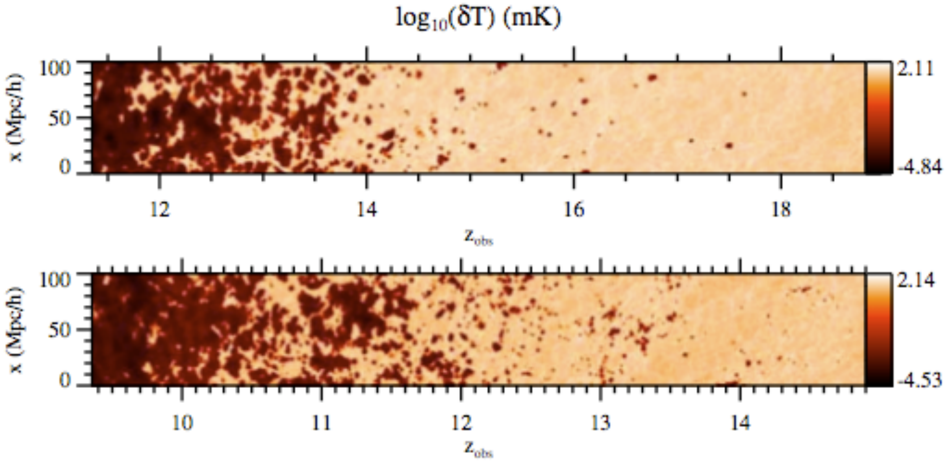
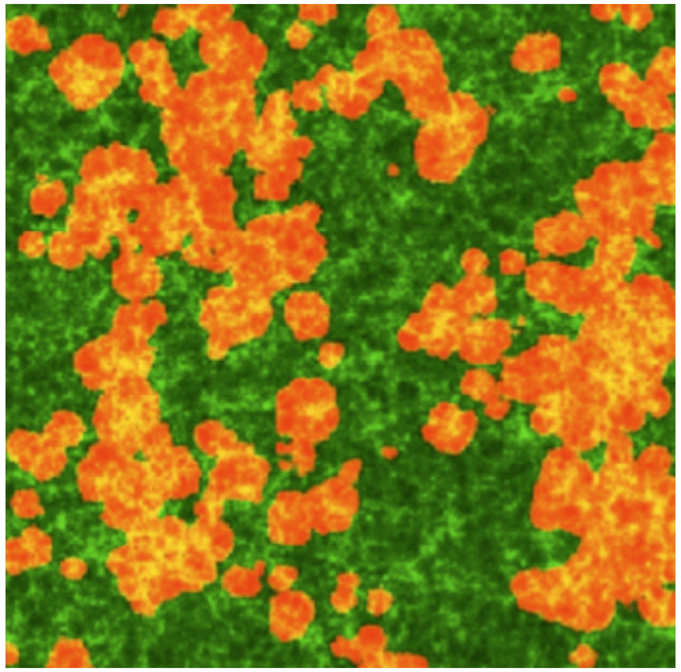
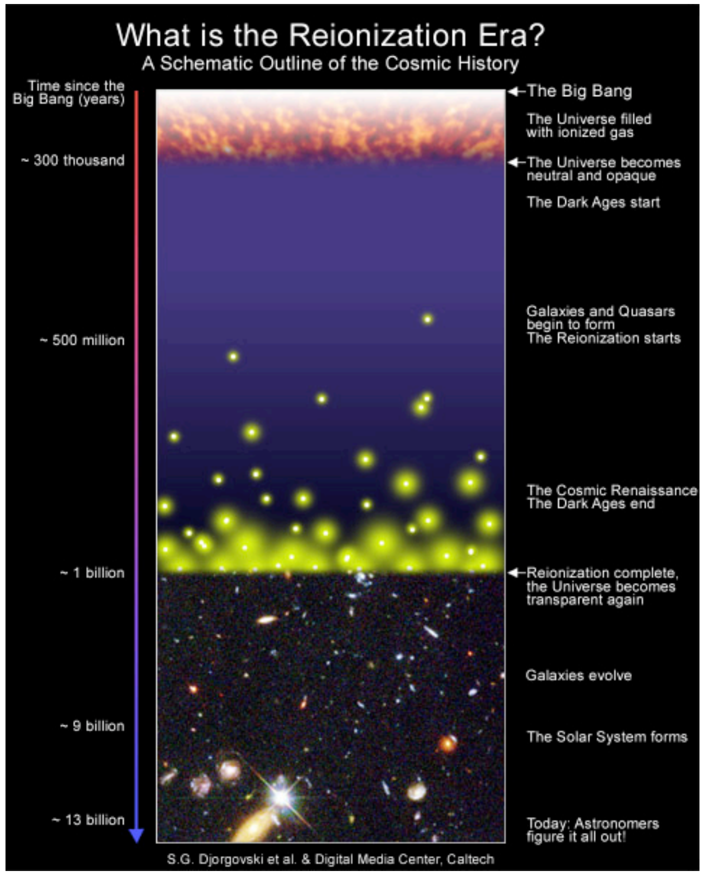
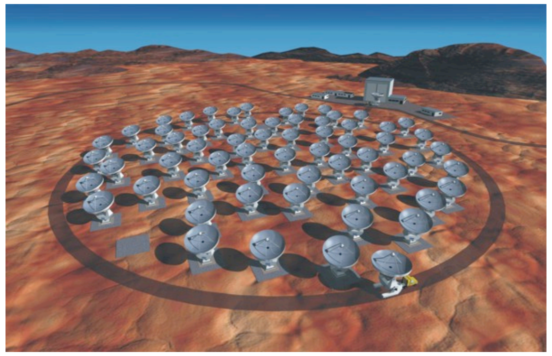
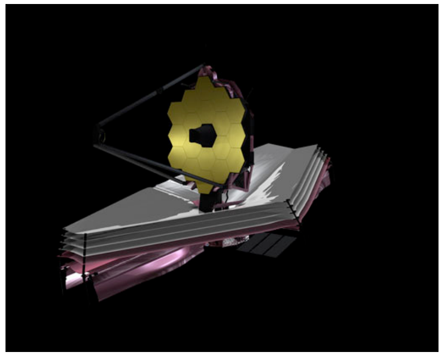




Cosmic reionization







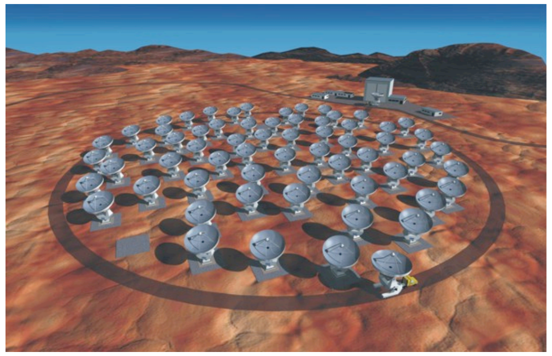
Cosmic reionization

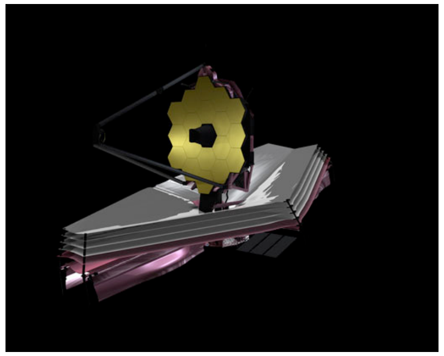
Further reading:

"In the Beginning: The First Sources of Light and the Reionization of the Universe"
Barkana & Loeb, Physics Reports (2001)

"The Astrophysics of Early Galaxy Formation"
Madau, Winter School (2007)

"Observational Constraints on Cosmic Reionization"
Fan, Carilli & Keating, ARA&A (2006)



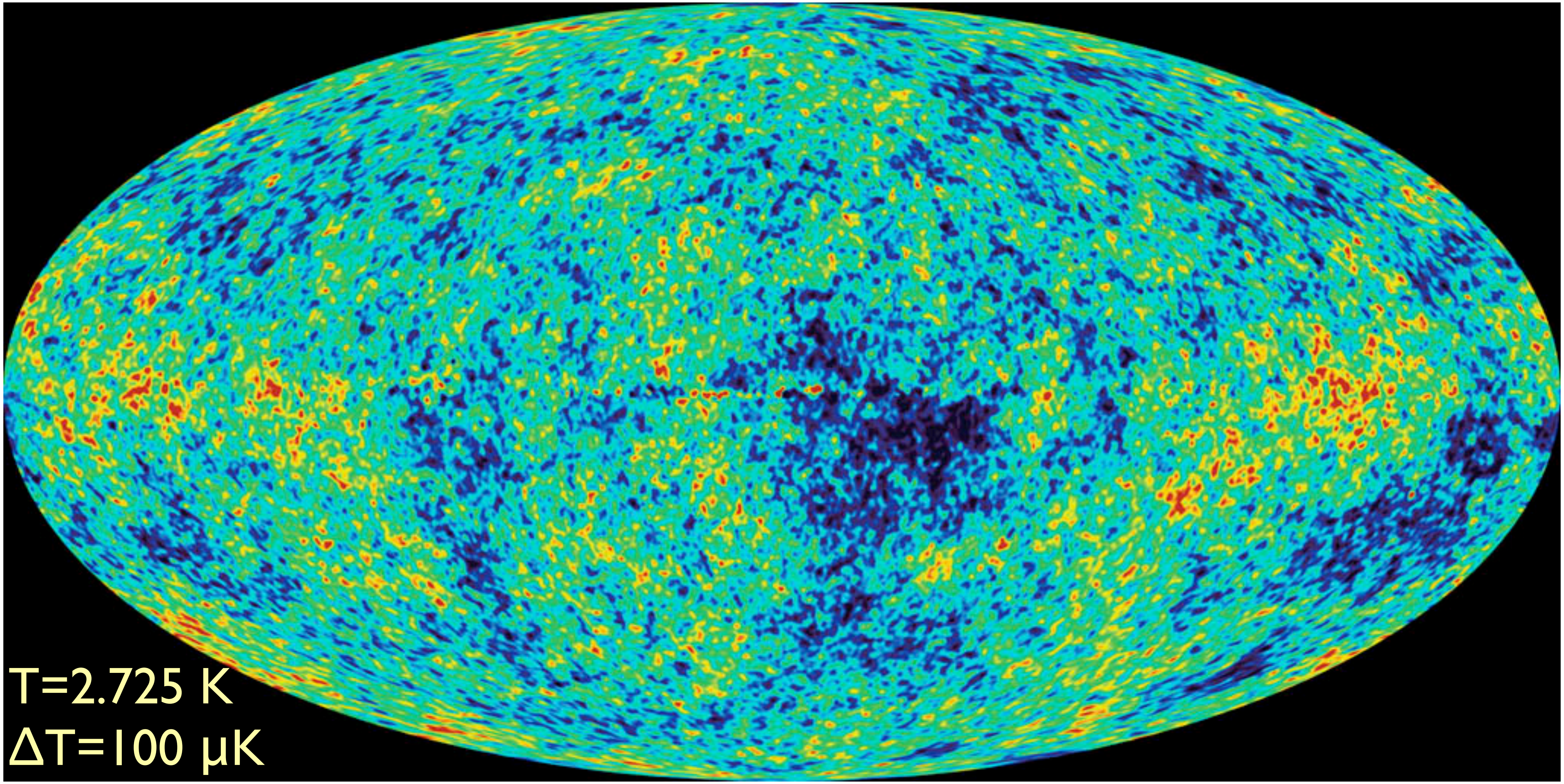



Reionization (theory)

1. Introduction
2. Ionization and Recombination
3. Reionization Sources
4. Models
5. Effects of reionization

View of the Universe at the epoch of recombination z=1000

WMAP



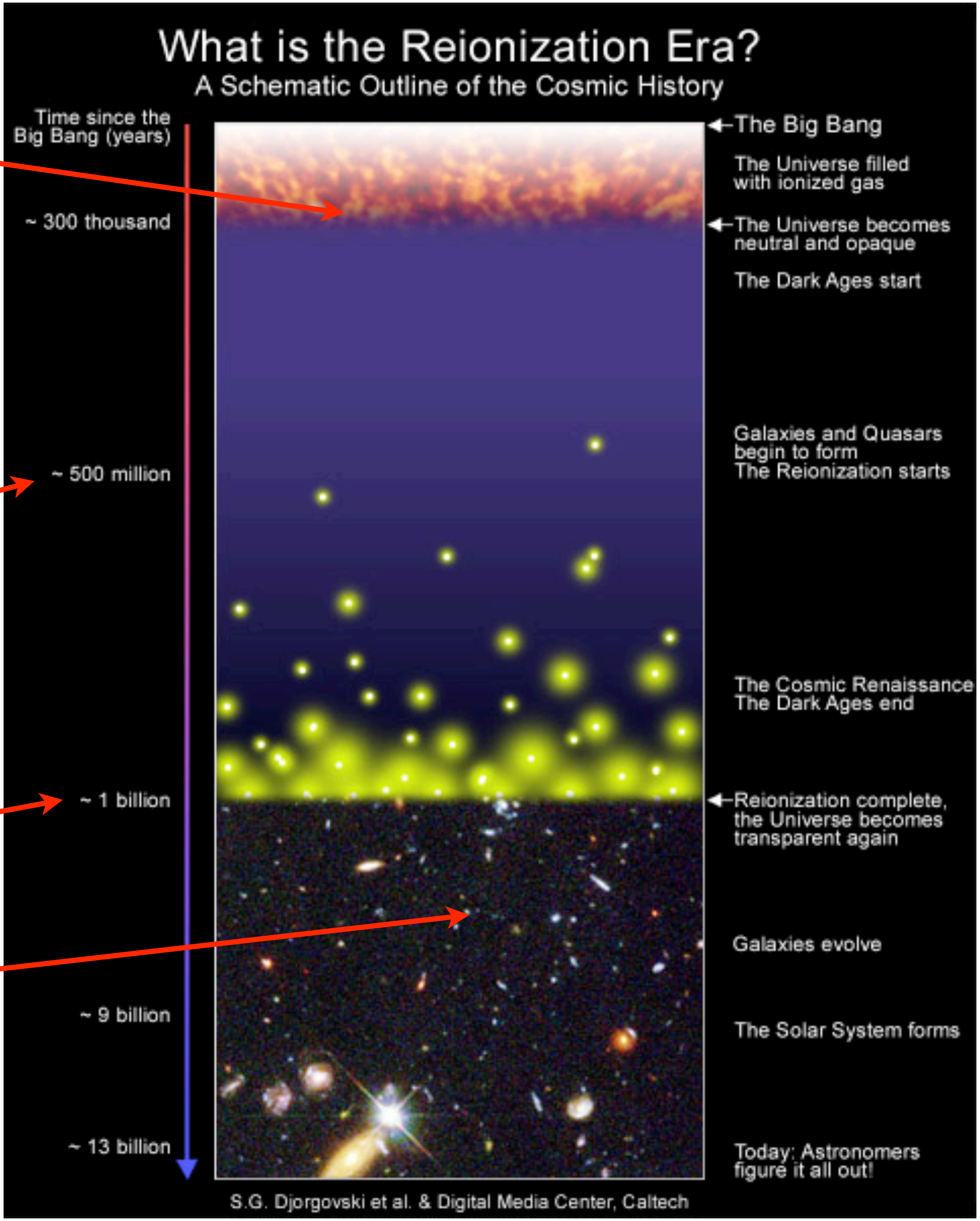
CMB

The reionization of diffuse intergalactic hydrogen is the most recent phase change of the universe.

z=10

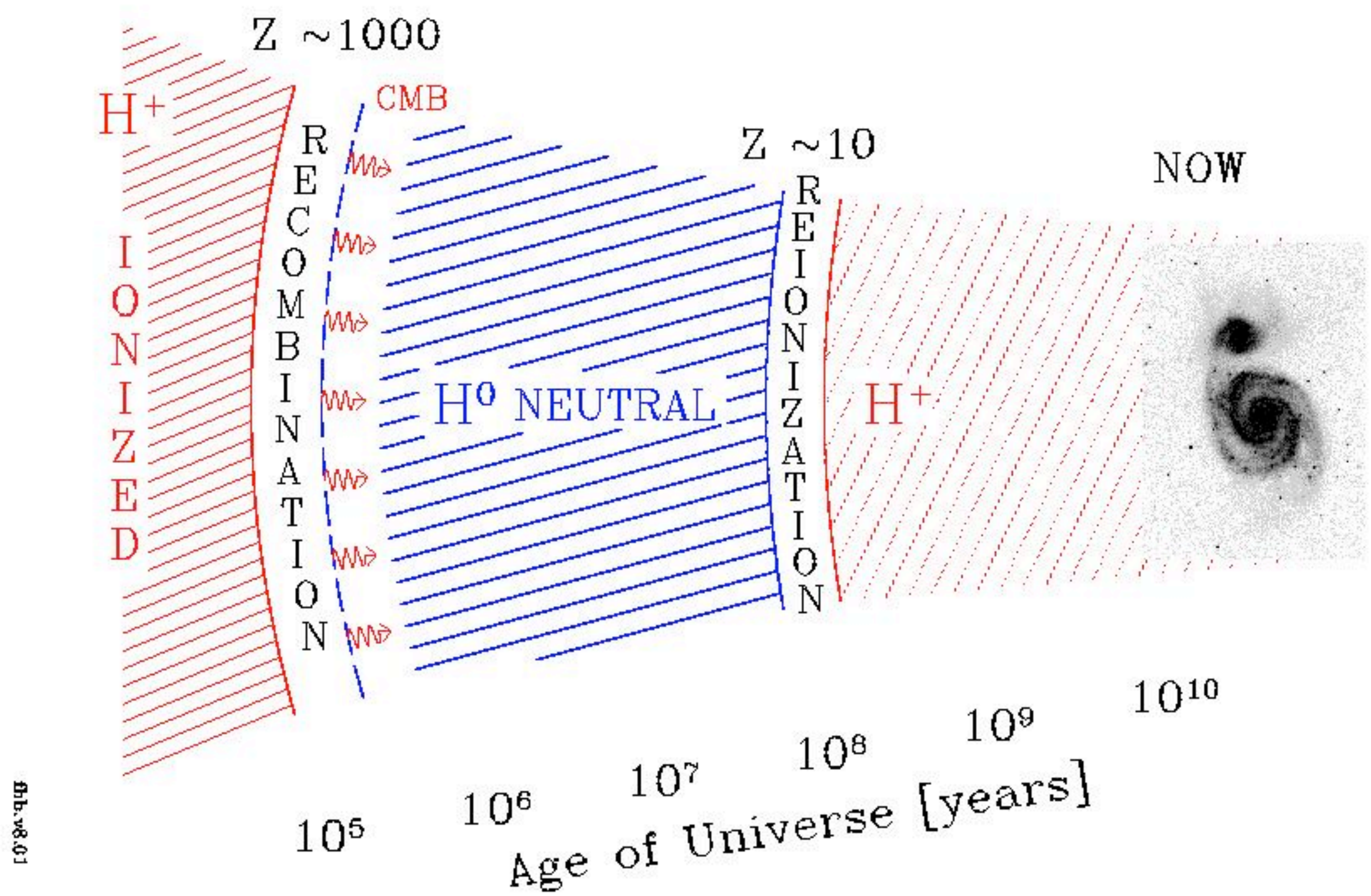
z=6

Galaxies and quasars have only been discovered to redshifts of z<7



S.G. Djorgovski et al. & Digital Media Center, Caltech

Evolution of the ionization state of diffuse hydrogen



- Reionization caused by the first stars, galaxies and black holes.

- Therefore observations of reionization will tell us details of the formation of these first objects (which may be otherwise unobservable).

- Stars and black holes emit UV photons, some of which escape the host galaxy and photoionize hydrogen atoms in the diffuse intergalactic medium (IGM).

- At some point, the ionizing radiation field is strong enough that it (re-)ionizes all the diffuse hydrogen in the universe.

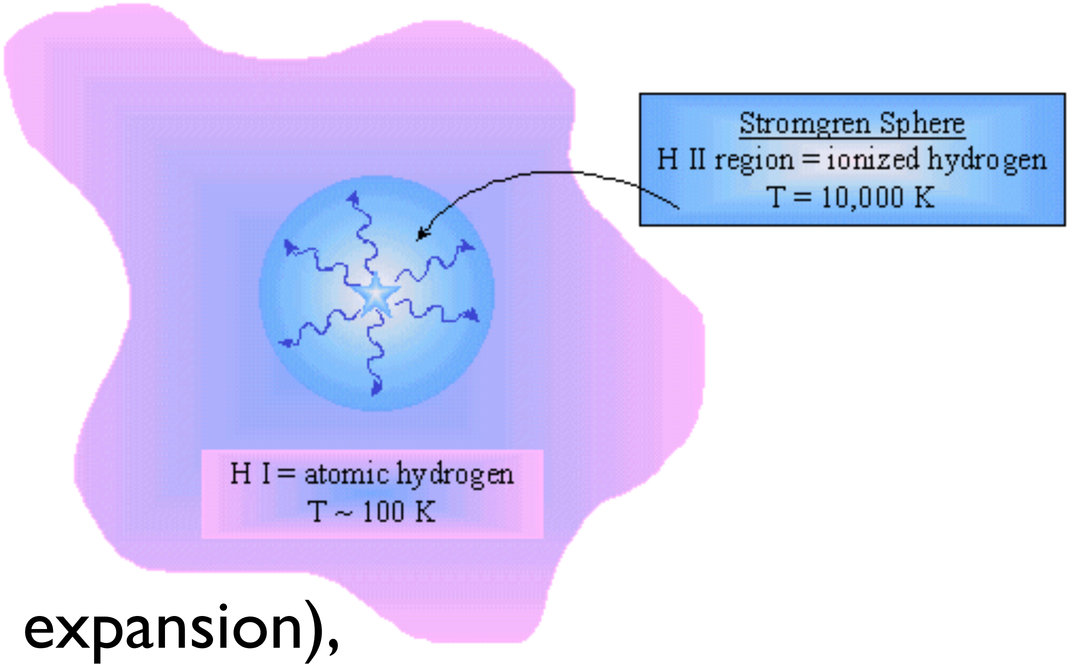
- Nuclear fusion releases ~7×10^{6} eV per hydrogen atom but ionization of hydrogen only requires 13.6 eV.

- Therefore only a small fraction of the baryonic mass in the universe (10^{-5}) needs to be involved in star formation to put out enough radiation to ionize all the diffuse hydrogen in the universe.

- Consider ionization of a spherical volume surrounding a UV source

- In the absence of recombinations, each hydrogen atom in the IGM would only have to be ionized once, and the ionized proper volume Vp would be determined by

$$\bar{n}_{\mathrm{H}} V_p = N_\gamma$$



- But recombinations may occur.

- Recombination rate depends on density squared.

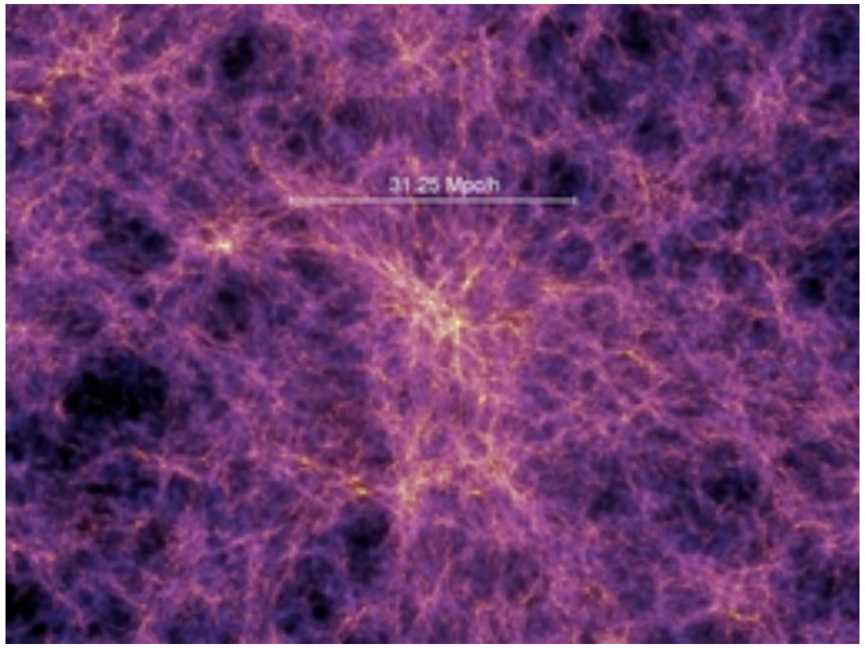
- For a steady ionizing source (neglect cosmological expansion), a steady-state volume would be reached corresponding to the Strongren sphere, with recombinations balancing ionizations:

$$\alpha_{\mathrm{B}} \bar{n}_{\mathrm{H}}^2 V_p = \frac{\mathrm{d}N_\gamma}{\mathrm{d}t}$$

Recombination coefficient: $\alpha_{\mathrm{B}} = 2.6 \times 10^{-13}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

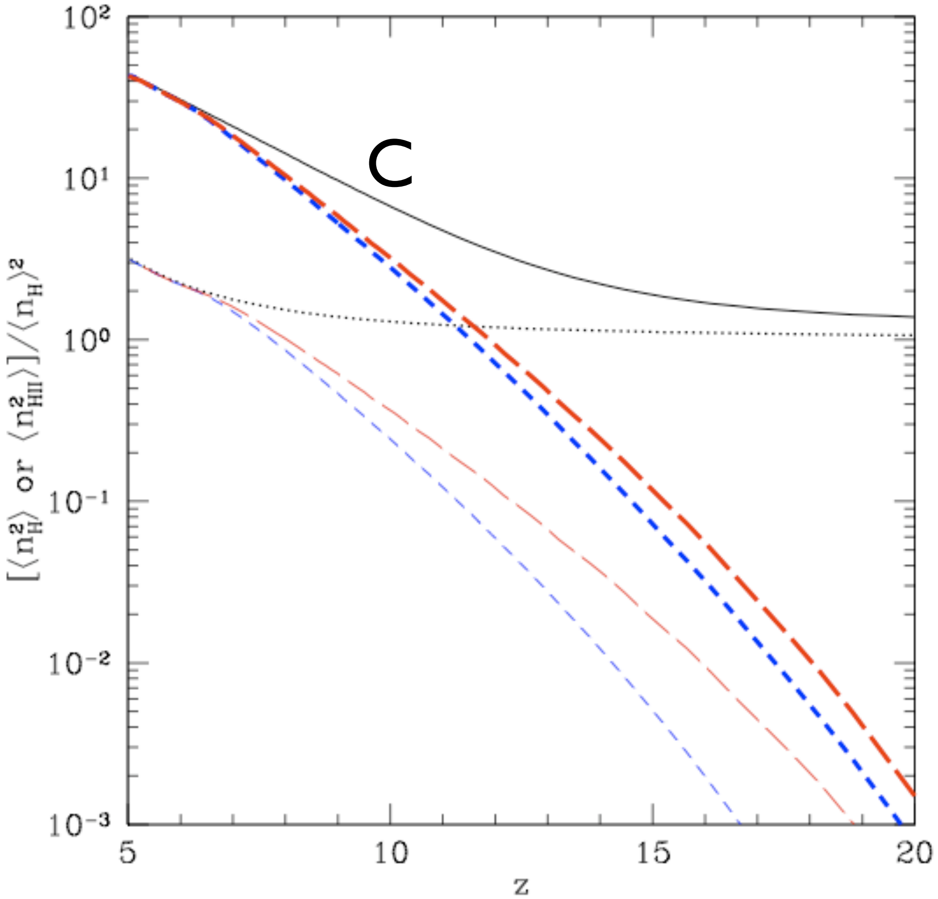
$\rho \propto (1+z)^3$ due to cosmological expansion,
so smaller volumes will be ionized at higher redshifts.

- IGM is not uniform.
- High density regions will dominate recombinations.



z=5.7

- Need to introduce volume-averaged clumping factor: $C = \langle n_{\rm H}^2 \rangle / \bar{n}_{\rm H}^2$
- Higher clumping factor means more recombinations and hence tougher to achieve reionization.
- Numerical simulations show that C is higher at lower redshifts.
- Values of 5-30 are commonly adopted at end of reionization.



Trac & Cen (2008)

Source of Ionizing Photons

- Possible photon sources: stars, AGN, dark matter annihilation.
- Both stars and AGN form in the first galaxies - need to review galaxy formation.
- Galaxies form where gas can cool in dark matter halos.

Galaxy Formation

When atoms recombine to become neutral (at CMB epoch), radiation and matter *decouple*.

The baryonic matter (gas) then cools as it expands adiabatically.

Adiabatic index for ideal gas is γ=5/3 $P \propto \rho^{5/3}$

$$P = \frac{\Re}{\mu}\rho T$$ Ideal Gas equation

Combine to get temperature dependence on density:

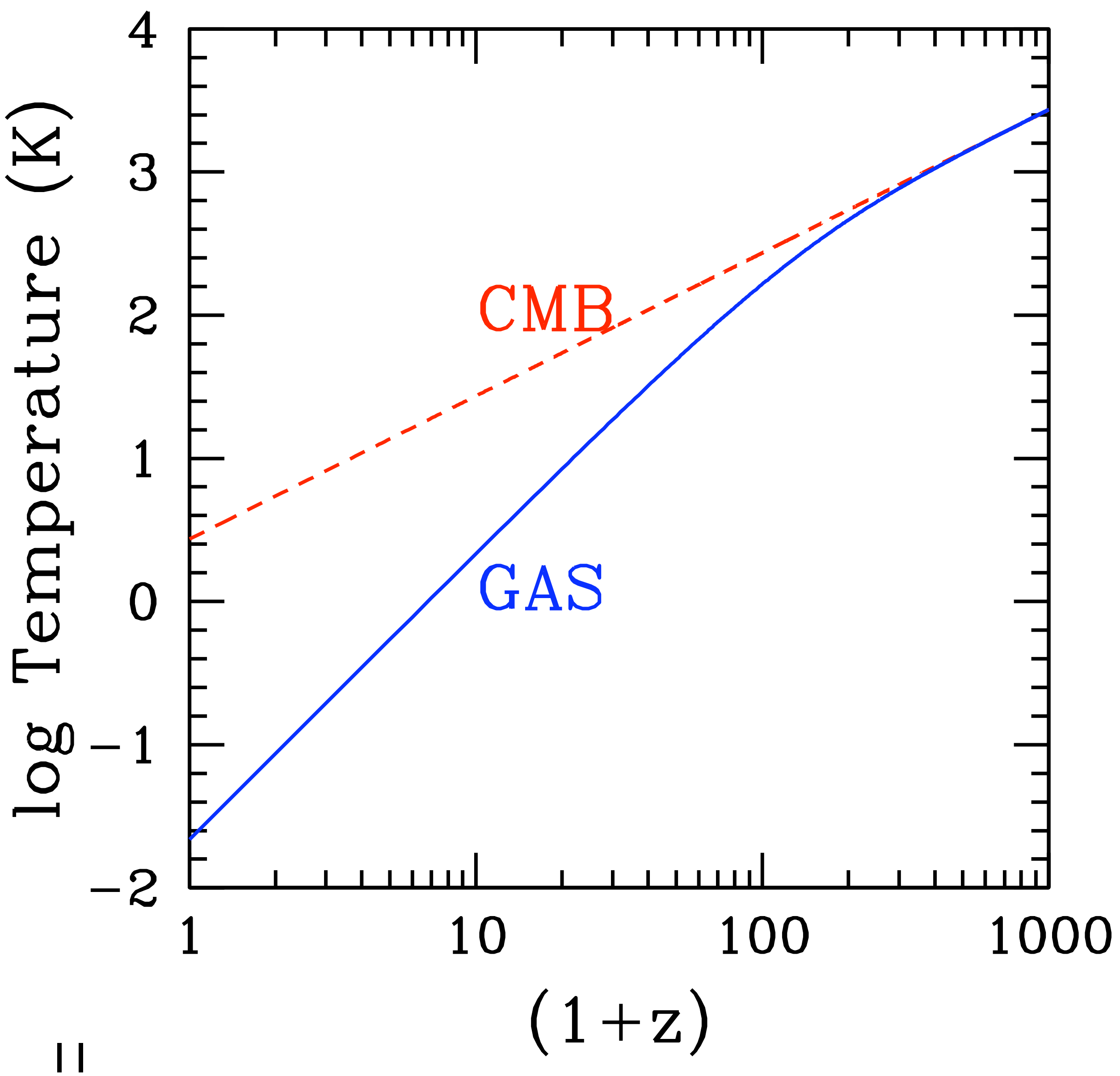
$$\rho^{5/3} \propto \rho T \Rightarrow \rho^{2/3} \propto T$$

Expansion of universe gives:

$$\rho \propto (1+z)^3$$

so $T \propto (1+z)^2$ for gas.

Madau (2007)



Galaxy Formation

Dark matter halos only form if mass is above the Jeans mass limit:

$$M_{\rm J} = \left[\left(\frac{3}{4\pi}\right)^{1/2}\left(\frac{3}{\alpha}\right)^{3/2}\right]\left(\frac{\Re T}{\mu G}\right)^{3/2}\left(\frac{1}{\rho}\right)^{1/2}$$

meaning $M_{\rm J} \propto \left(\frac{T^3}{\rho}\right)^{1/2}$

Evolution of the Jeans mass:

$$\rho \propto (1+z)^3$$

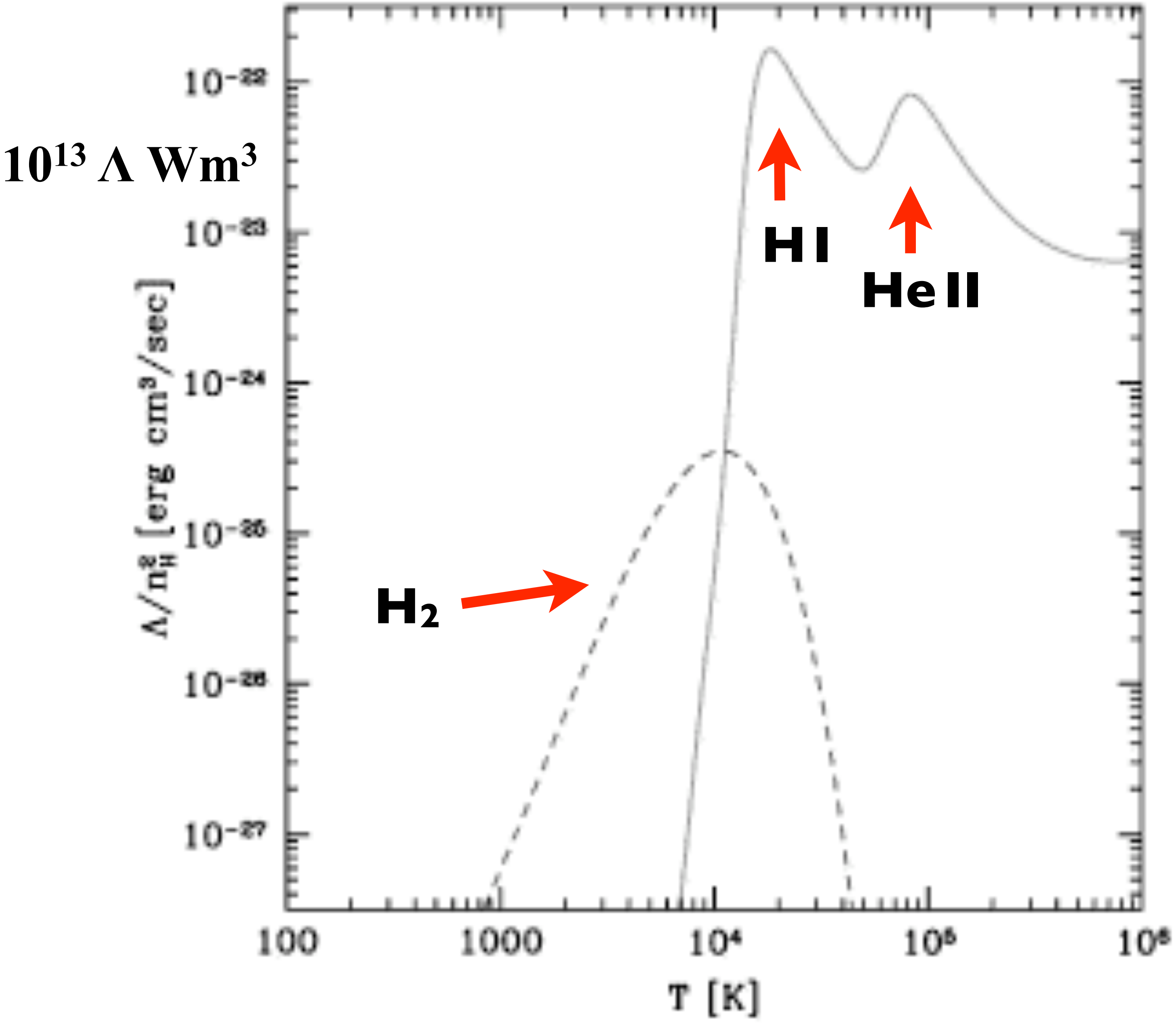
In the radiation era, $T \propto (1+z)$, so $M_{\rm J}$ is almost independent of redshift ($M_{\rm J} \sim 10^5\,{\rm M}_\odot$).

In the matter dominated era, $T \propto (1+z)^2$ for gas, so $M_{\rm J}$ declines at lower redshift.

The Cooling Function

We need to know the rate at which the gas can cool. This depends upon the specific cooling process that is most efficient, so depends upon temperature and composition. The cooling rate $r_{\rm cool}$ is dependent upon n^2 because of collisions and the cooling function, $\Lambda(T)$:

$$r_{\rm cool} = n^2 \Lambda(T)$$ units of energy per unit time per unit volume



Cooling curve for primordial composition.

Barkana & Loeb (2001)

The Cooling Function

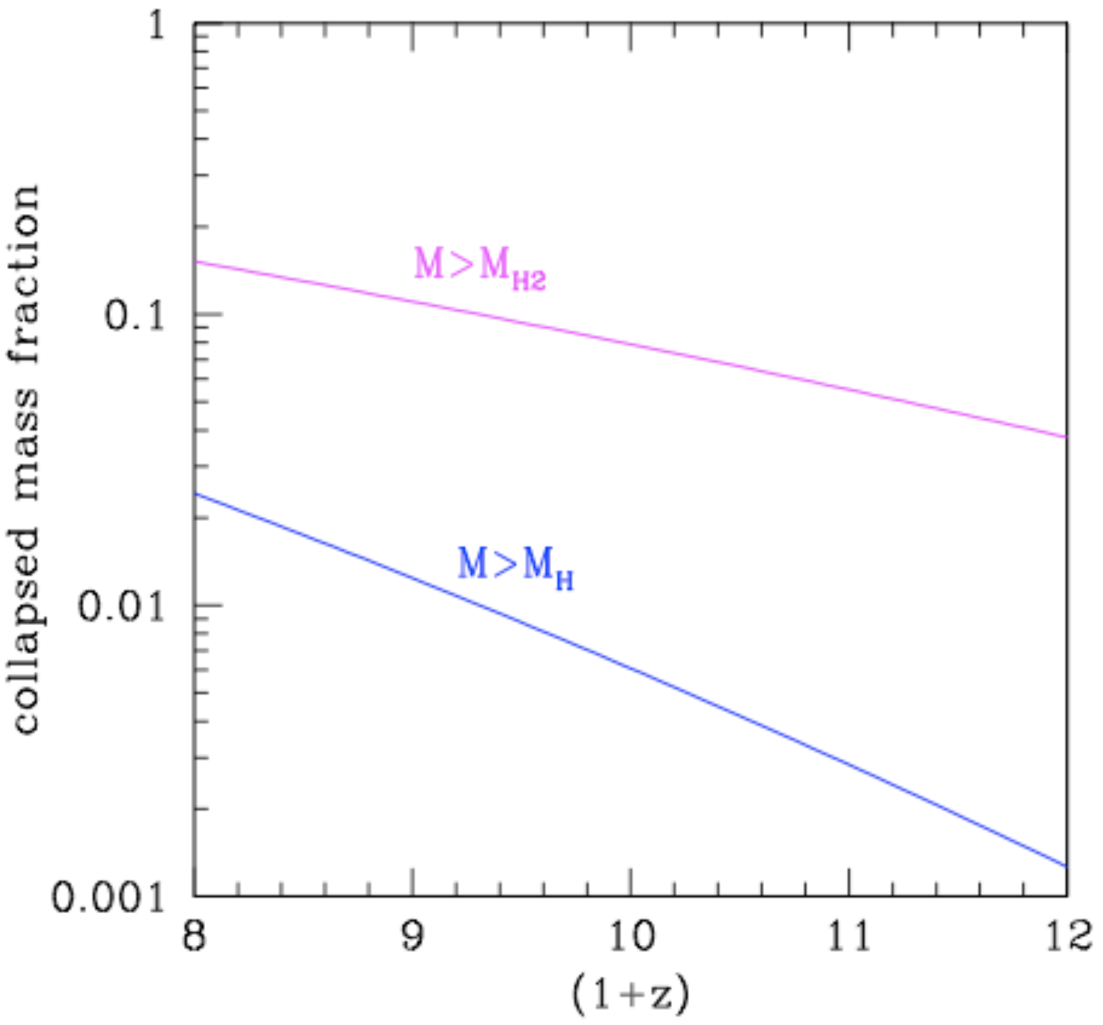
As a dark matter halo grows and virializes above the cosmological Jeans mass through merging and accretion, baryonic material is shock heated to the effective virial temperature of the host and compressed to the same fractional overdensity as the dark matter.

The subsequent behavior of gas in a dark matter halo depends on the efficiency with which it can cool.

It is useful here to identify two mass scales for the host halos:

(1) a molecular cooling mass M_{H2} above which gas can cool via roto-vibrational levels of H_2 and contract, $M_{H2} \approx 10^5 [(1 + z)/10]^{-3/2} M_\odot$ (T > 200 K);

(2) an atomic cooling mass M_H above which gas can cool efficiently and fragment via excitation of hydrogen Lyα, $M_H \approx 10^8 [(1 + z)/10]^{-3/2} M_\odot$ $(T > 10^4 K)$.



Madau (2007)

The First Stars

The first galaxies that formed at the highest redshifts had zero *metallicity*.

The first stars to form are therefore Pop III stars.

How are these different to Pop I (solar metallicity) and II (low metallicity) stars?

In star forming regions in our galaxy, most gas cooling is via molecular line and dust emission associated with metals.

Cooling function $\Lambda(T)$ much greater for high metallicity than for primordial.

Q: What is the consequence of this for the stars forming in the first galaxies?

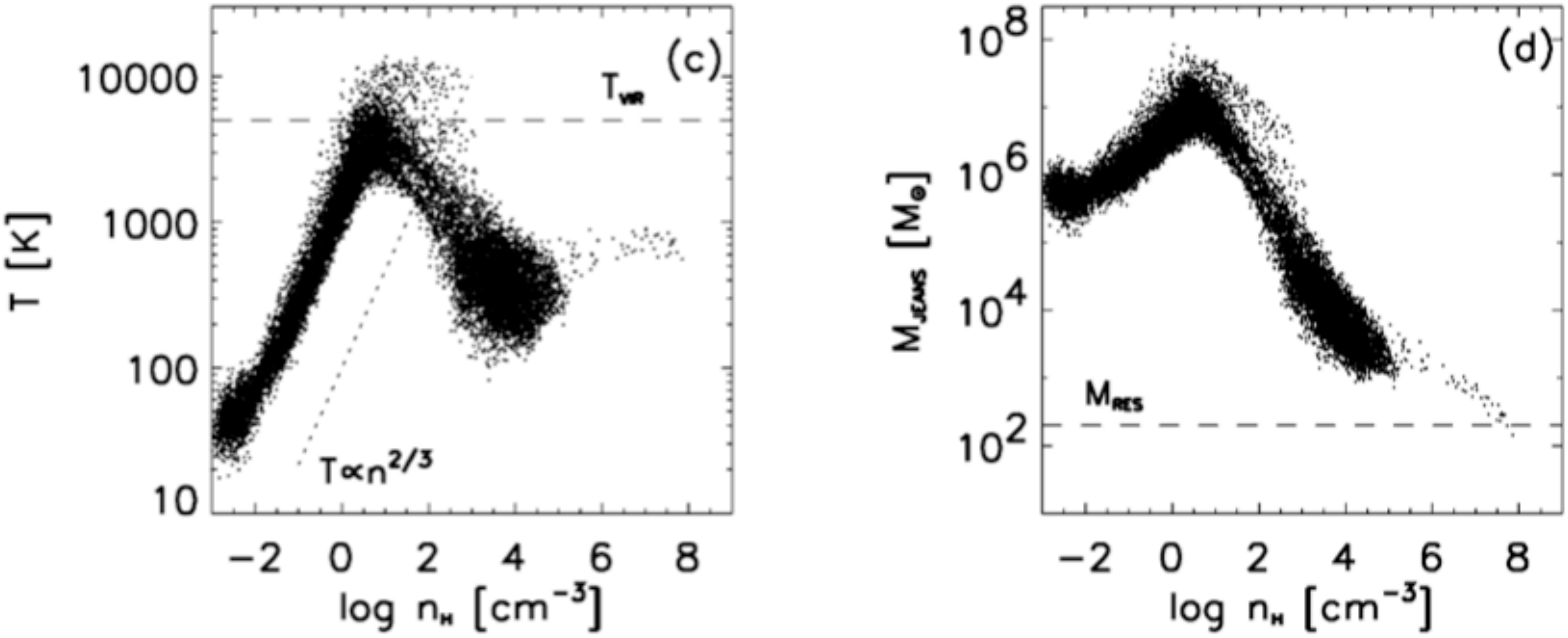
Jean's mass defines fragmentation mass threshold: $M_{\rm J} \propto \left(\frac{T^3}{\rho}\right)^{1/2}$

Collapsing gas doesn't cool so effectively and therefore does not fragment.

Result is formation of predominantly very massive ($\sim 100\,M_\odot$) stars.

The First Stars

Data points from a simulated primordial gas cloud forming the first stars:

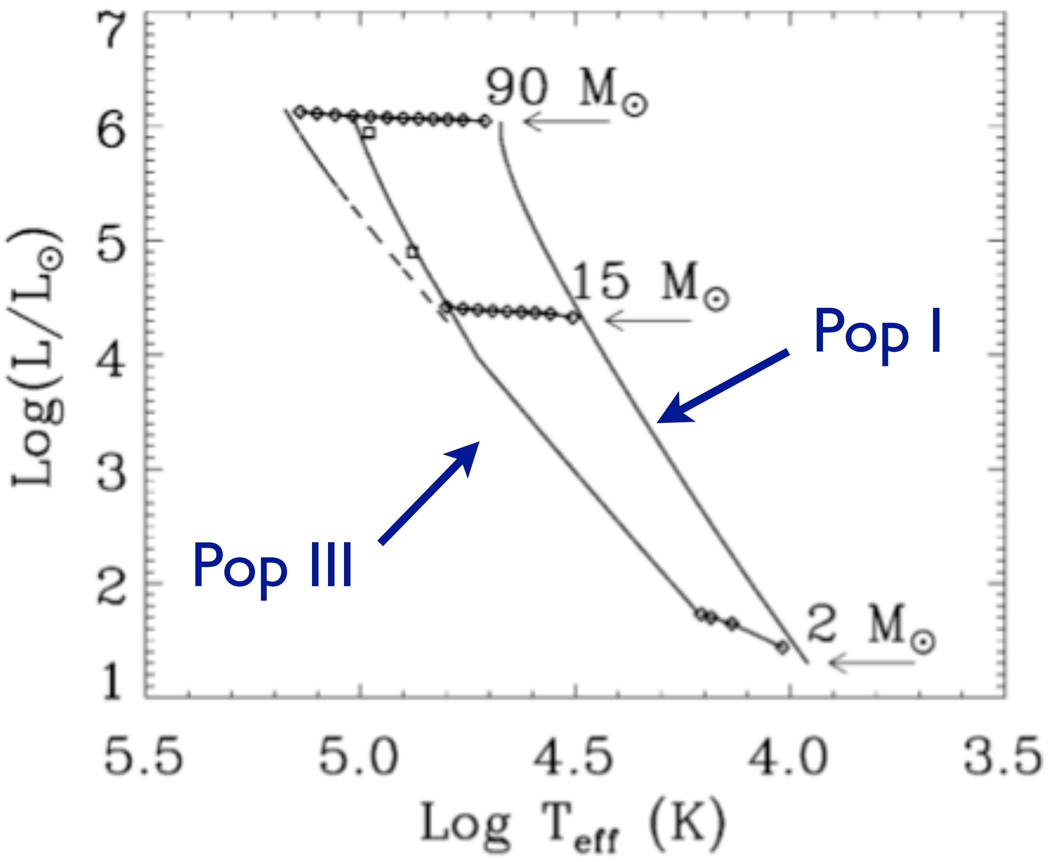


Bromm et al. (1999)

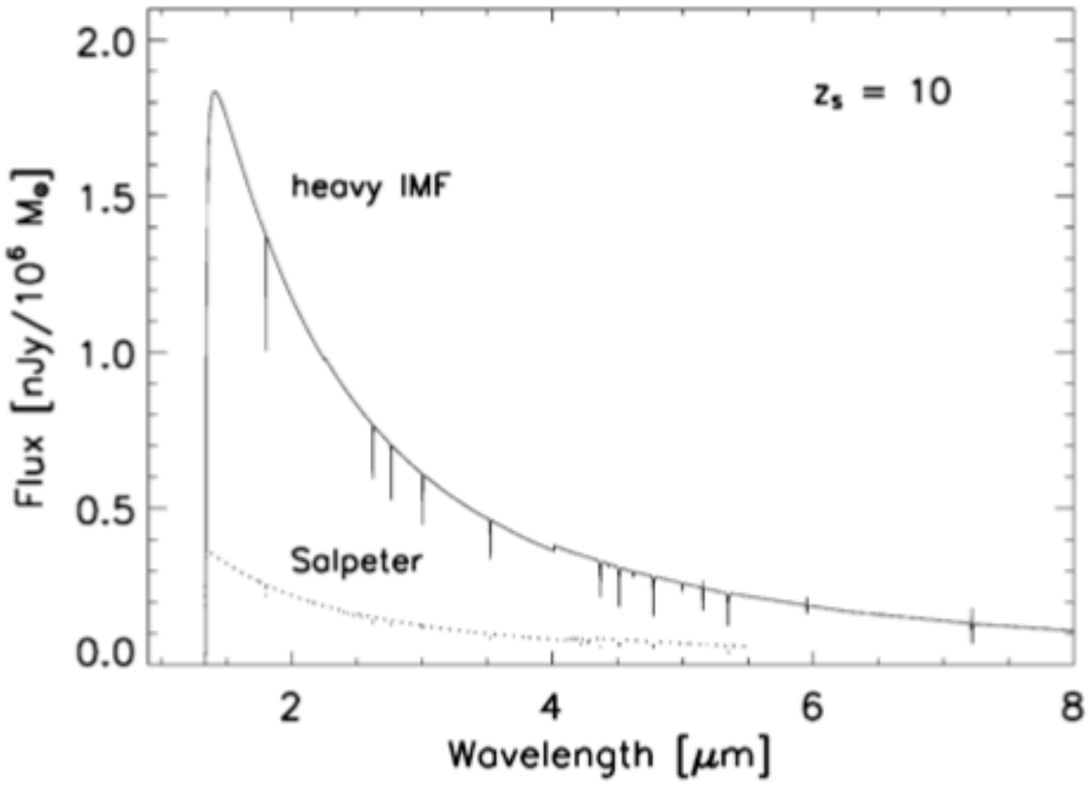
The First Stars

How are Pop III stars different?

- IMF biased to higher masses
- Stars of same mass hotter due to no initial CNO cycle.
- Hotter ➔ higher luminosity
- Hotter ➔ harder UV spectrum (more ionizing photons!)
- Able to photoionize He, so He emission lines as well as H lines from nebulae.
- Shorter lifetimes.
- Very massive black holes final point of stellar evolution?



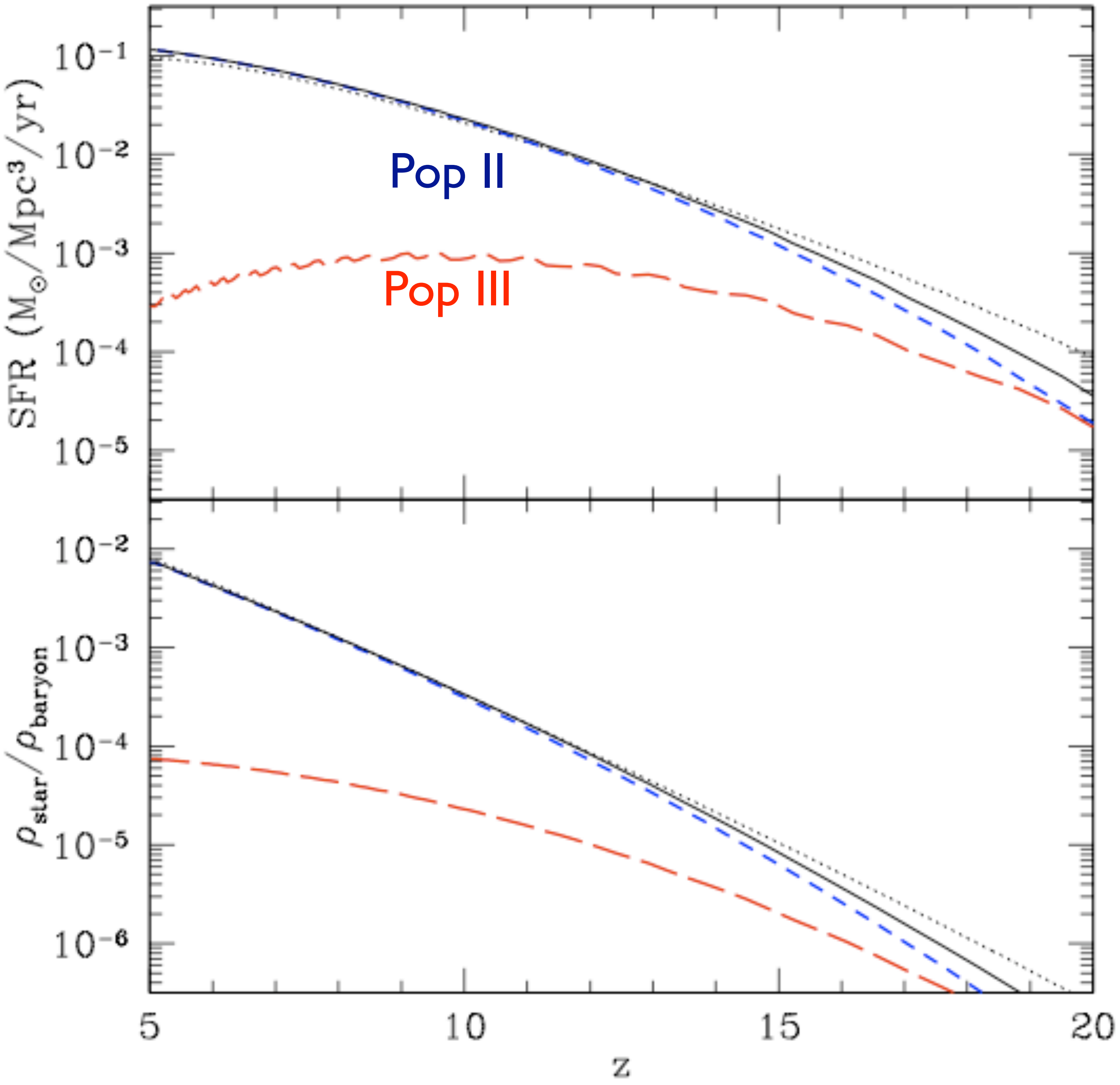
Tomlinson & Shull & (2000)



The First Stars

These properties of Pop III stars make them interesting for reionization.

But stellar winds and death of Pop III stars likely lead to quick metal enrichment of IGM, so only a small fraction of stars will be Pop III.



Trac & Cen (2008)

Reionization Modelling

Numerical simulations of dark matter halo growth

Prescription for star formation in halos (+ many assumptions).

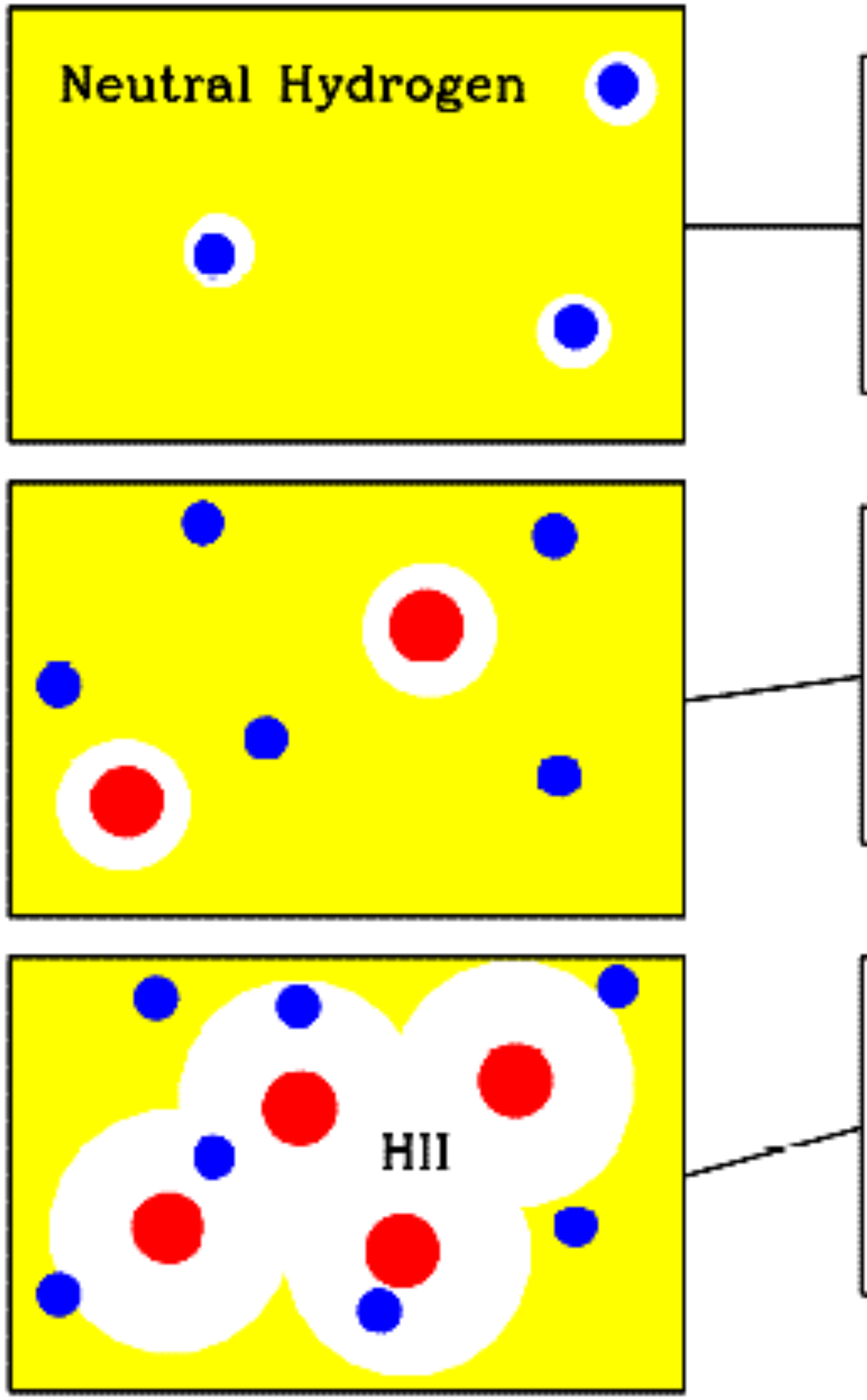
Ray tracing and radiative transfer

Track ionization and recombinations

Compare to observations and iterate, optimize and predict.

Need to deal with large and small scales makes computations very expensive.

Reionization Modelling



$z \sim 30$

- ☆ First stars form
- ☆ H_2 dissociates

$z \sim 15$

- ☆ Stars form in more massive halos

$z \sim 10$

- ☆ HII regions overlap
- ☆ UV intensity rises

● $T_{vir} < 10^4$ K

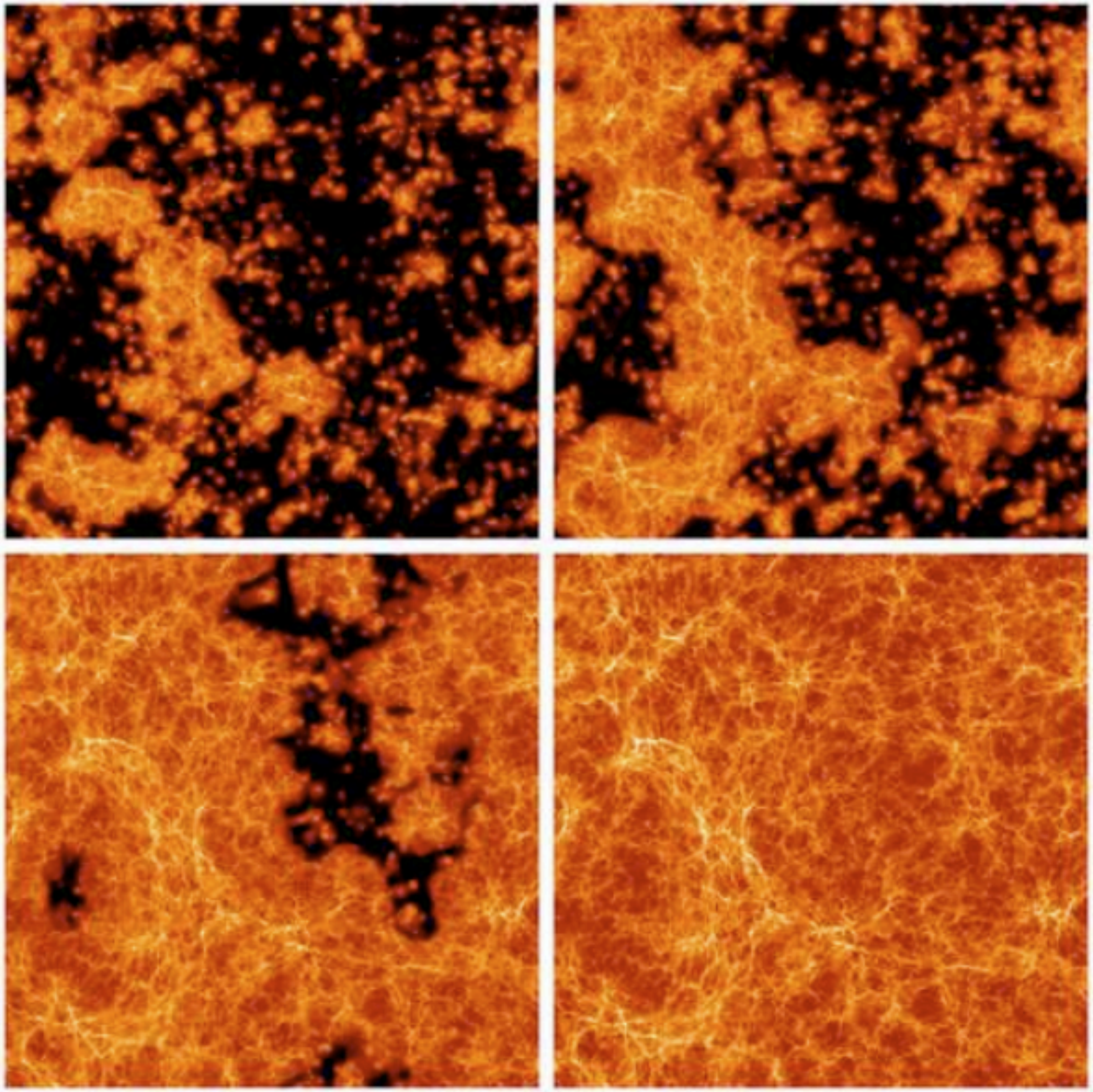
● $T_{vir} > 10^4$ K

Barkana & Loeb (2001)

Reionization Modelling

HII density in 1 Mpc/h deep slices through 50 Mpc/h simulation box

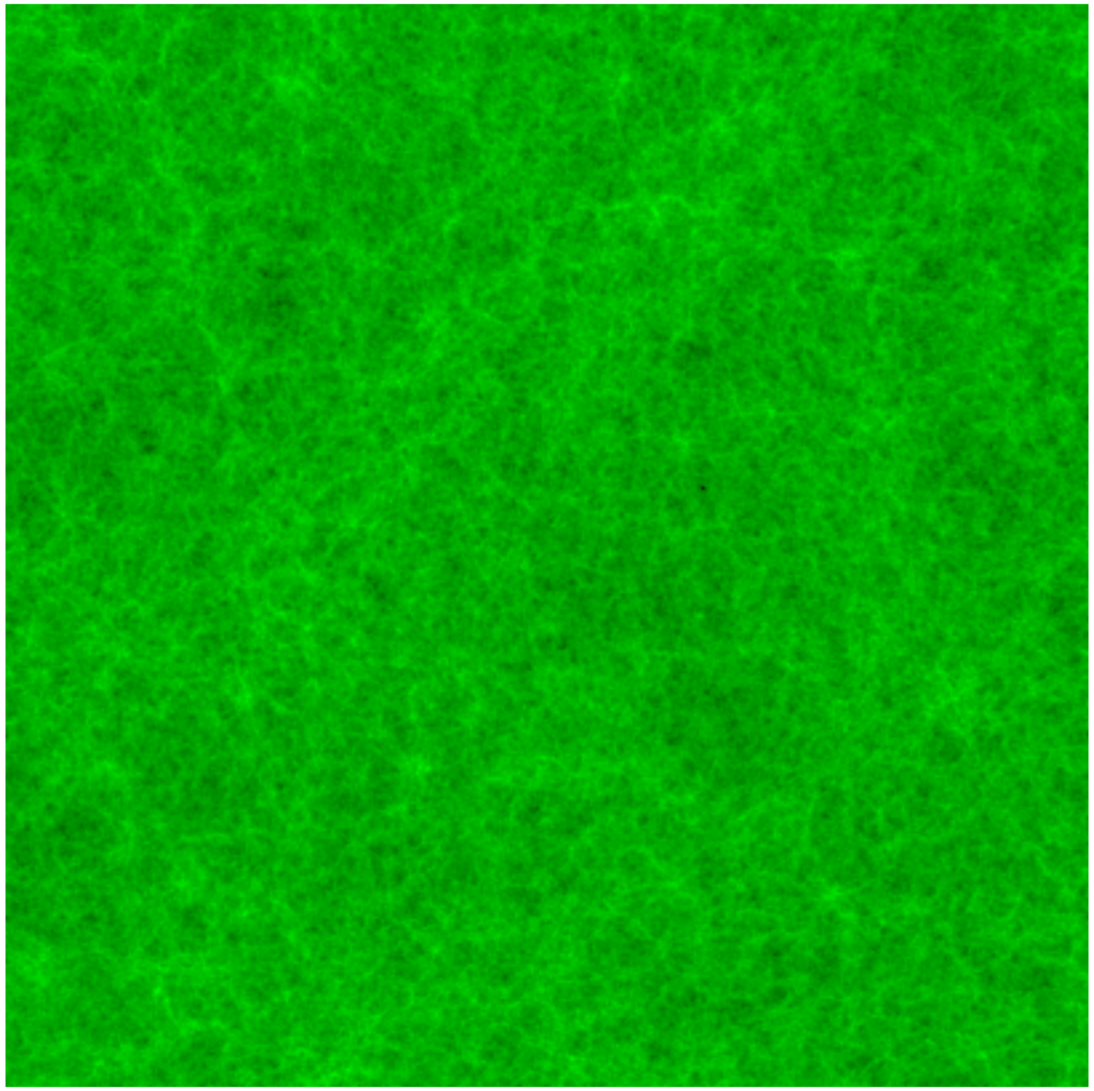
High or low density regions get ionized first?



Trac & Cen (2008)

Reionization Modelling

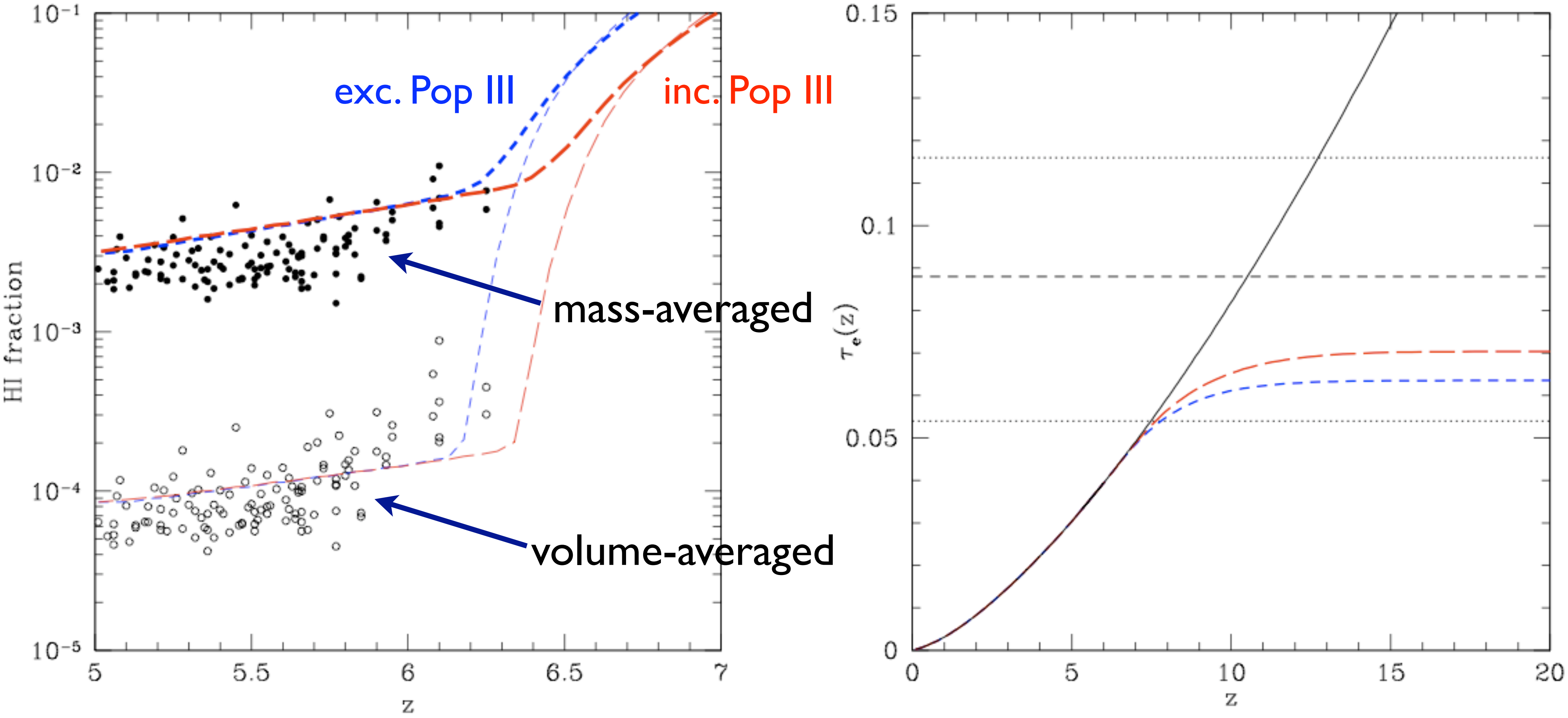
HII ionization and sources in 100 Mpc/h simulation box



Iliev et al. (2006)

Reionization Modelling

Predict ionization fraction and optical depth evolution and compare with observations.



exc. Pop III

inc. Pop III

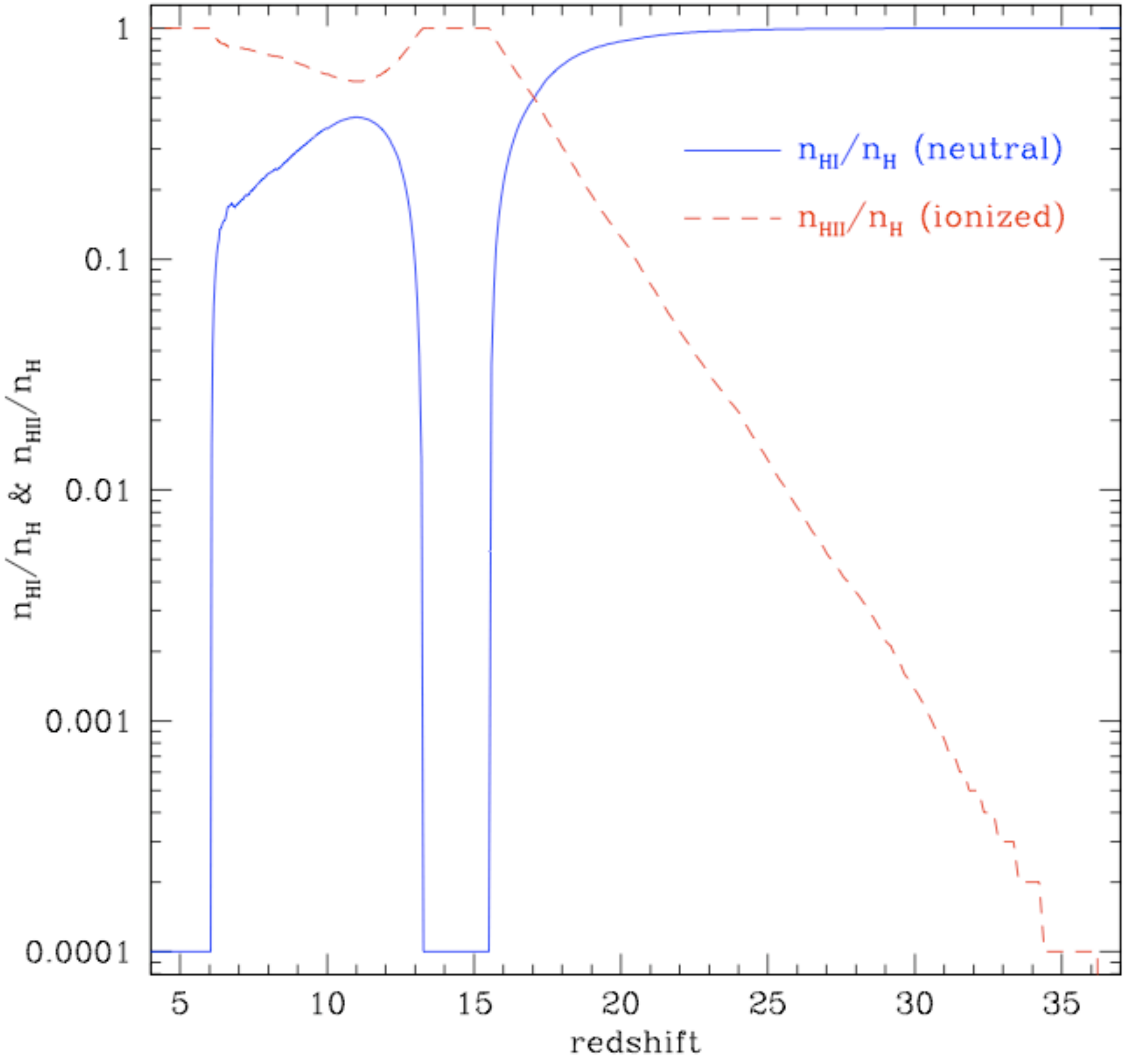
mass-averaged

volume-averaged

Trac & Cen (2008)

Reionization Modelling

Pop III star formation at high redshift only can give rise to double reionization models

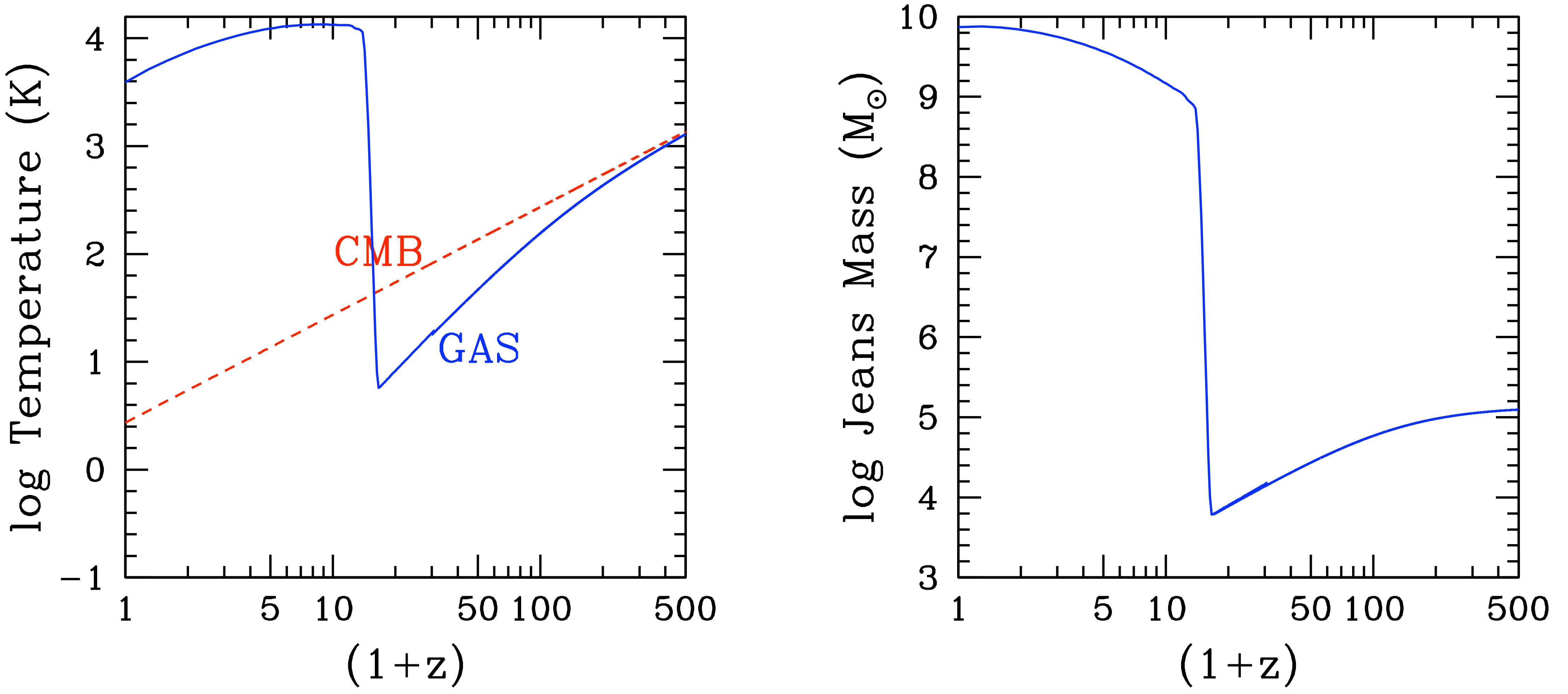


Cen (2003)

Effects of Reionization

Universe is transparent to ionizing photons again, so strong UV background.

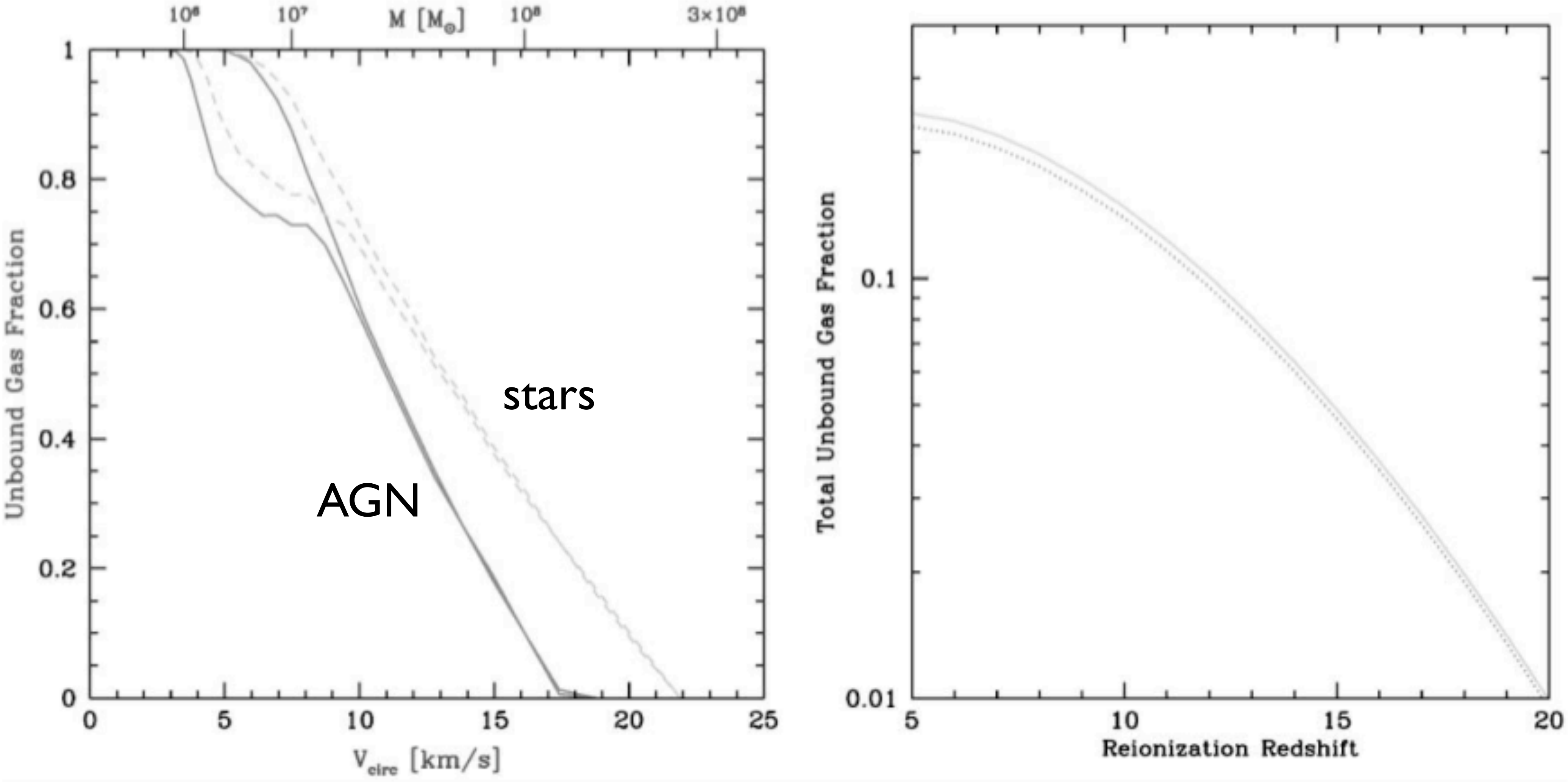
The *reionization* of the universe heats the gas temperature to $T \sim 10^4$ K and raises the cosmological Jeans mass limiting the formation of low mass galaxies.



Madau (2007)

Effects of Reionization

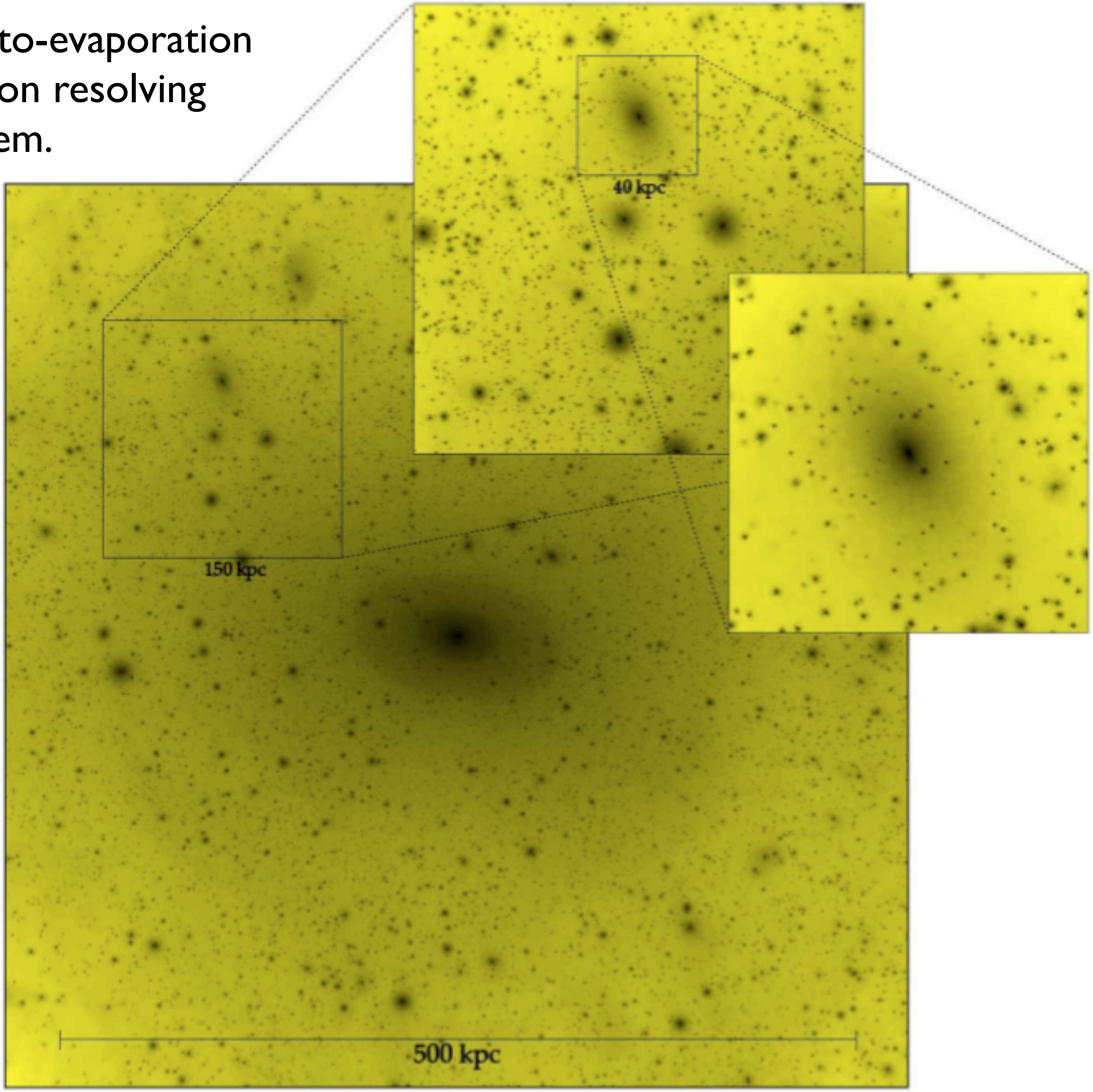
The high temperature also photo-evaporates the gas in low mass halos.



Barkana & Loeb (2001)

Effects of Reionization

Jeans mass filtering and photo-evaporation can have a significant effect on resolving the 'missing satellites' problem.



Kuhlen et al. (2008)

Effects of Reionization

- Universe becomes transparent to Lyman photons again.
- Lyman alpha emission lines visible from star-forming galaxies.
- Scattering of CMB photons by free electrons.