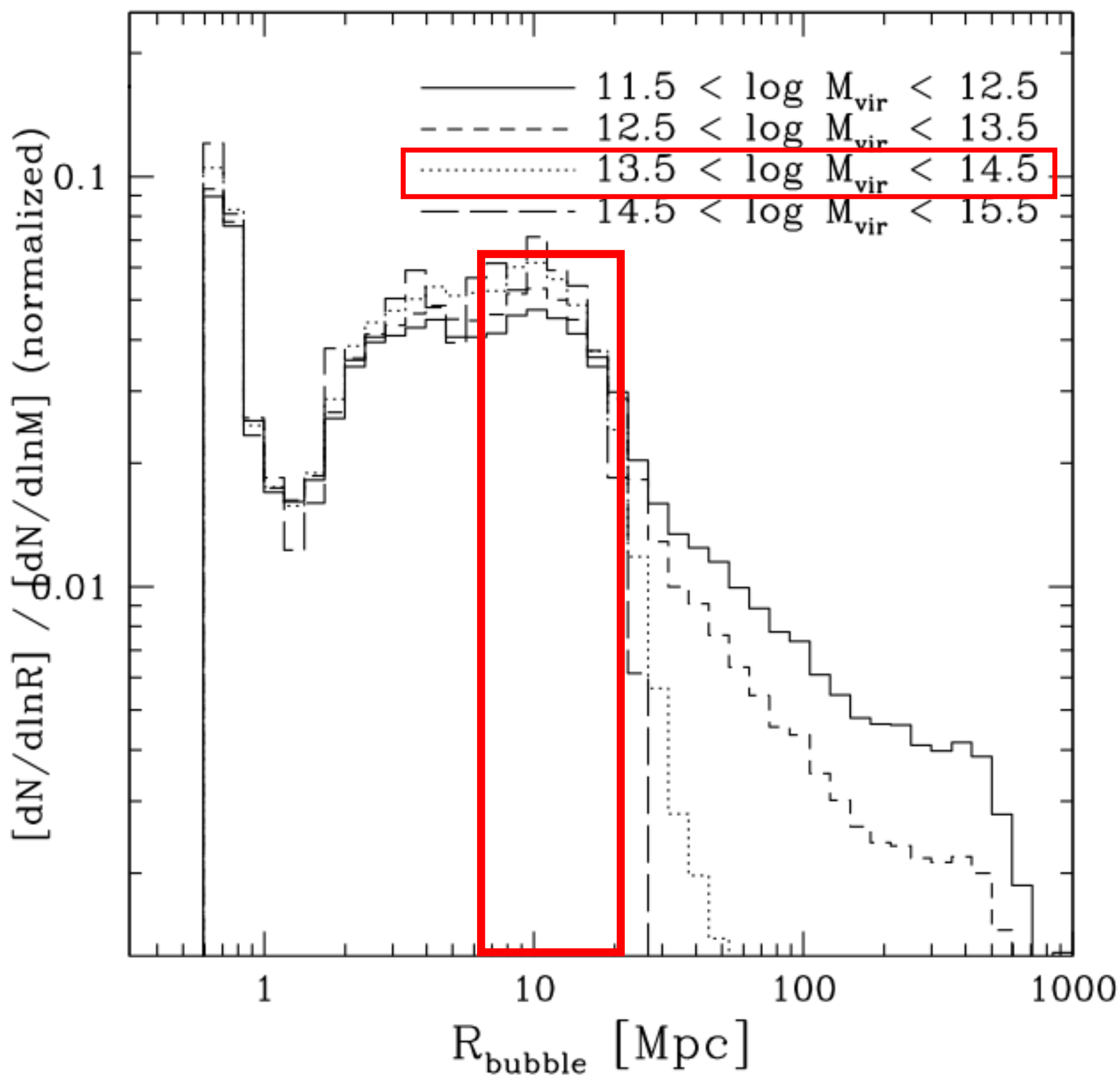

Alvarez et al. (2009)

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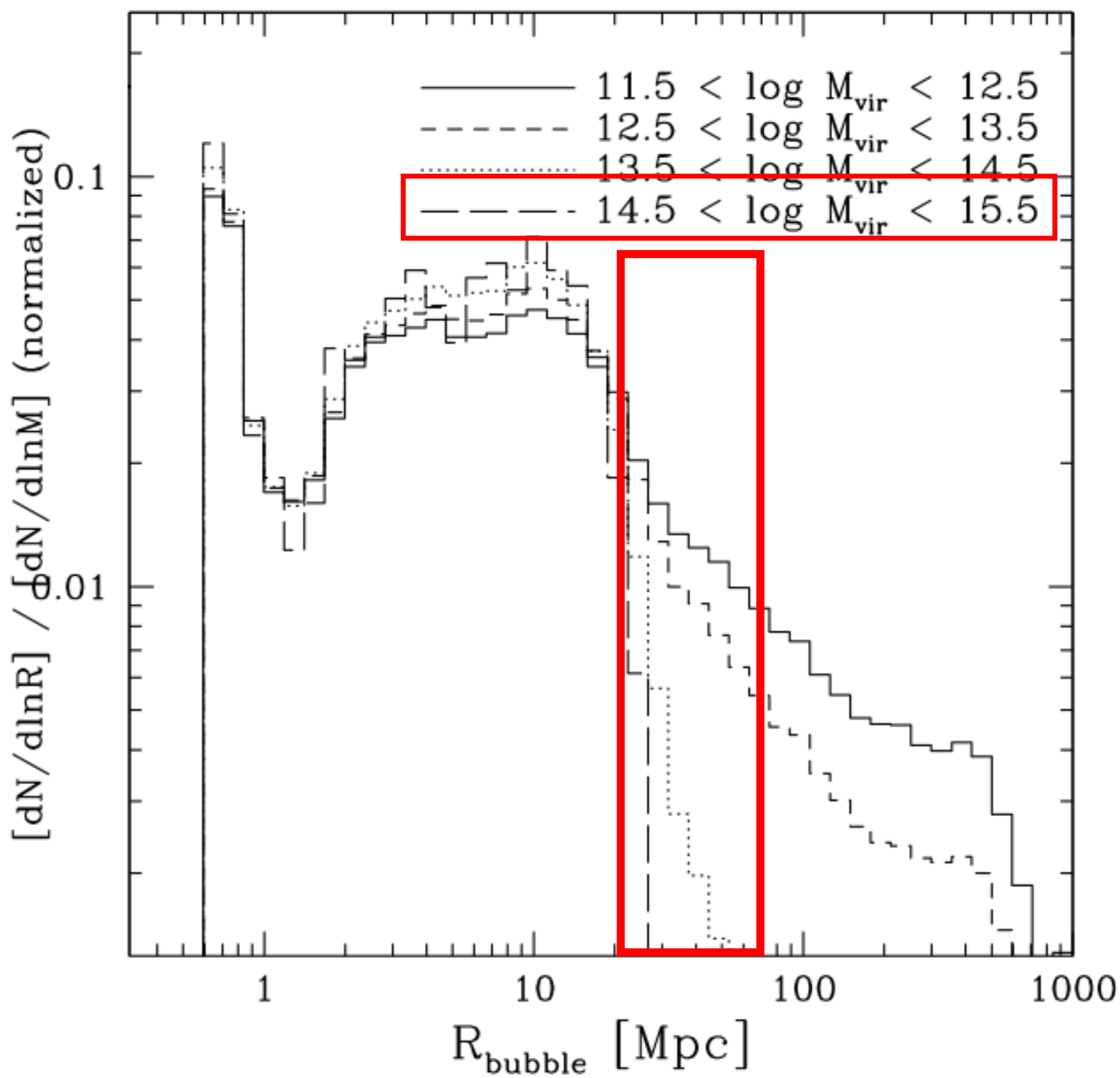
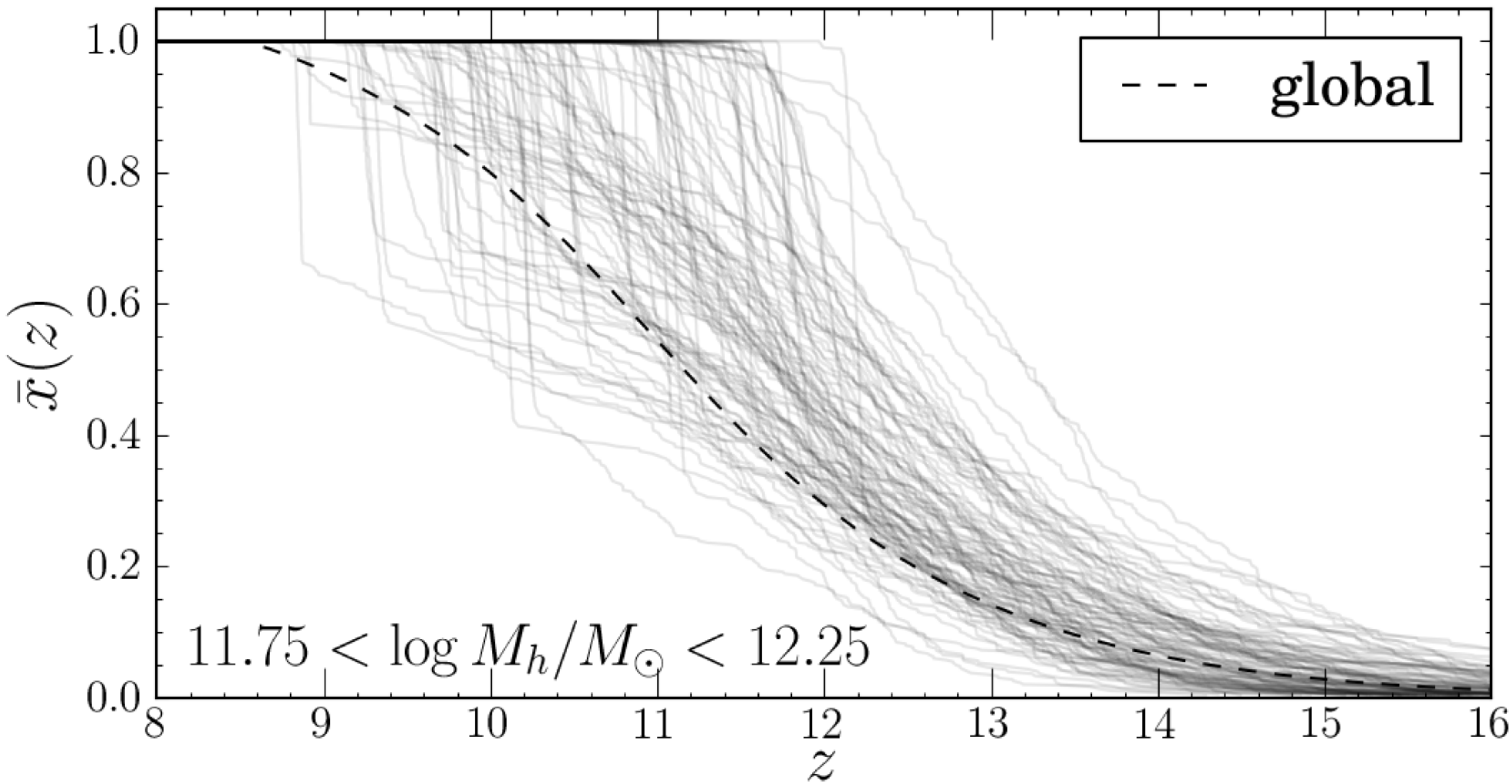


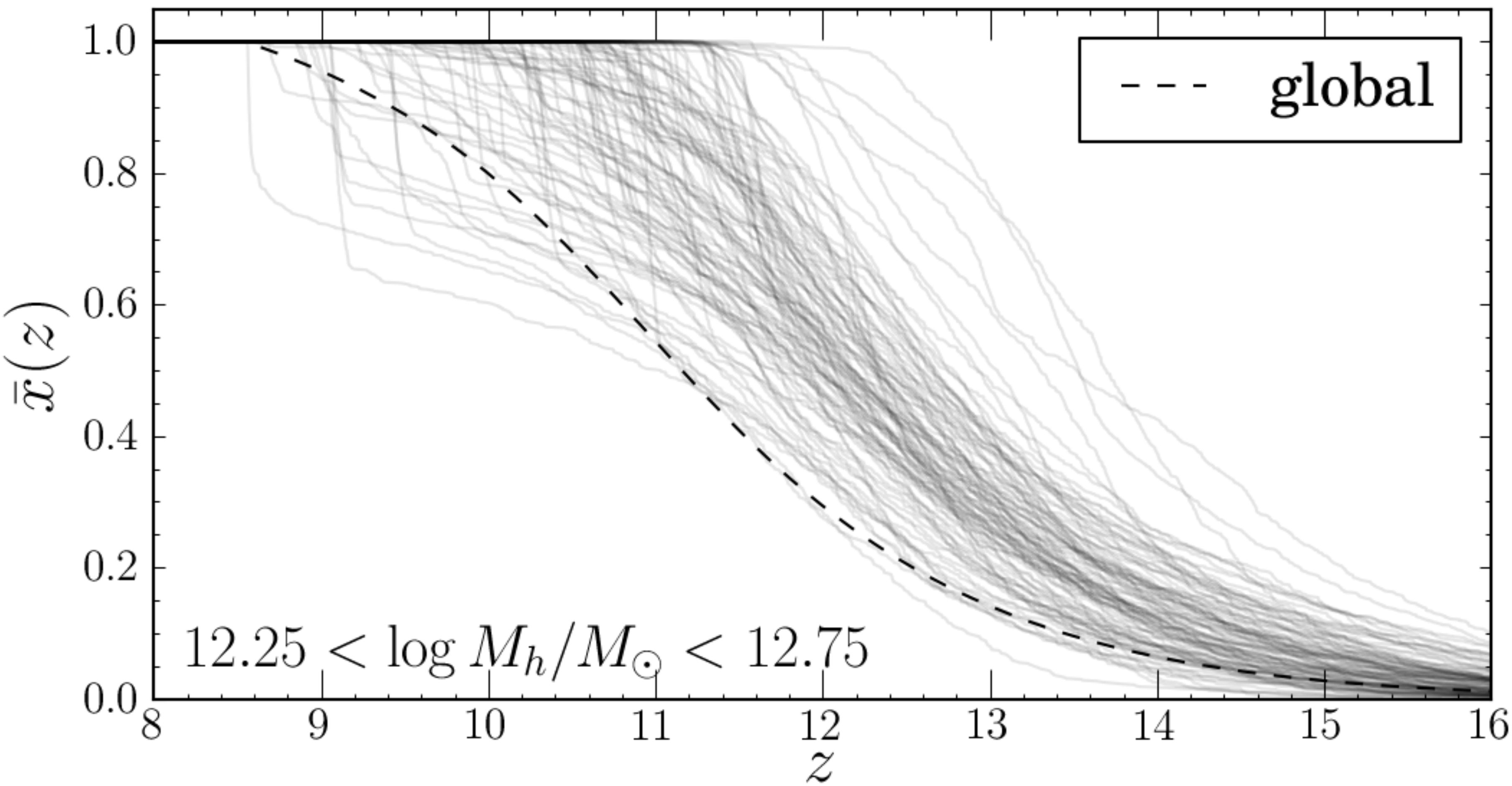
Alvarez et al. (2009)

Halo Reionization Histories



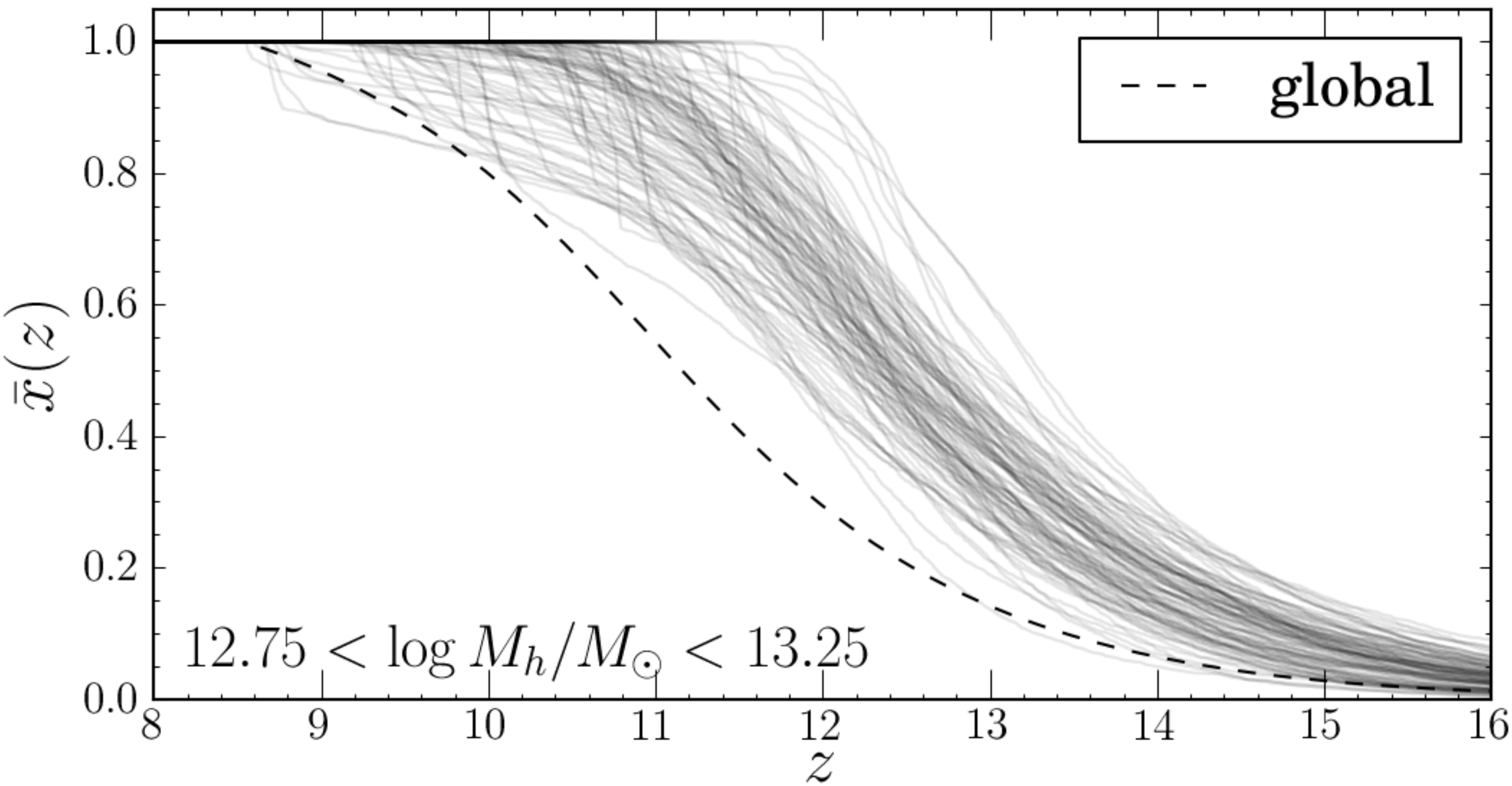
Li et al. (2012)

Halo Reionization Histories



Li et al. (2012)

Halo Reionization Histories



Li et al. (2012)

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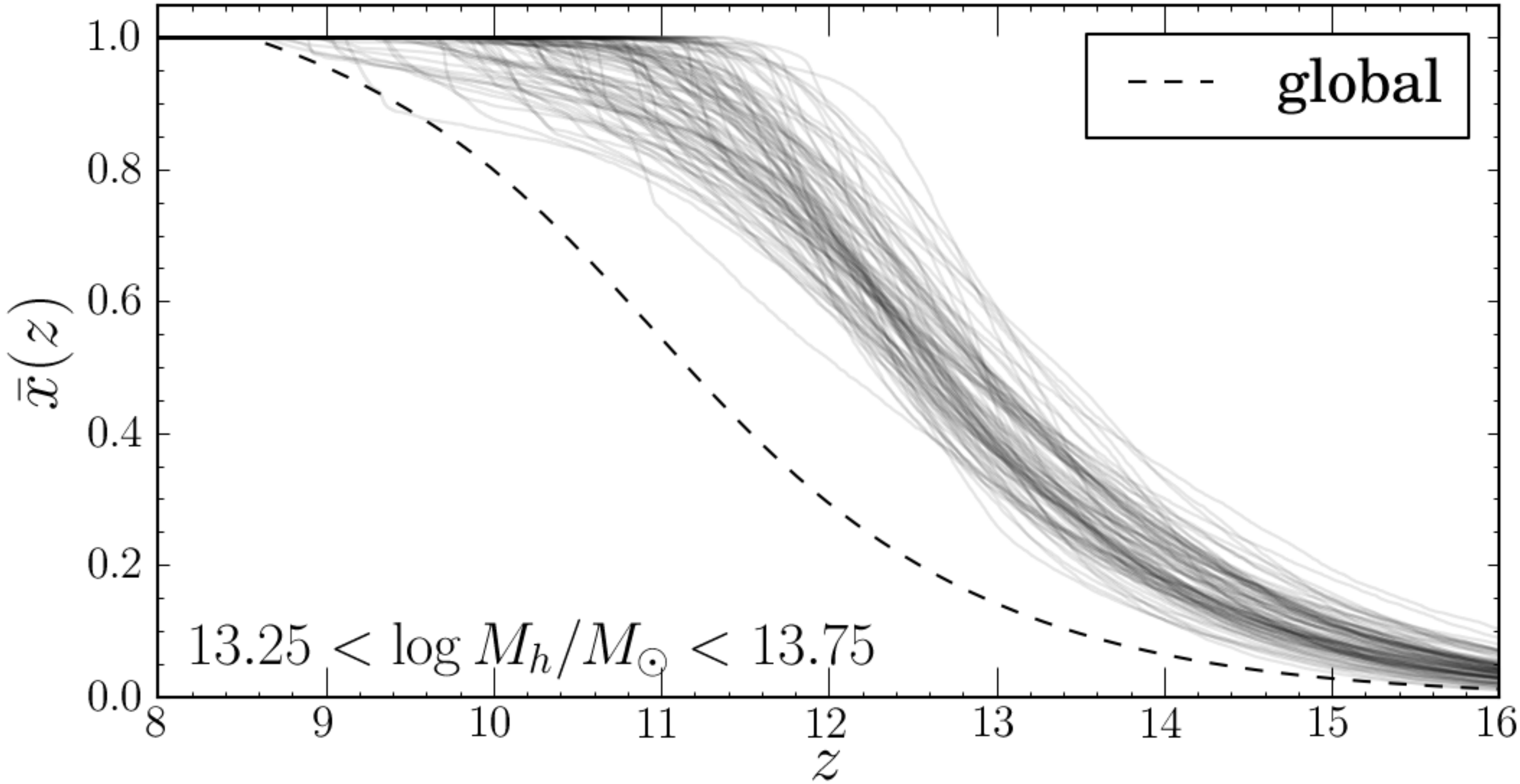
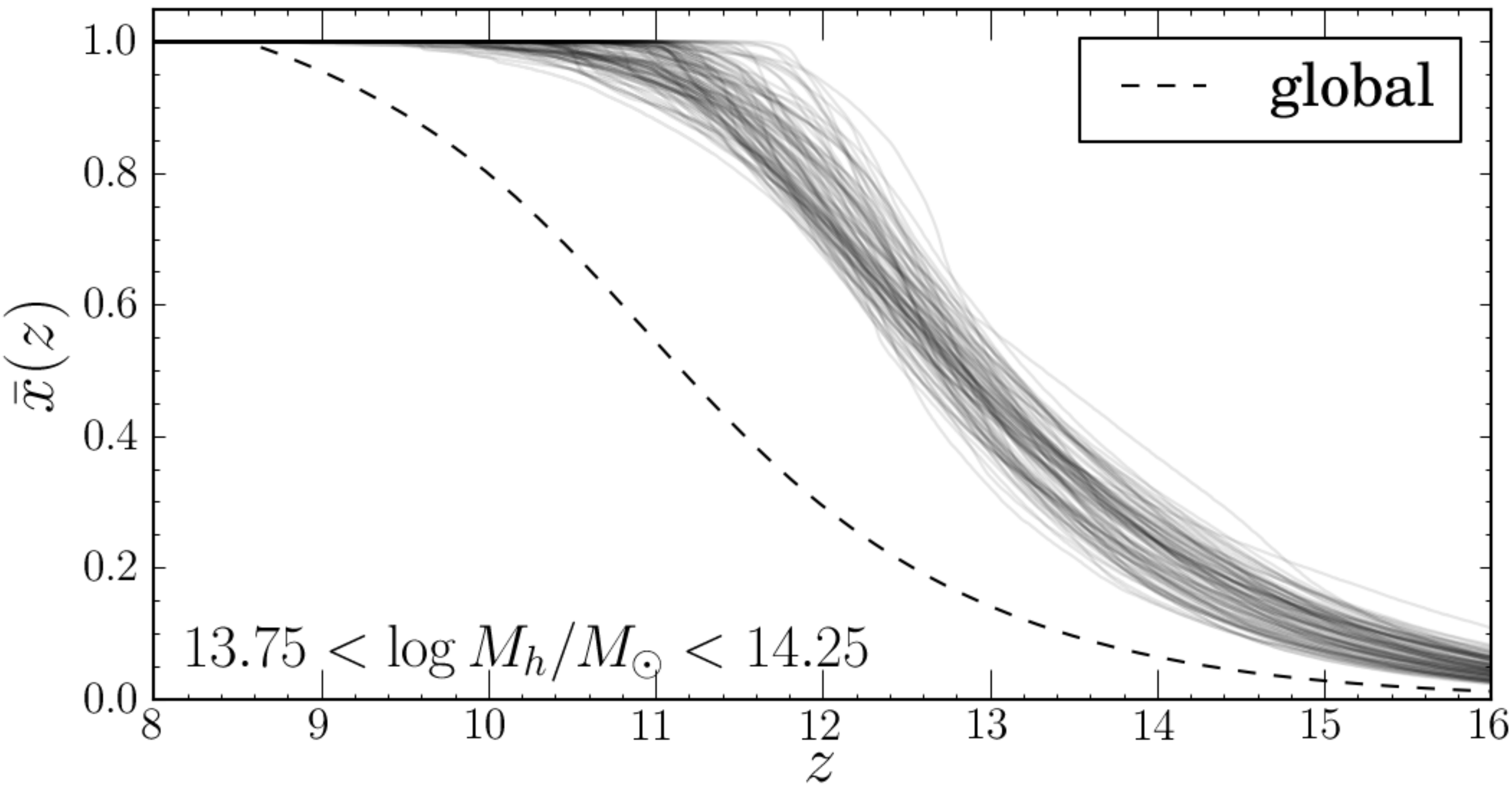


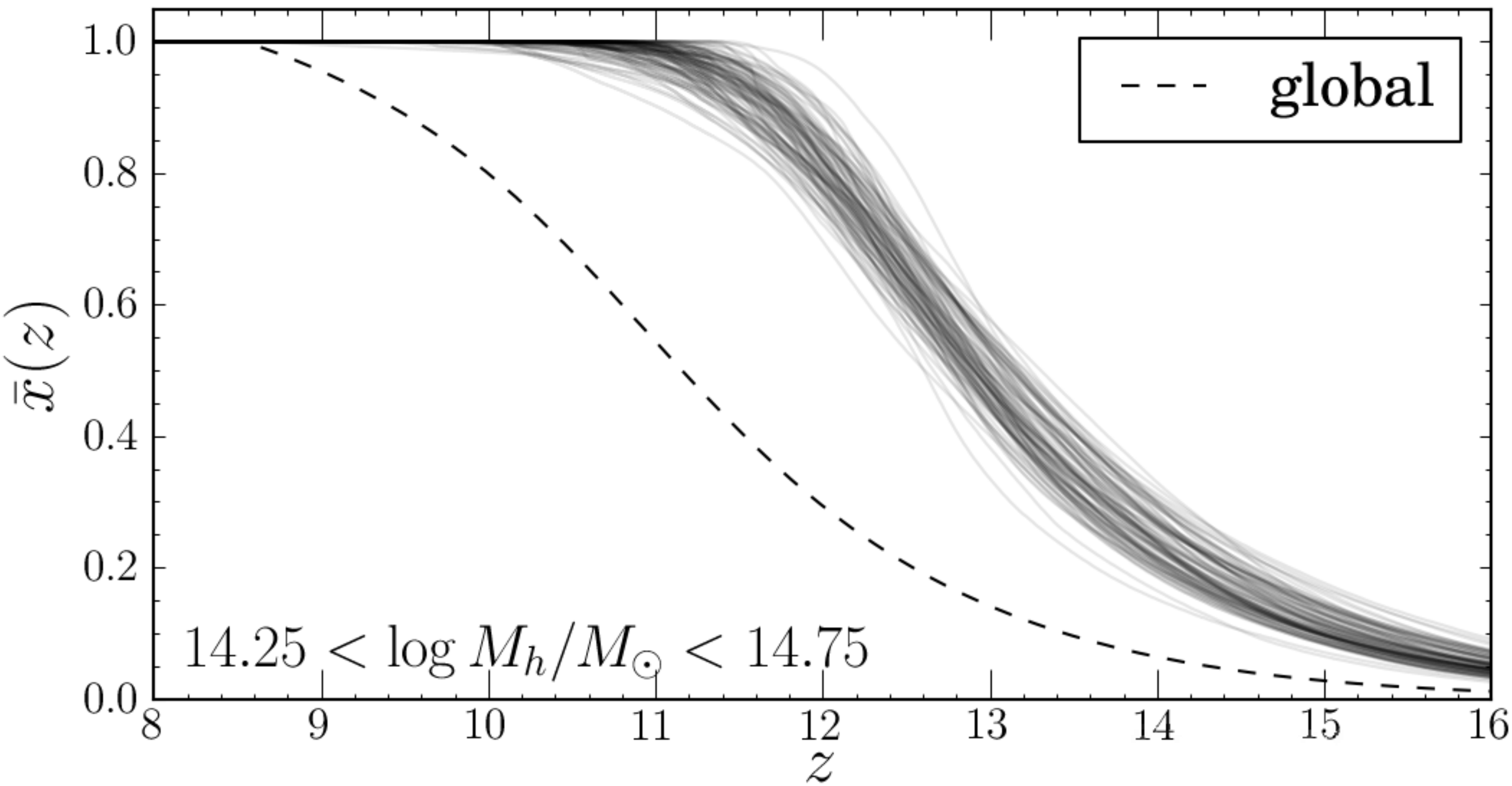
Li et al. (2012)

Halo Reionization Histories



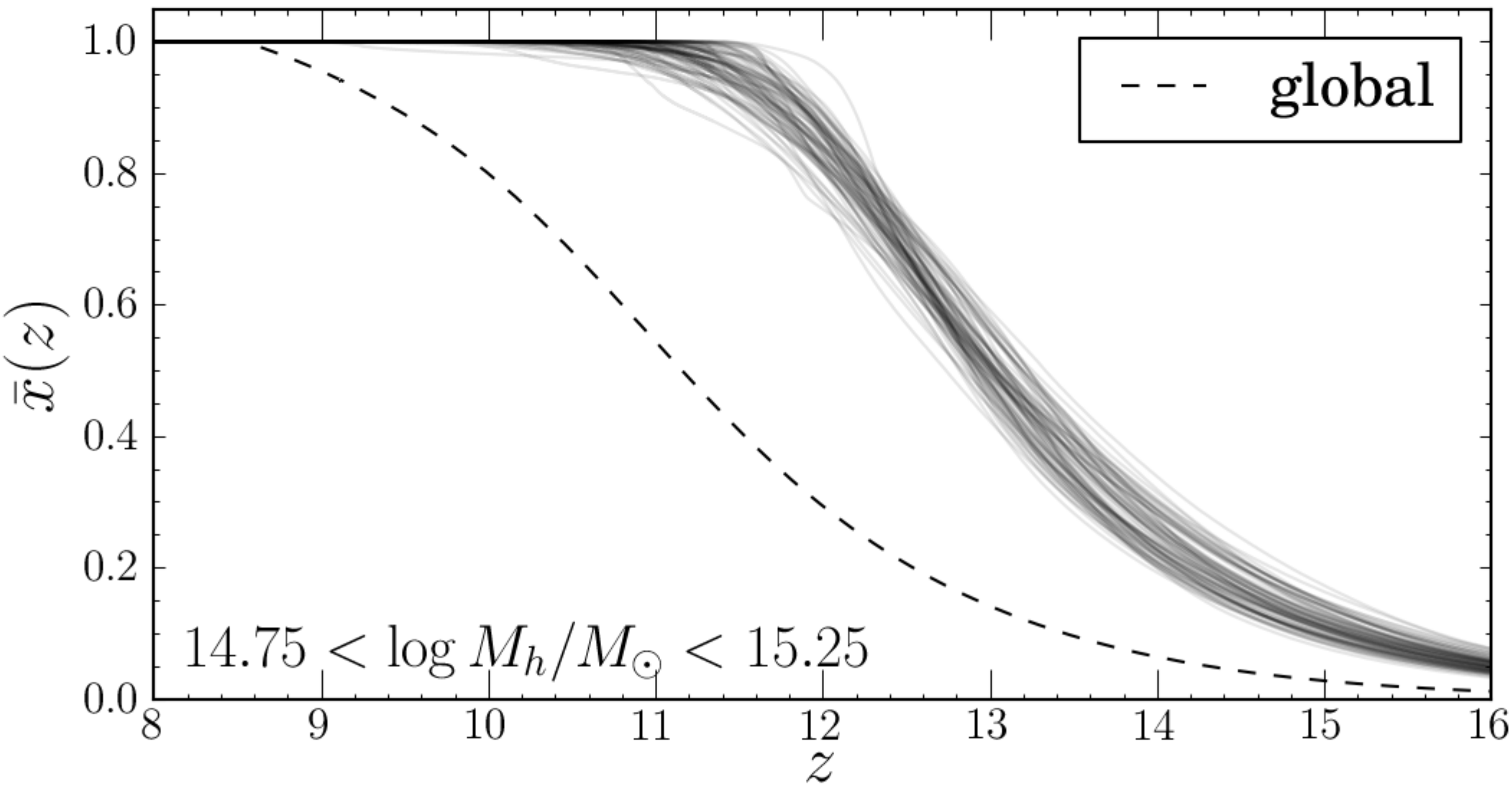
Li et al. (2012)

Halo Reionization Histories



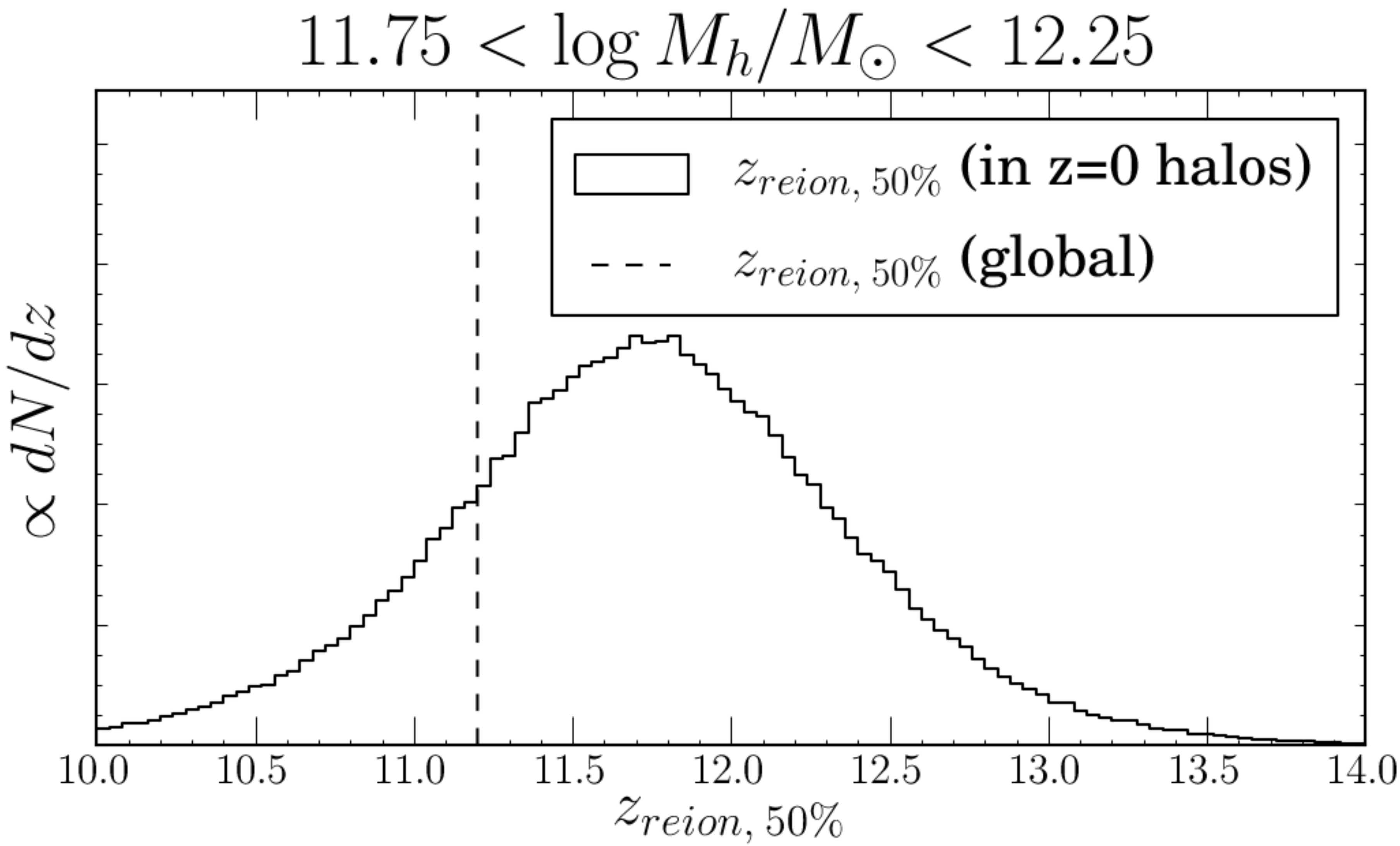
Li et al. (2012)

Halo Reionization Histories



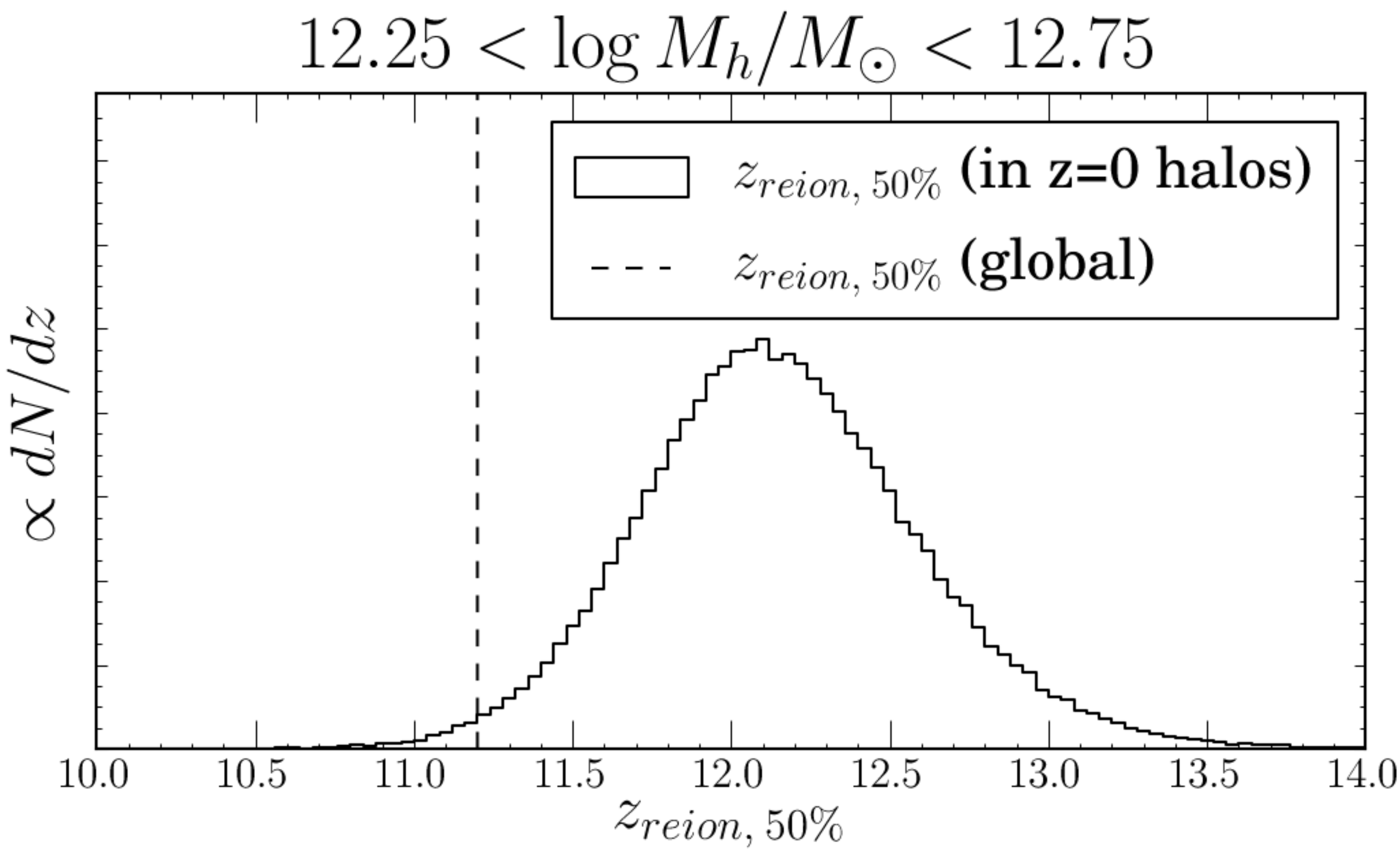
Li et al. (2012)

Halo Reionization Redshifts



Li et al. (2012)

Halo Reionization Redshifts



Li et al. (2012)

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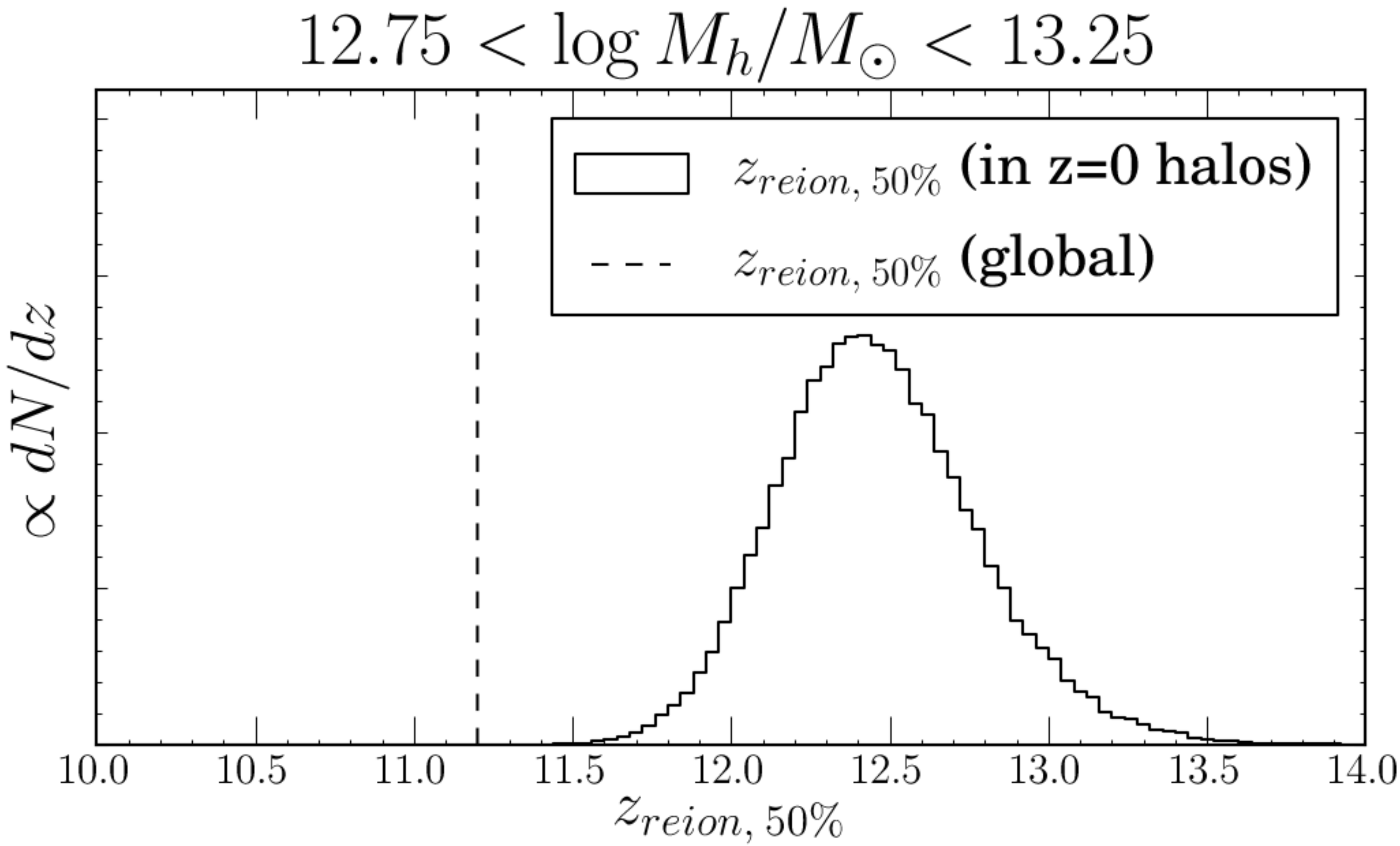
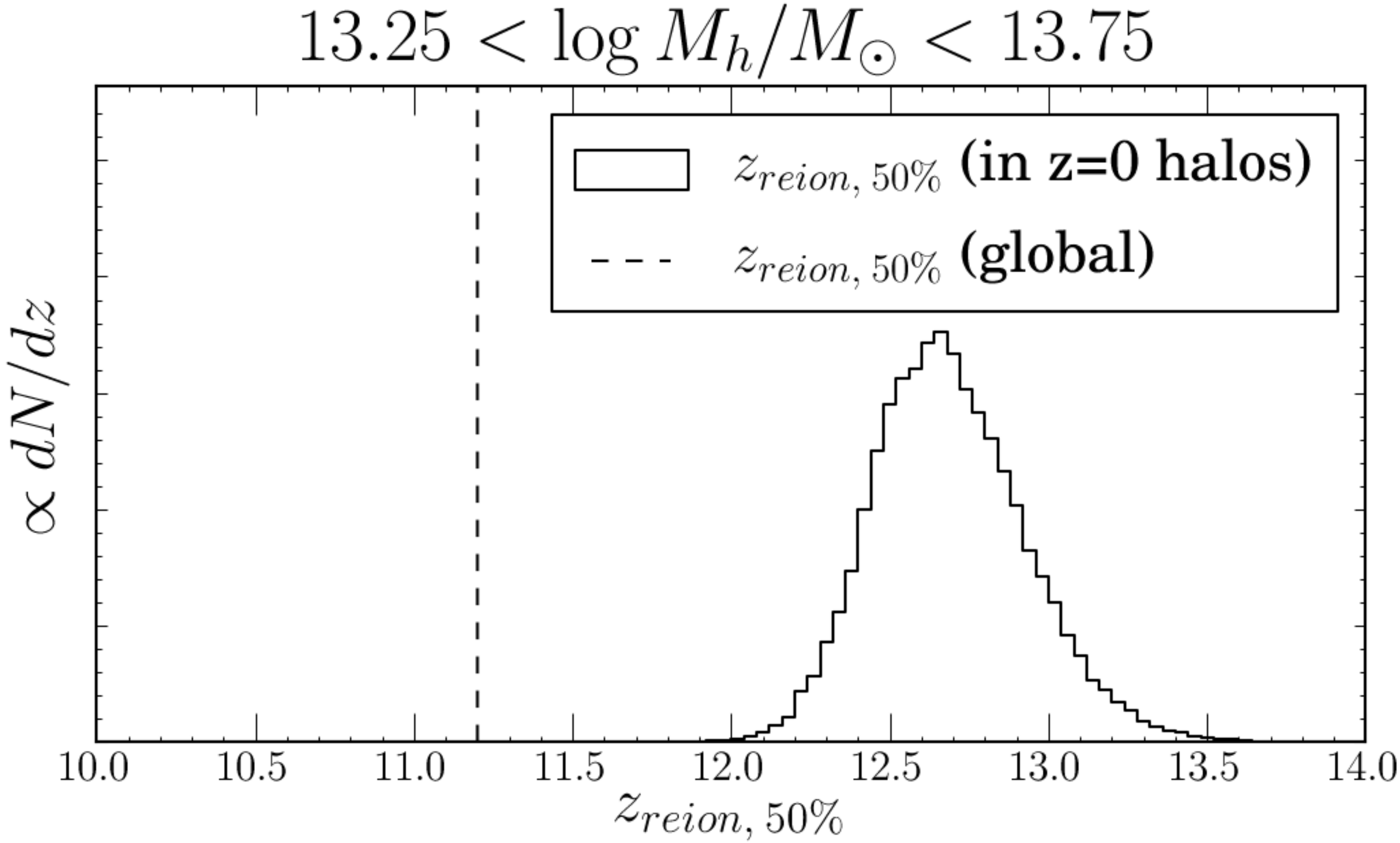


Li et al. (2012)

Halo Reionization Redshifts



Li et al. (2012)

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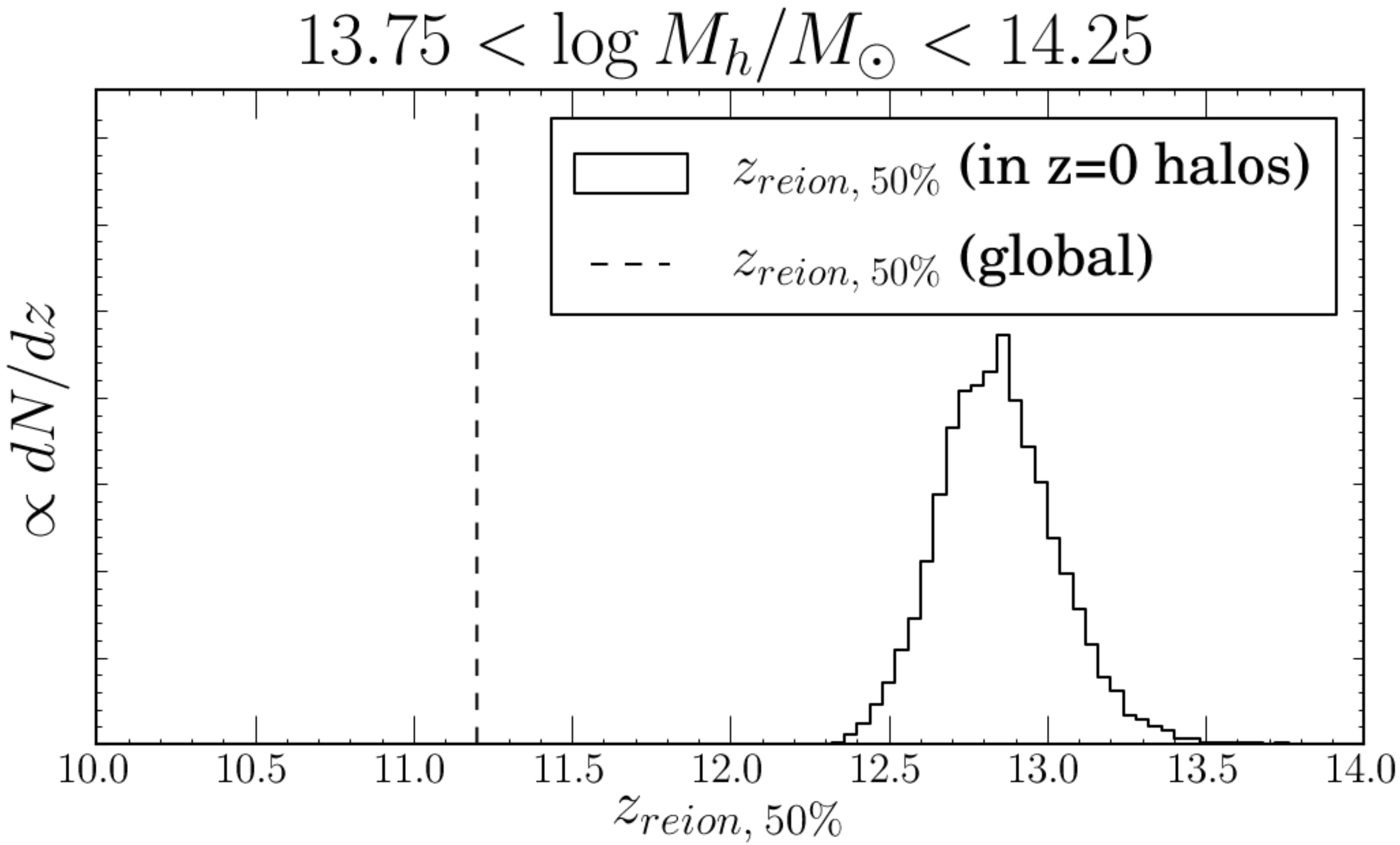
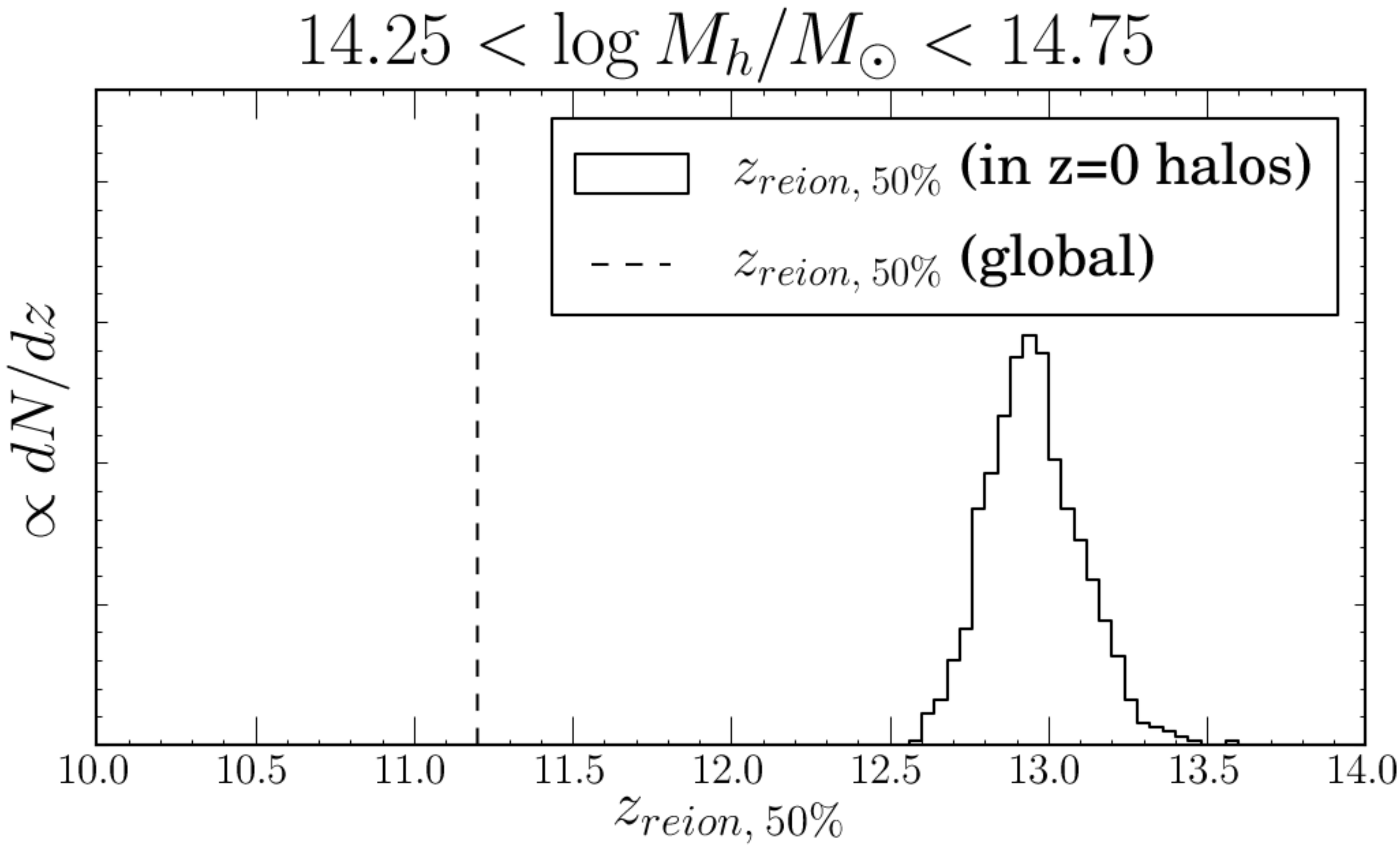


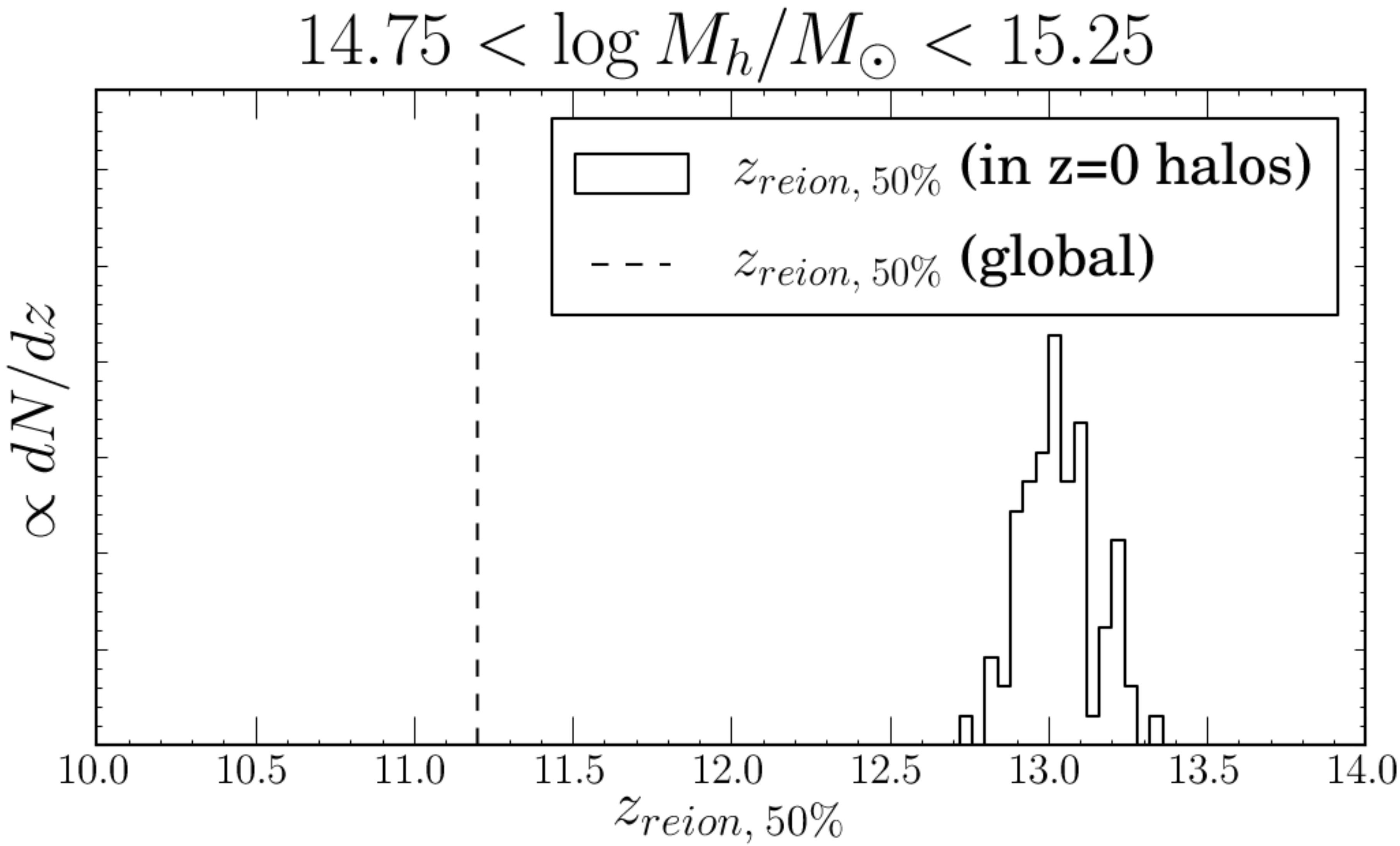
Li et al. (2012)

Halo Reionization Redshifts



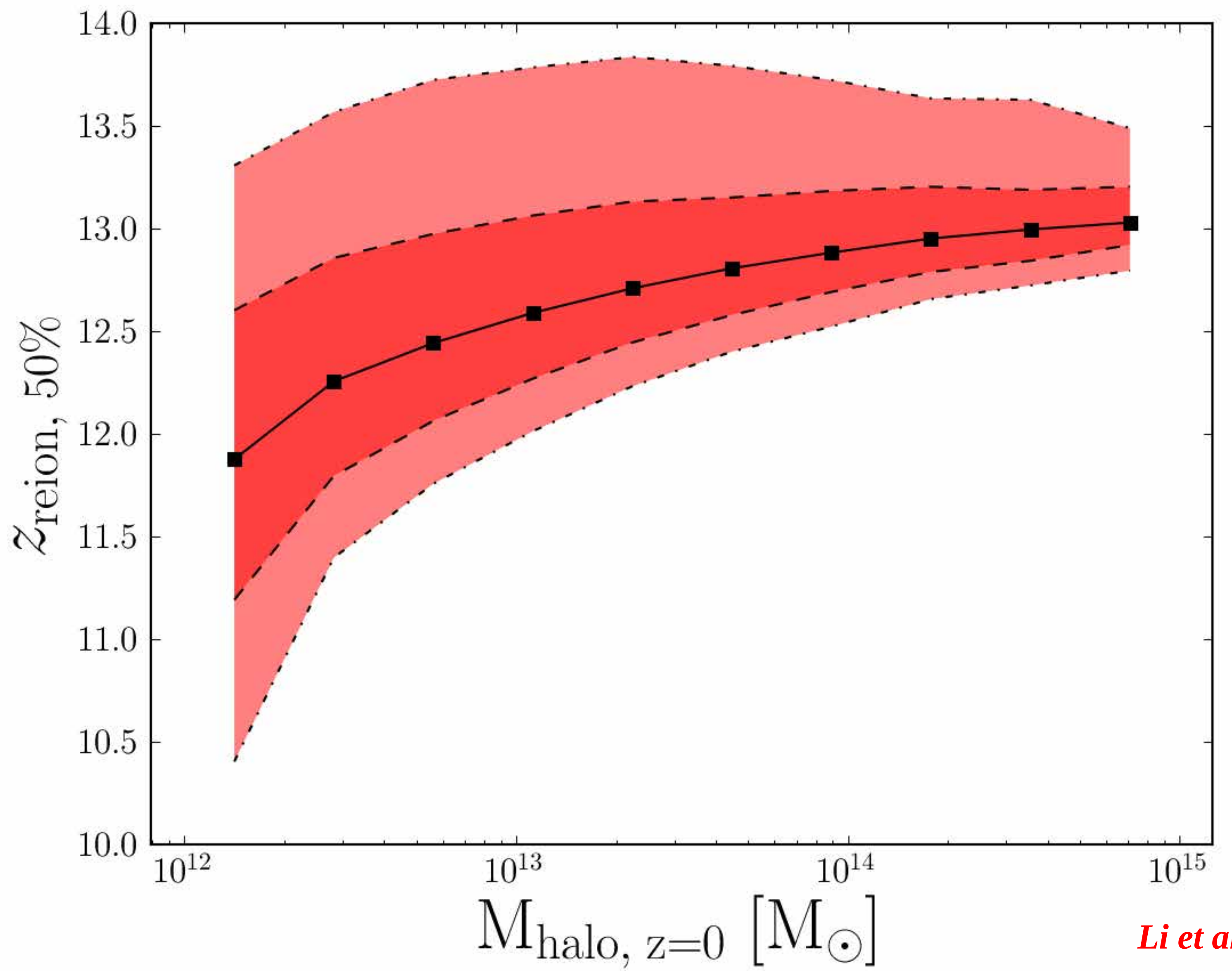
Li et al. (2012)

Halo Reionization Redshifts



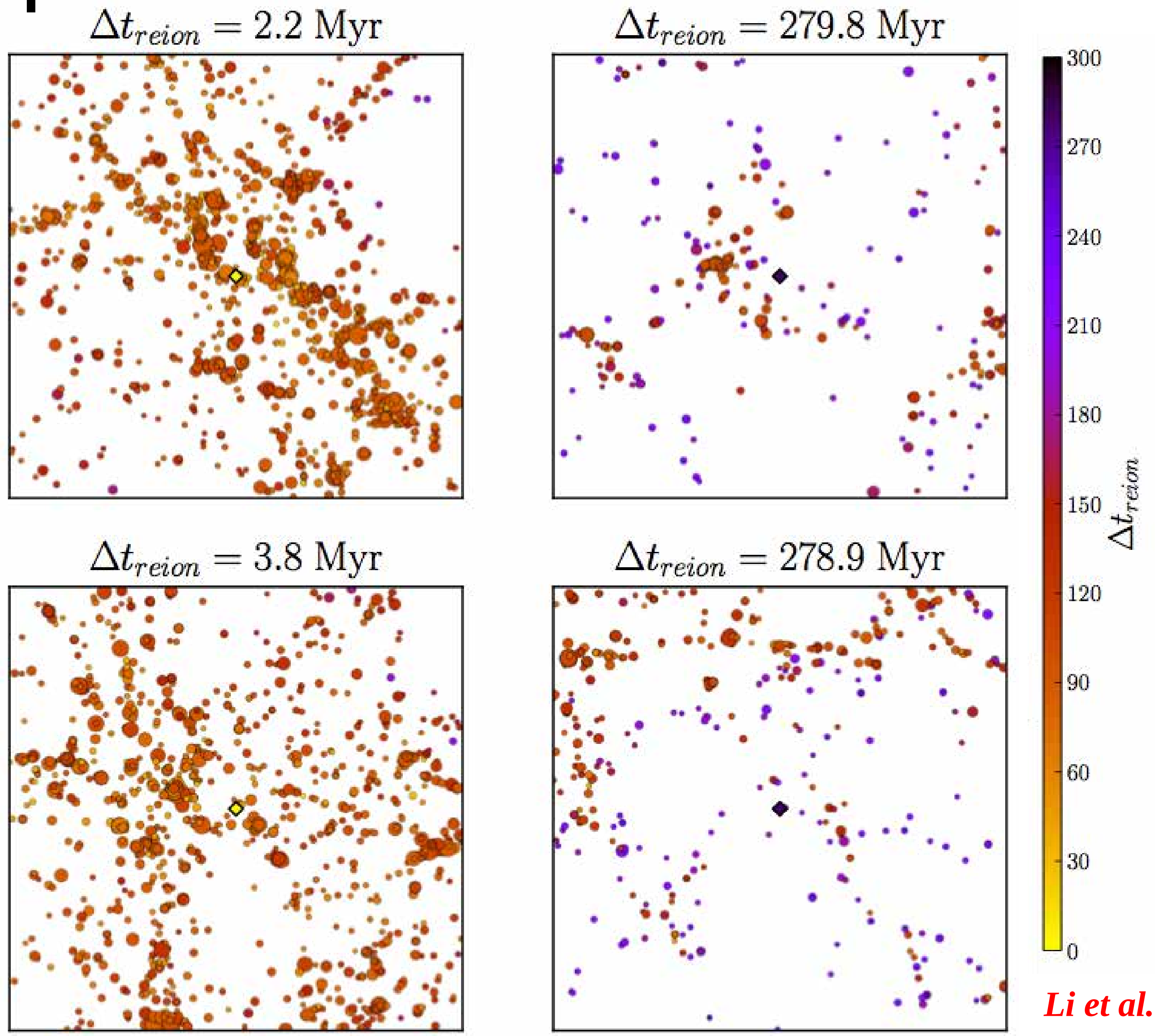
Li et al. (2012)

Halo Reionization Redshifts



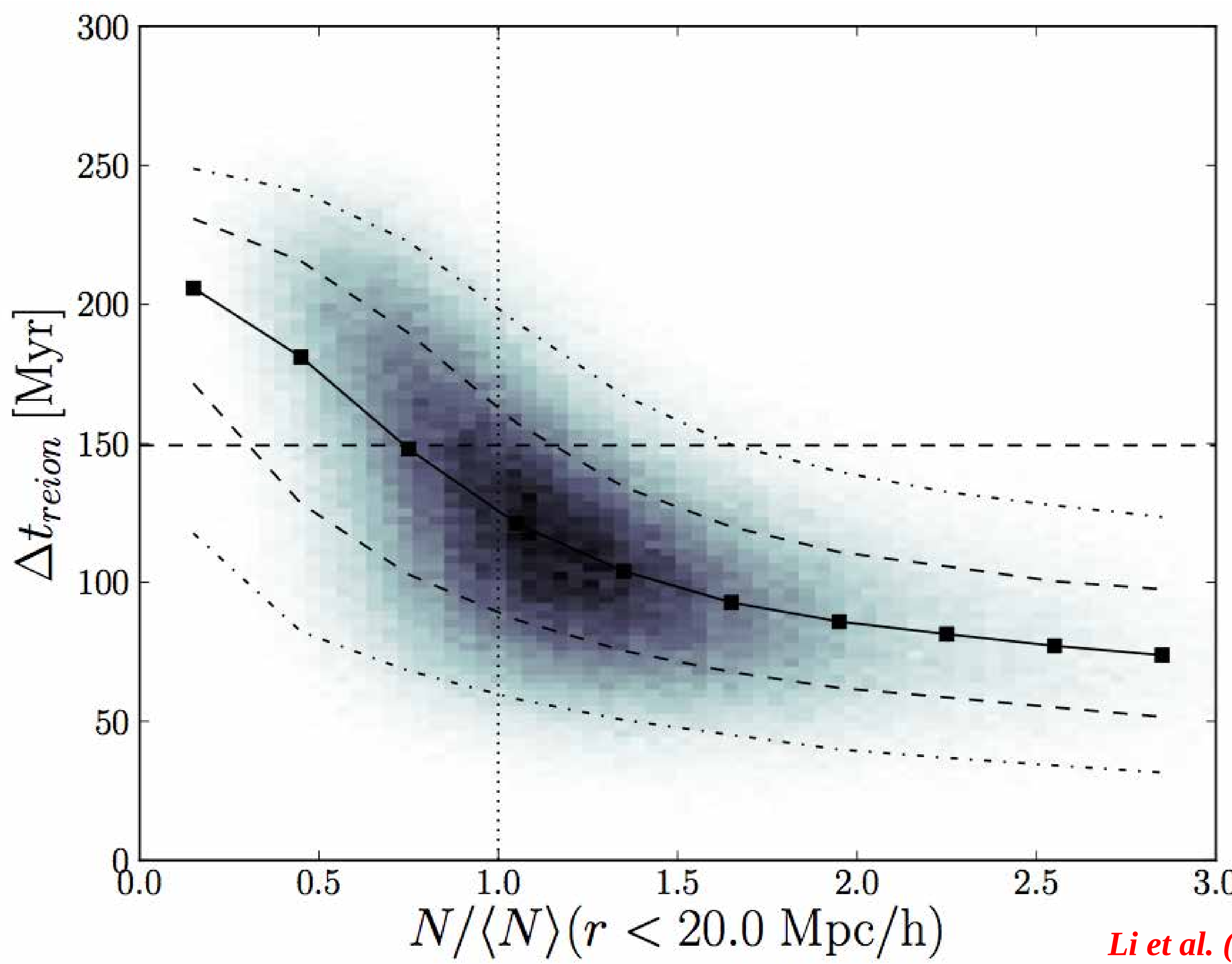
Li et al. (2012)

Dependence on Environment



Li et al. (2012)

Dependence on Environment



Li et al. (2012)

Summary

- Ionizing Efficiency of the First Galaxies
  - Minimal reionization model matches
    - Relatively low emissivity of ionizing photons at end of reionization
    - Relatively high Thomson scattering optical depth of ~0.09 reported by WMAP
    - Rapid decline in star formation rate density in high mass halos towards high redshift predicted from abundance matching LBGs
  - No need to invoke Pop III stars or star formation in minihalos -- we use standard Salpeter IMF and Pop II metallicity and only atomic cooling halos
  - Rapid increase in escape fraction required by Haardt & Madau (2012) and Kuhlen & Faucher-Giguere (2012) naturally explained by suppression of star formation in low-mass halos possesing high escape fractions
- Effect of Radiative Feedback on the Local Universe
  - Timing of reionization in local environment strongly affects number of satellites when radiative feedback is assumed to be sudden
  - High mass halos at z=0 (I.e. clusters) were ionized internally, while lower mass halos (I.e. galaxies) could have been ionized either externally or internally depending on environment
  - Halos in high-density regions were ionized mostly externally and much faster than halos in low-density regions