The 21cm Signal From Reionization

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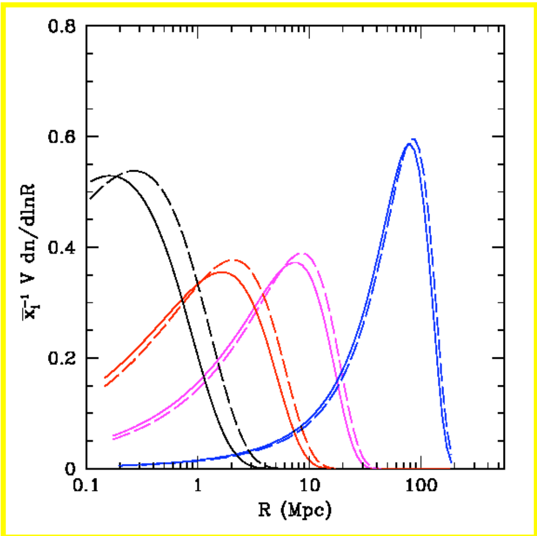
Outline

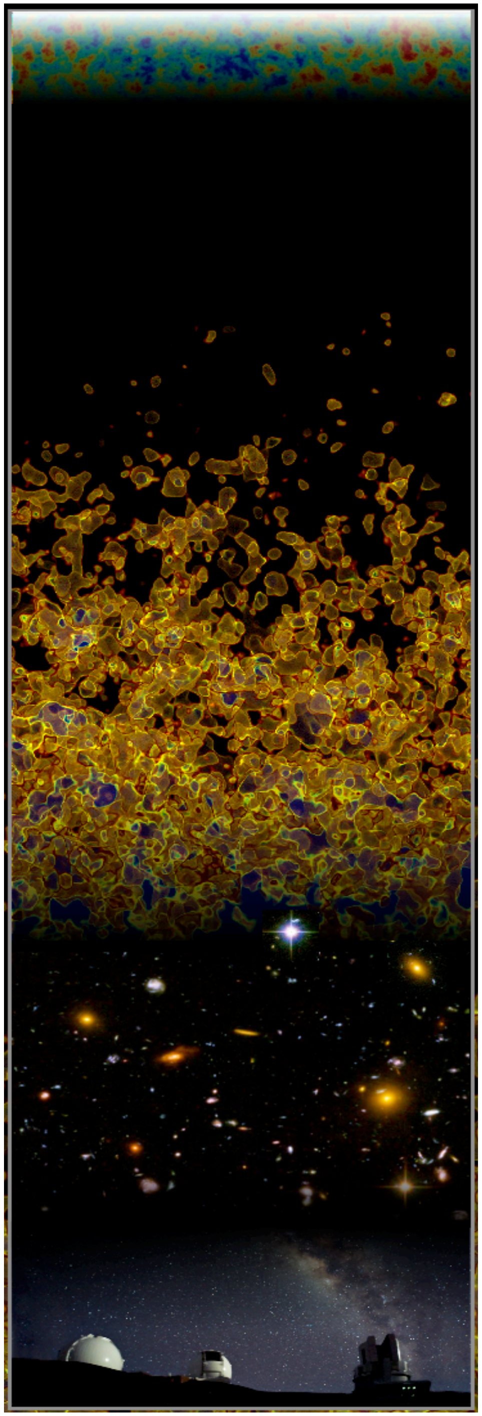
- Introduction
- Small Scale Structure and Reionization
- Lyman limit systems and the morphology of reionization
- Fluctuating 21cm background from reionization
- Summary

The Scales of Reionization

- Vast range of scales are important:
  - First H II regions have sizes order 150 comoving kpc
  - Toward end of reionization, H II regions grow and merge to typical sizes tens of Mpc
- Many approximations necessary



Furlanetto et al. (2007)



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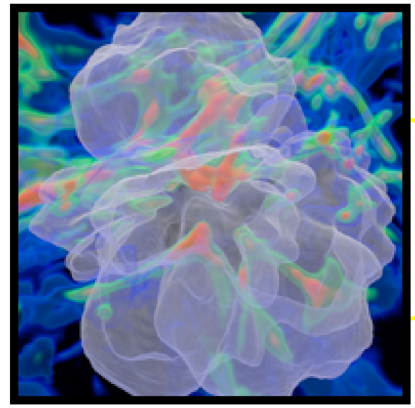
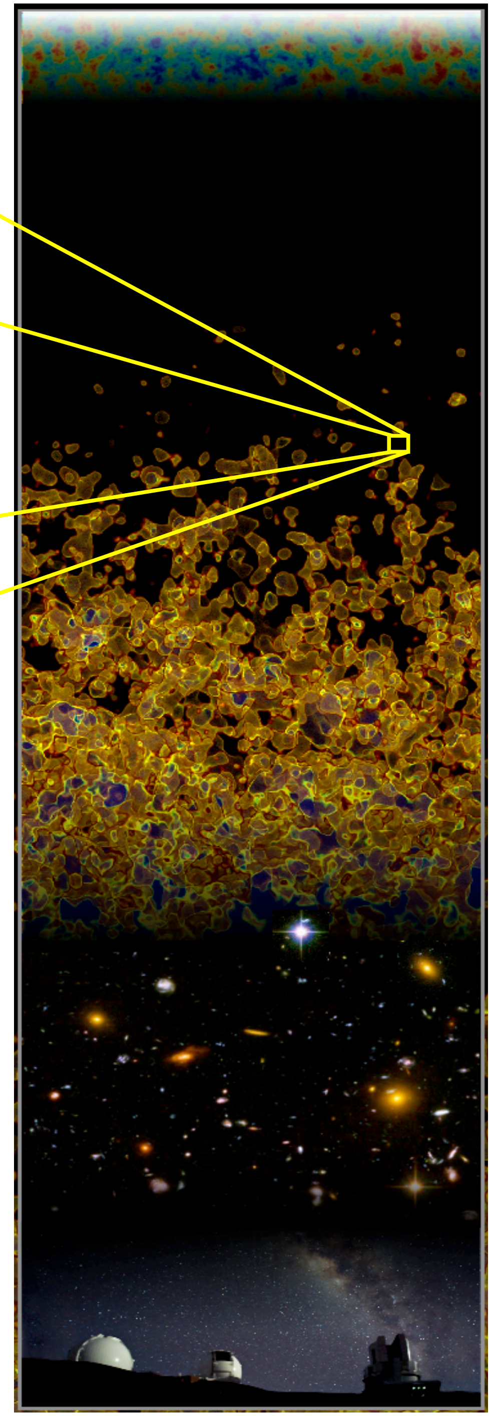
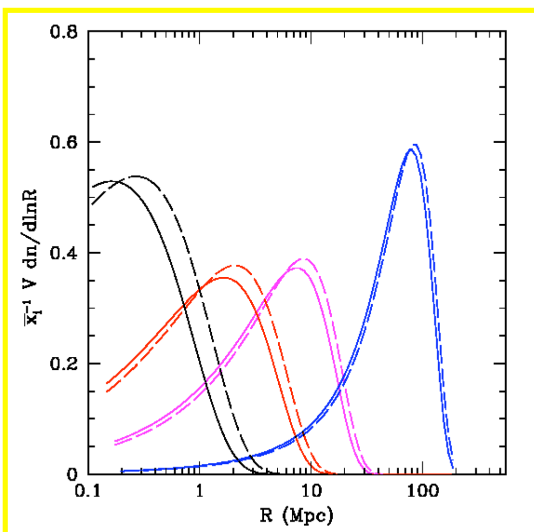


~150 kpc





Furlanetto et al. (2007)

~150 Mpc

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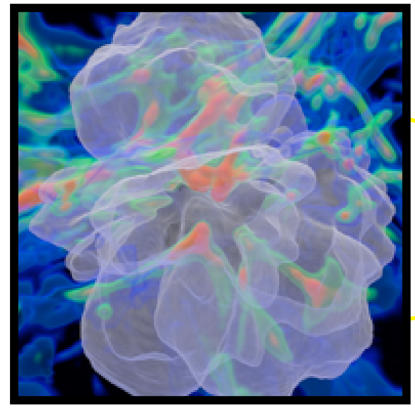
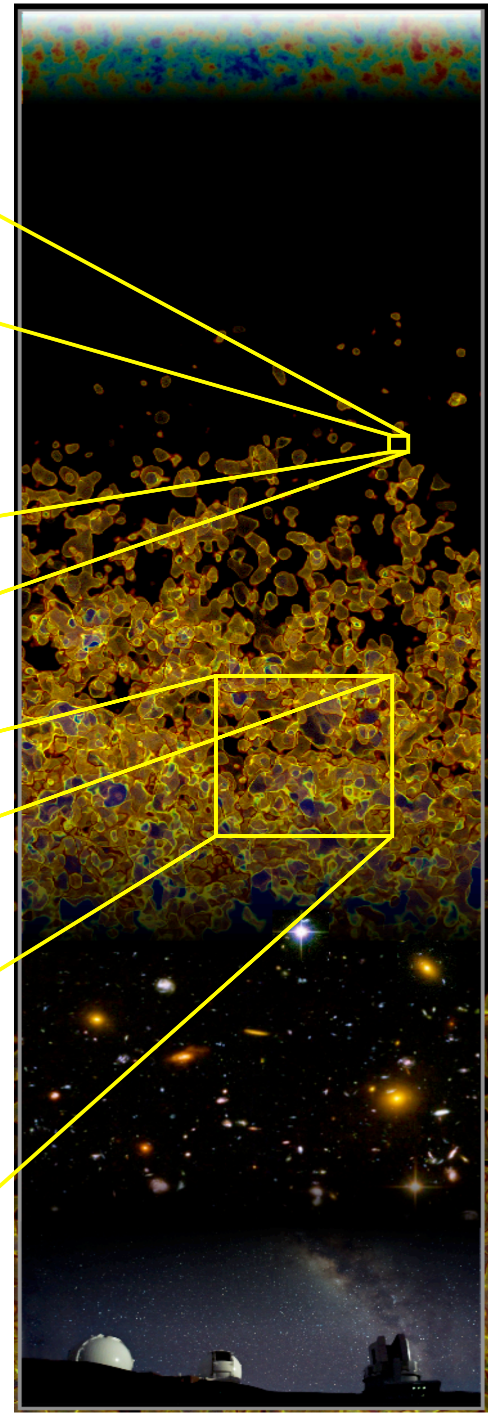
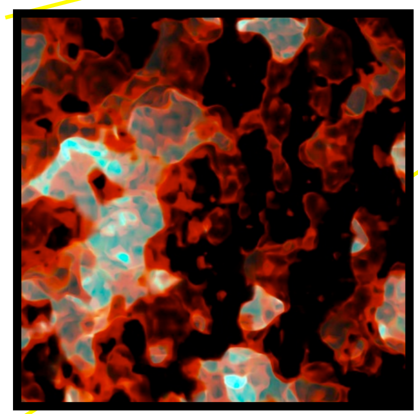
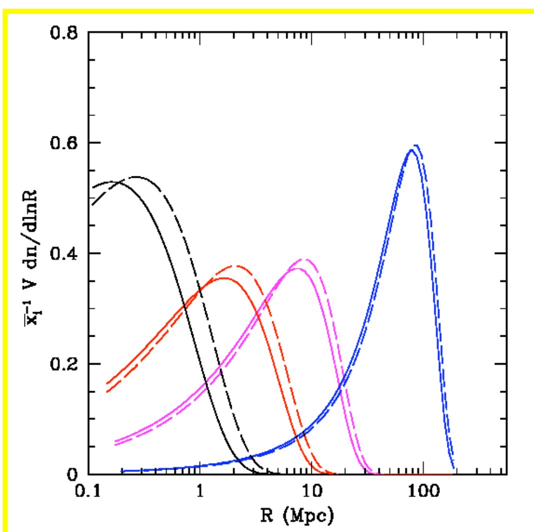


~150 kpc





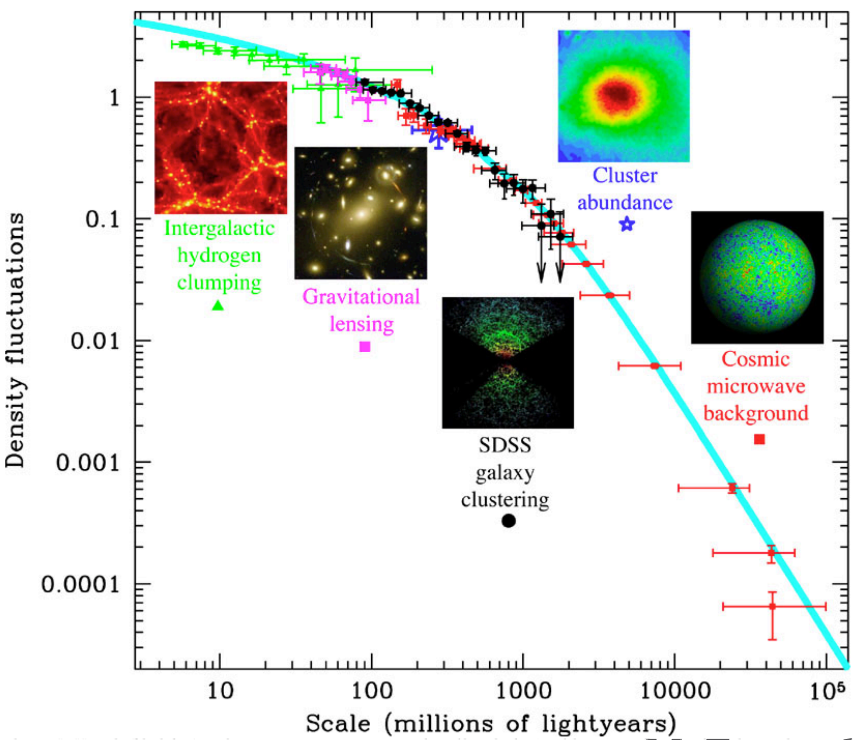
~150 Mpc



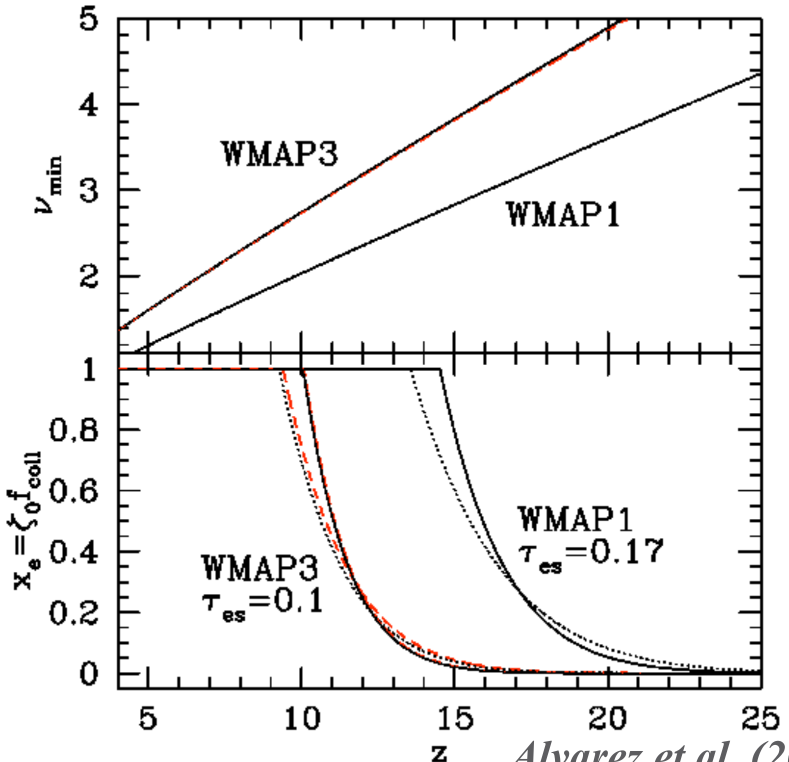
Furlanetto et al. (2007)

Caveats!

- P(k) unkown at small scales
  – Running of spectral index sensitive to inflaton potential
  – Cosmic strings at small scales
  – Non-Gaussianity can change abundance of rare objects
- “Exotic” physics
  – Dark stars or DM burners
  – Decaying DM
  – Magnetic fields
- And much more….



M. Tegmark



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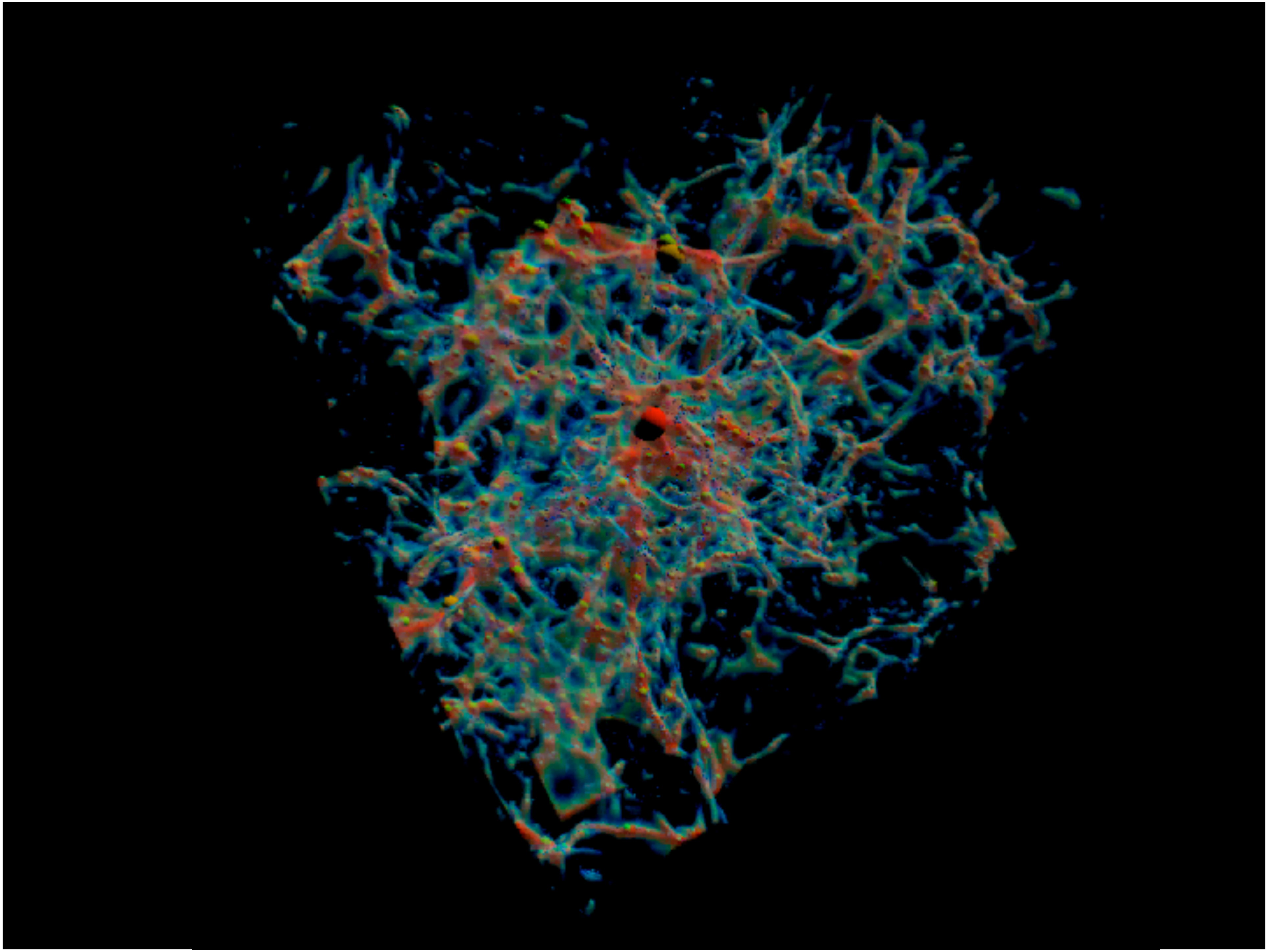
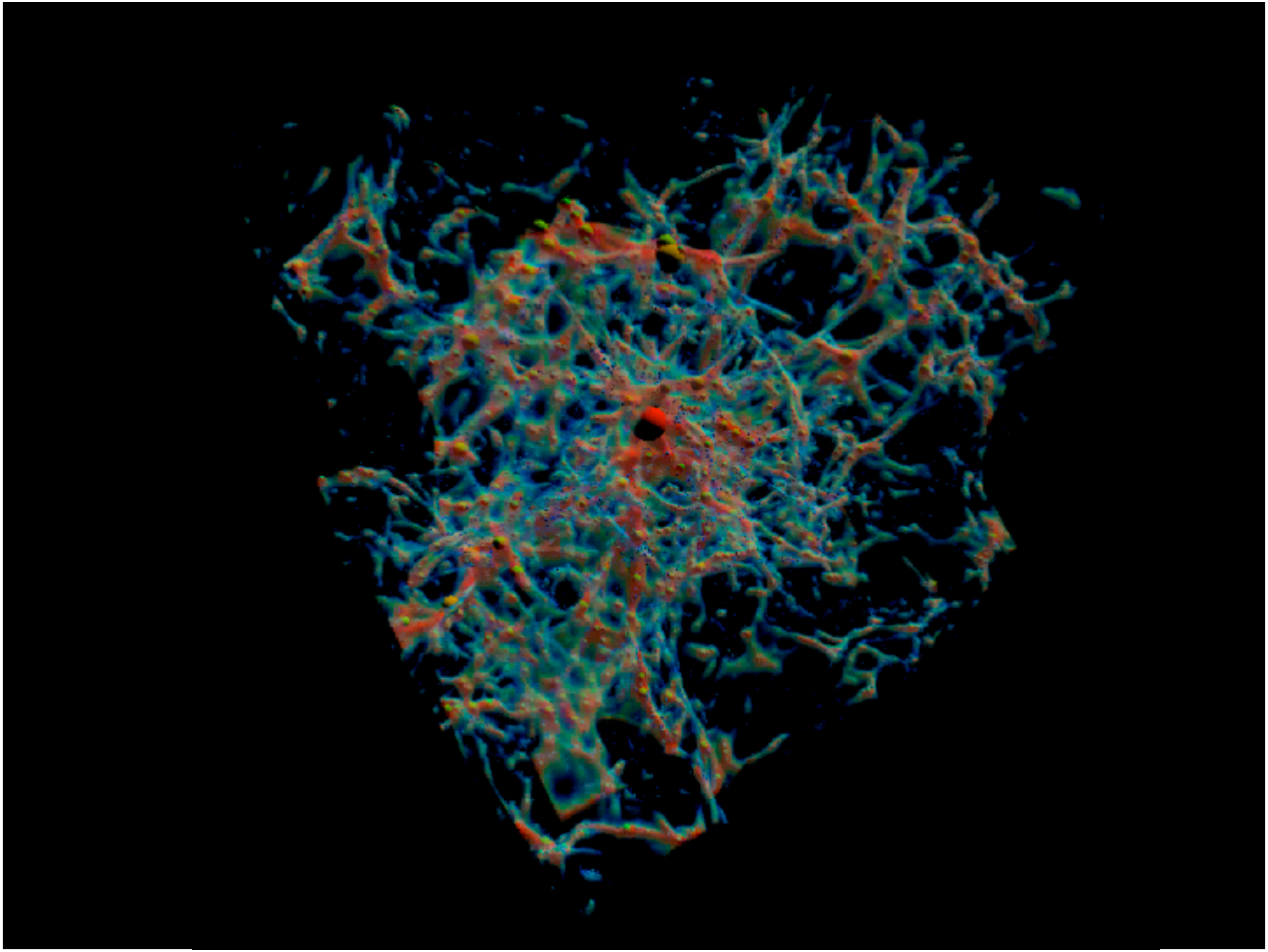
Small Scale Structure and Reionization

- First stars in "minihalos" probably polluted the gas before it fell into atomic cooling halos $T > 10^4$ K (Wise & Abel 2007)
- Atomic cooling halos could have formed many stars that began the end of reionization
- Minihalos that surrounded these protogalaxies would be subject to strong radiative feedback from photoionization heating

The ubiquitous minihalos

- Minihalos that were sterilized (e.g. Haiman, Abel, Rees 1999) by dissociating UV background would be subject to photoevaporation
- This photoevaporation process permanently robs halos of cold gas before they can reach atomic cooling limit
- If these were the progenitors of Milky Way satellite halos, they would be highly dark matter dominated
- Minihalos are prime candidates for “Lyman limit systems” (LLS)





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Lyman Limit Systems and the Structure of Reionization

- At end of reionization, mean free path determined by Lyman limit systems (LLS)
- According to Storrie-Lombardi et al. (1994), comoving abundance is:

  $$dN/dz \sim 3.27[(1+z)/5]^{1.6}$$

  implying a comoving mean free path:

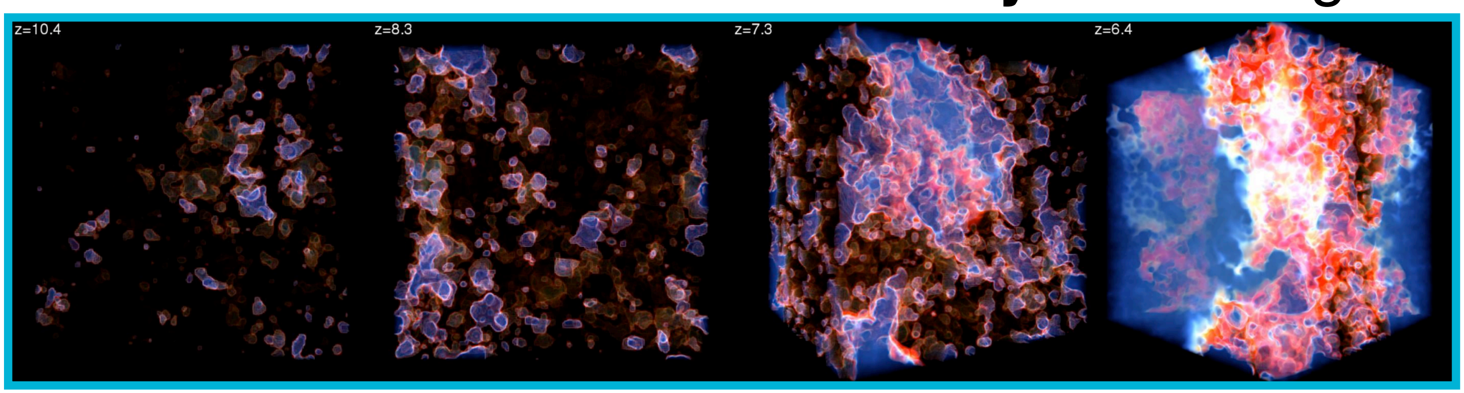
  $$R_{lls}(z) \sim 120 \text{ Mpc } [(1+z)/5]^{-3.1}$$

  $$R_{lls}(z=9,8,7,6) \sim (14, 20, 30, 40) \text{ Mpc}$$

- But these values are
  - An extrapolation beyond $z=4$
  - Subject to significant uncertainty even at $z<4$

3D reionization calculations

- Zahn et al. (2006) developed a technique for producing 3D evolving ionization field without doing radiative transfer (see also Mesinger & Furlanetto 2007 for extensions)
- 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



Modeling effect of Lyman limit systems on reionization in 3D

- Given the substantial uncertainties, we take a simplified approach:
  - Assume LLS mean free path is constant (in comoving coordinates) and spatially uniform during reionization

  and

  - Include effect of LLS in the calculations by only smoothing over scales less than the mean free path

Modeling effect of Lyman limit systems on reionization in 3D

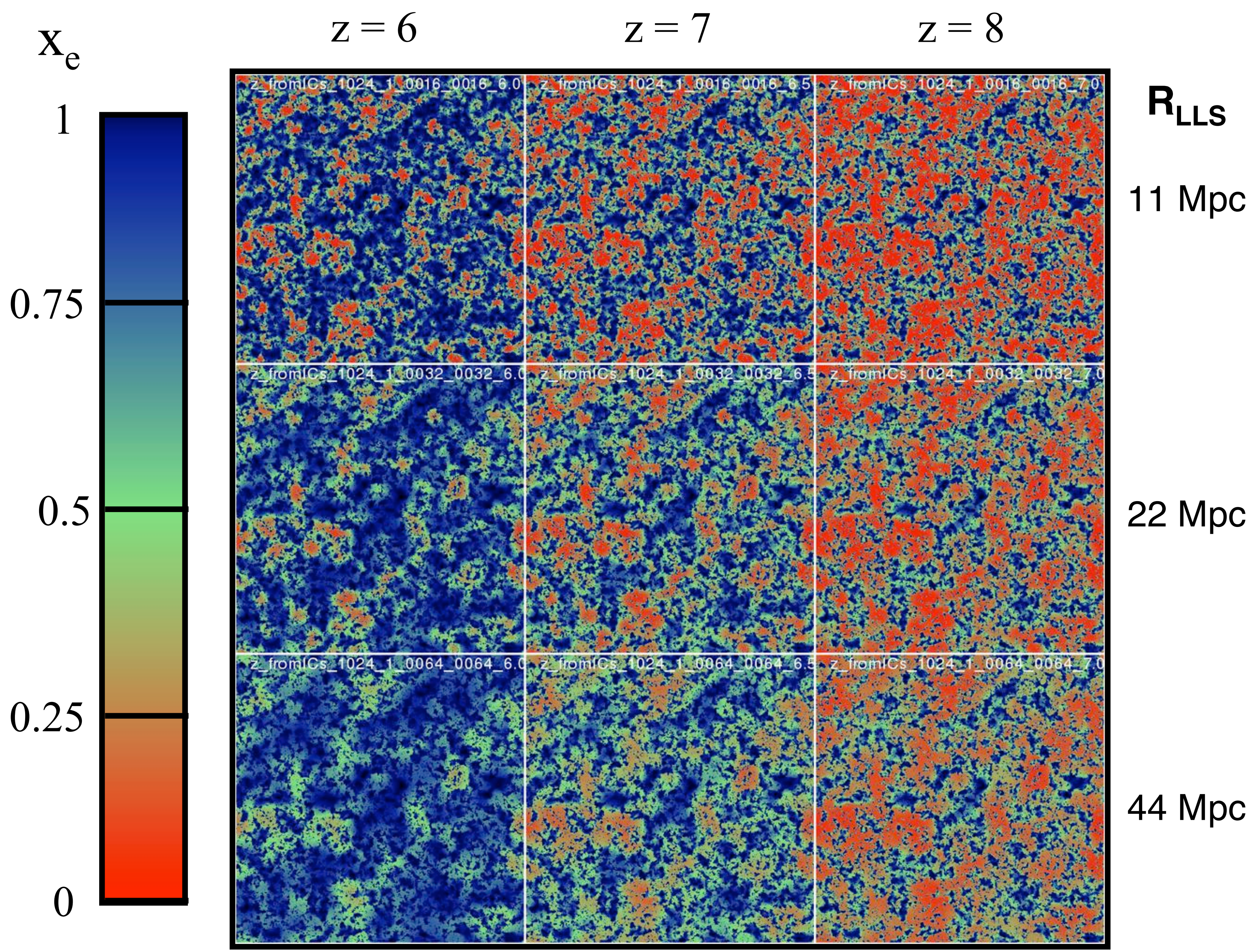
- Box sizes (resolutions):
  - 0.5 Gpc/h (1024^3), 1 Gpc/h (2048^3), 1.5 Gpc/h (3072^3)
- Ran 4 different cases with mean free paths

  R_{LLS}= 8 Mpc/h ~ 11 Mpc

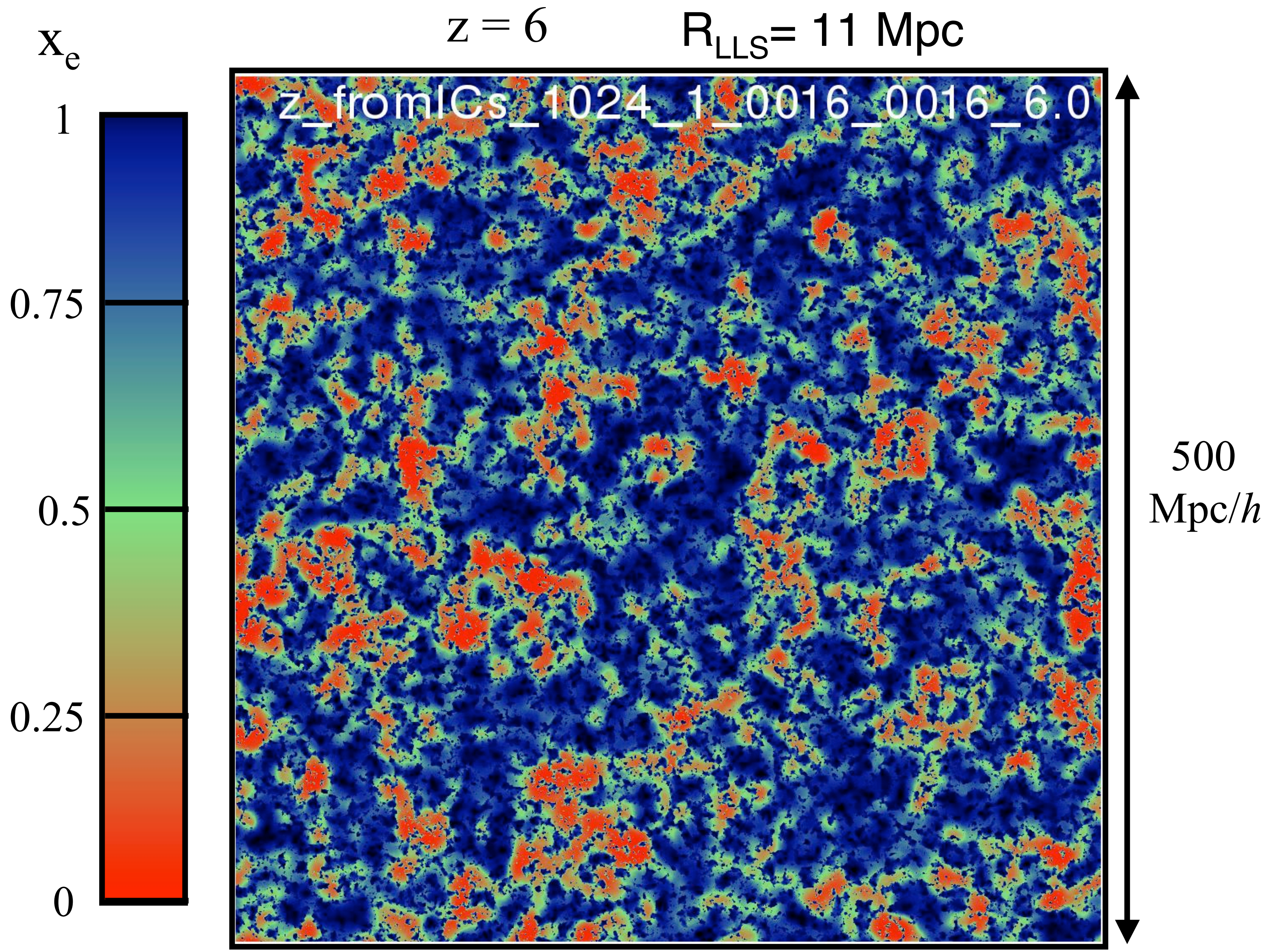
  R_{LLS}= 16 Mpc/h ~ 22 Mpc

  R_{LLS}= 32 Mpc/h ~ 44 Mpc

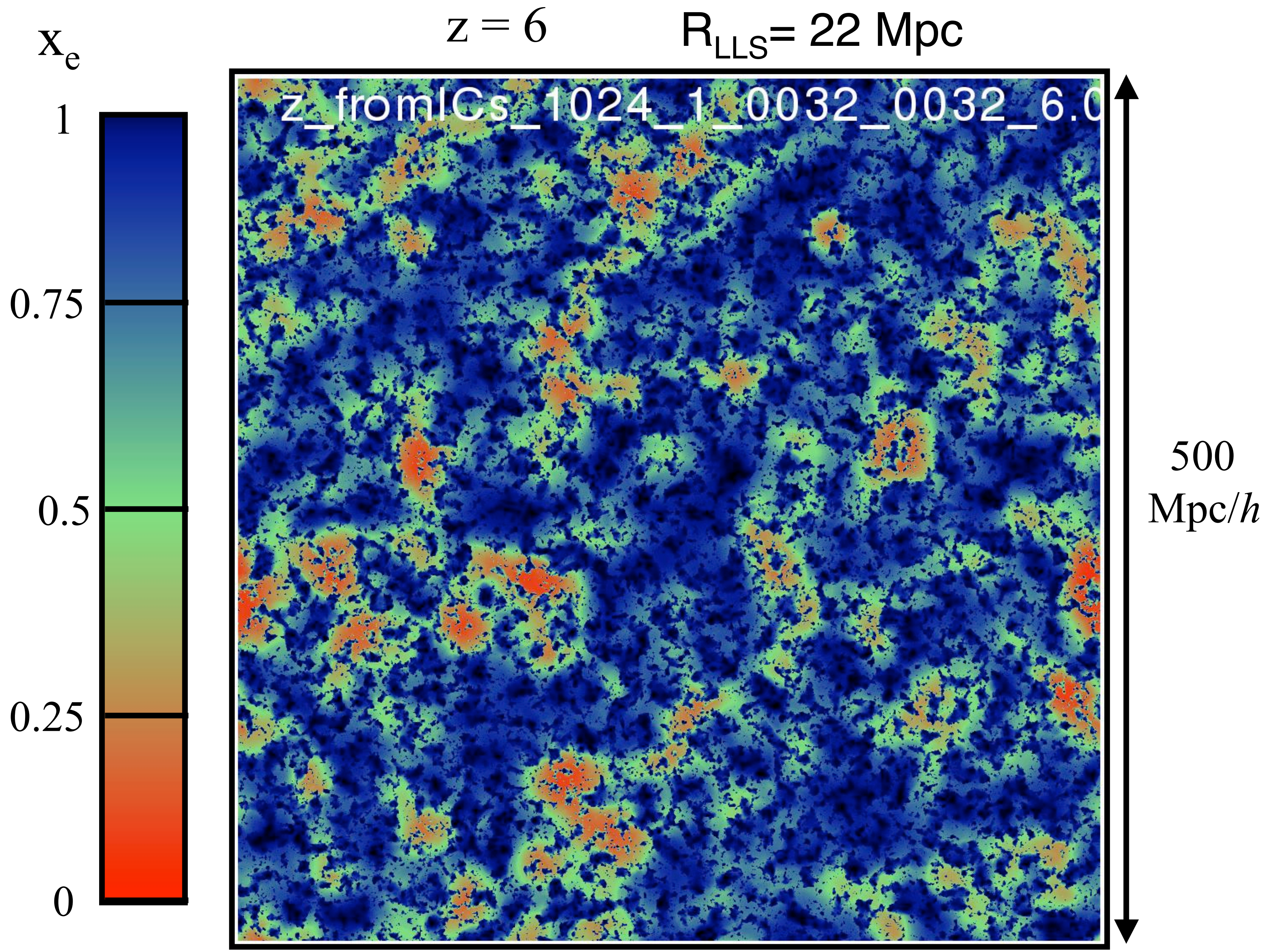
  R_{LLS}= 64 Mpc/h ~ 88 Mpc



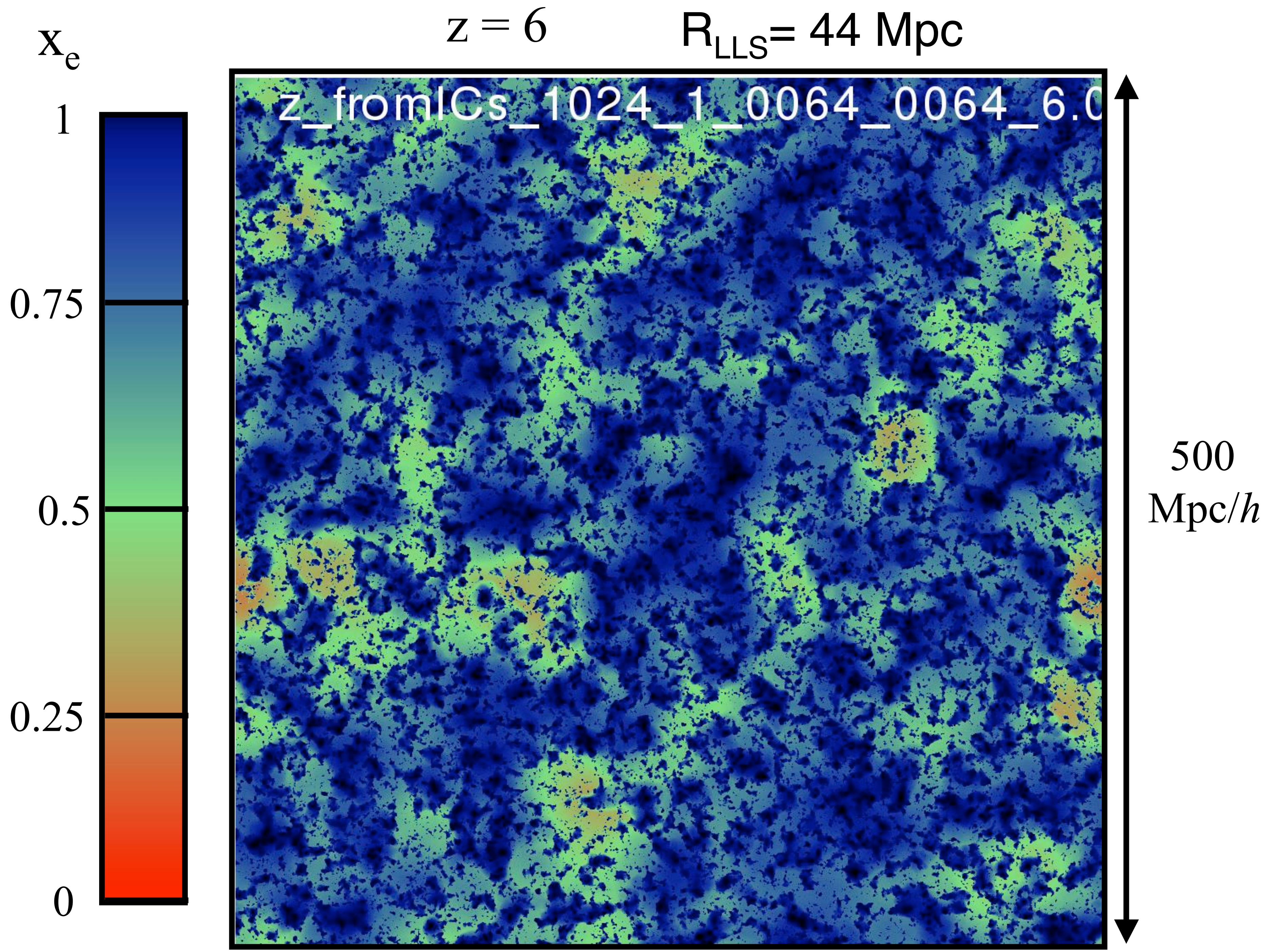
x_e
1
0.75
0.5
0.25
0
z = 6
z = 7
z = 8
R_LLS
11 Mpc
22 Mpc
44 Mpc
z_fromICs_1024_1_0016_0016_6.0
z_fromICs_1024_1_0016_0016_6.5
z_fromICs_1024_1_0016_0016_7.0
z_fromICs_1024_1_0032_0032_6.0
z_fromICs_1024_1_0032_0032_6.5
z_fromICs_1024_1_0032_0032_7.0
z_fromICs_1024_1_0064_0064_6.0
z_fromICs_1024_1_0064_0064_6.5
z_fromICs_1024_1_0064_0064_7.0



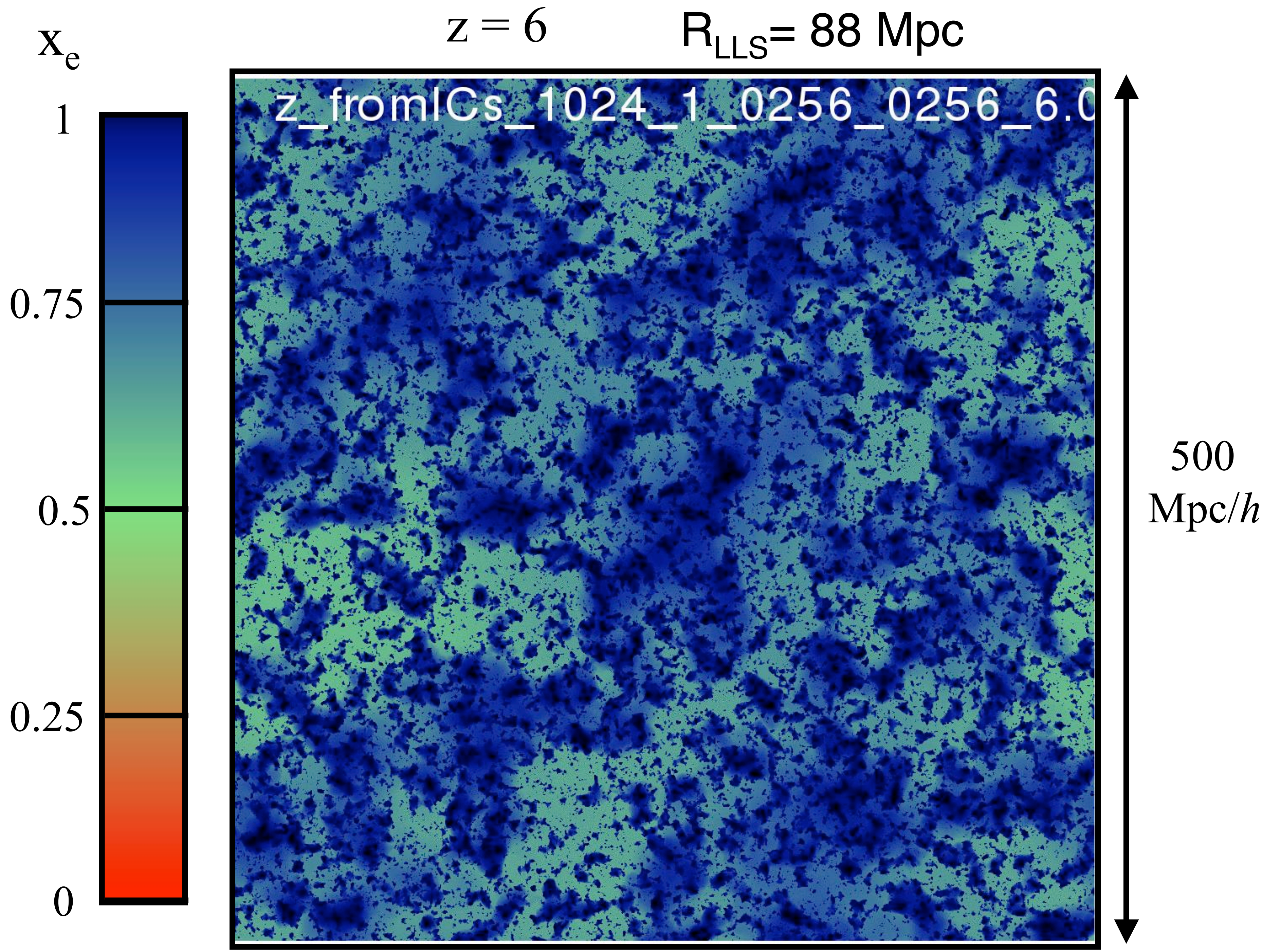
z = 6
R_LLS= 11 Mpc
x_e
1
0.75
0.5
0.25
0
z_fromICs_1024_1_0016_0016_6.0
500
Mpc/h

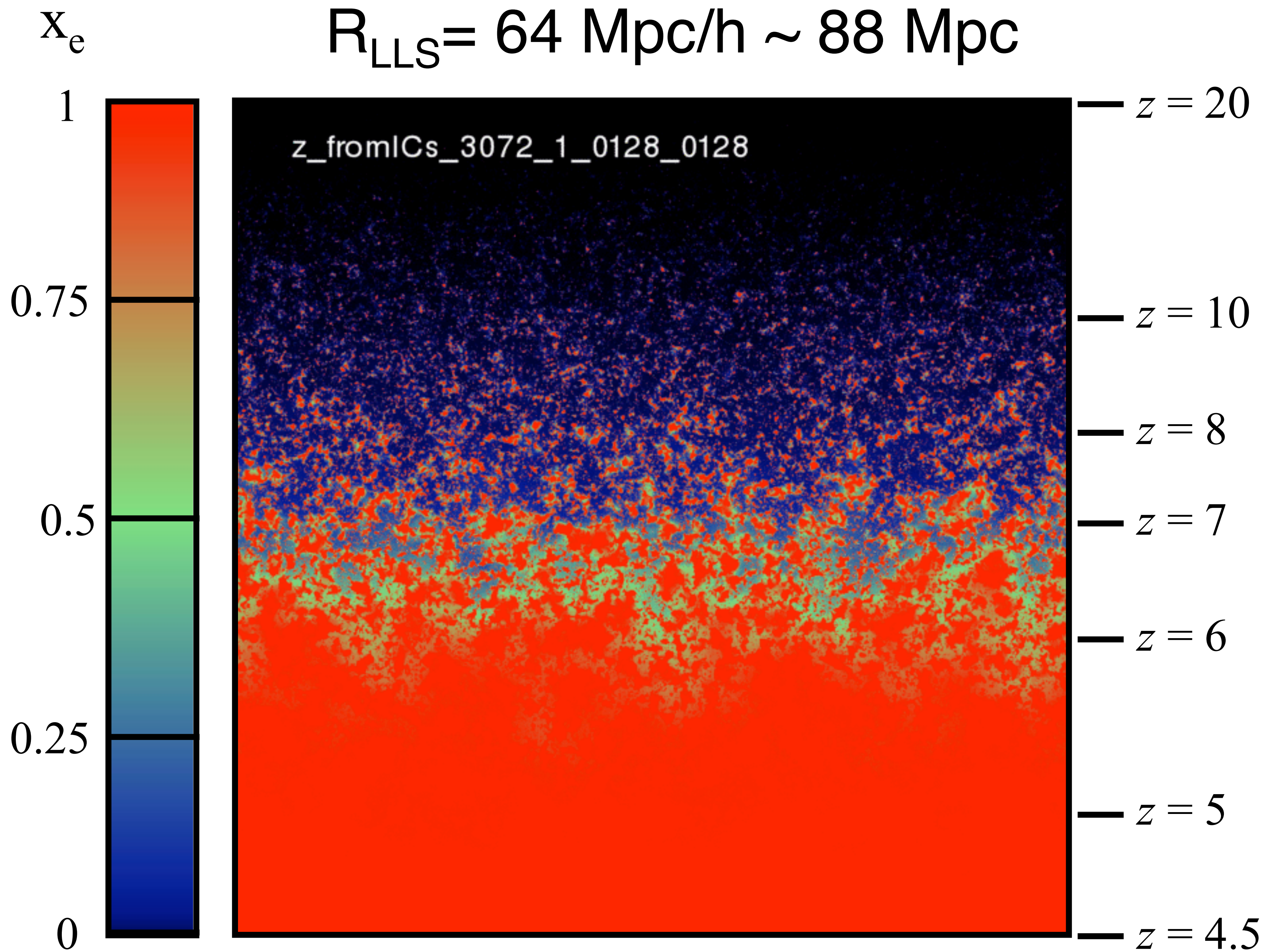


x_e
1
0.75
0.5
0.25
0
z = 6
R_LLS= 22 Mpc
z_fromICs_1024_1_0032_0032_6.0
500
Mpc/h

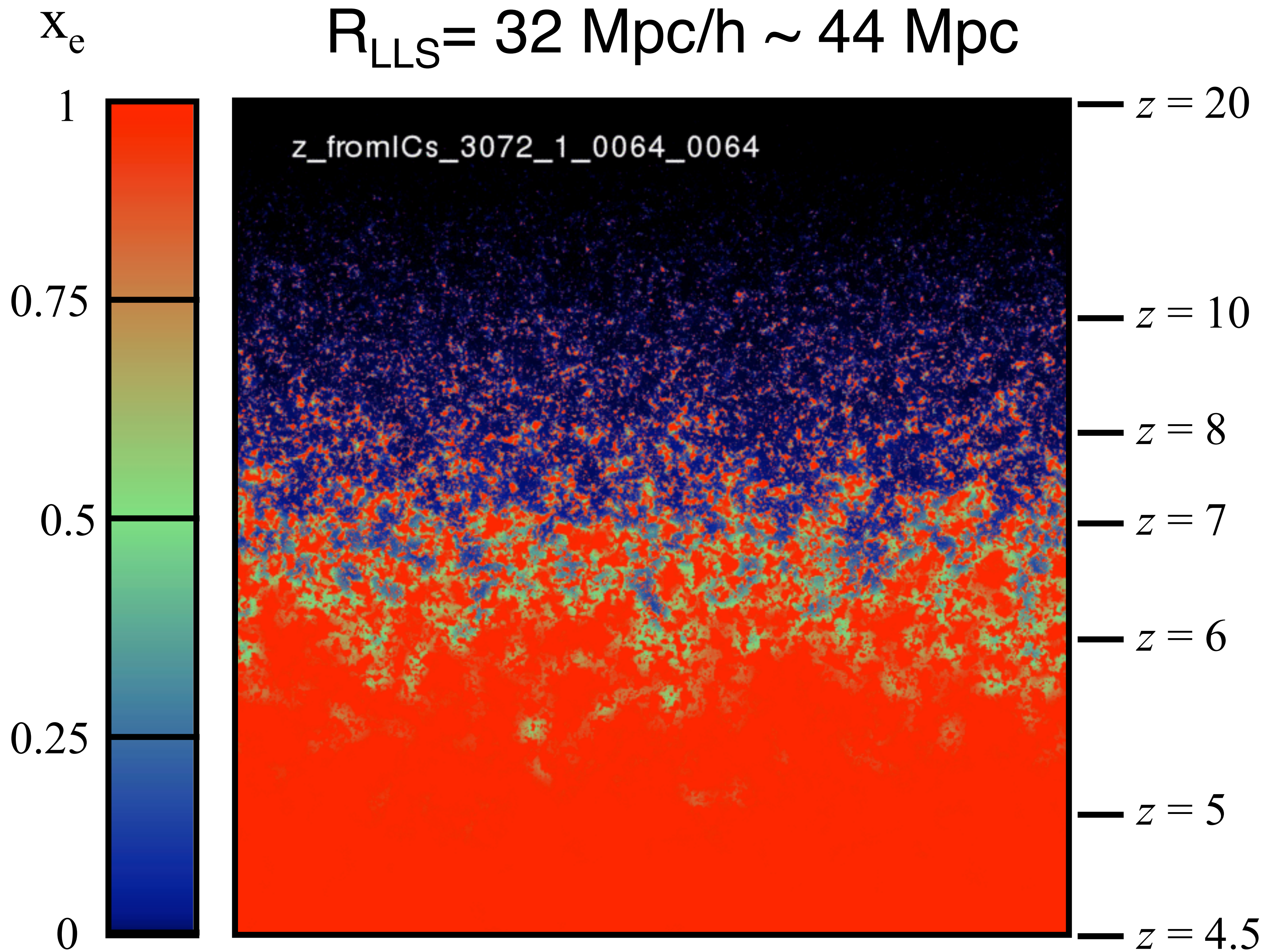


z = 6
R_LLS= 44 Mpc
x_e
1
0.75
0.5
0.25
0
z_fromICs_1024_1_0064_0064_6.0
500
Mpc/h

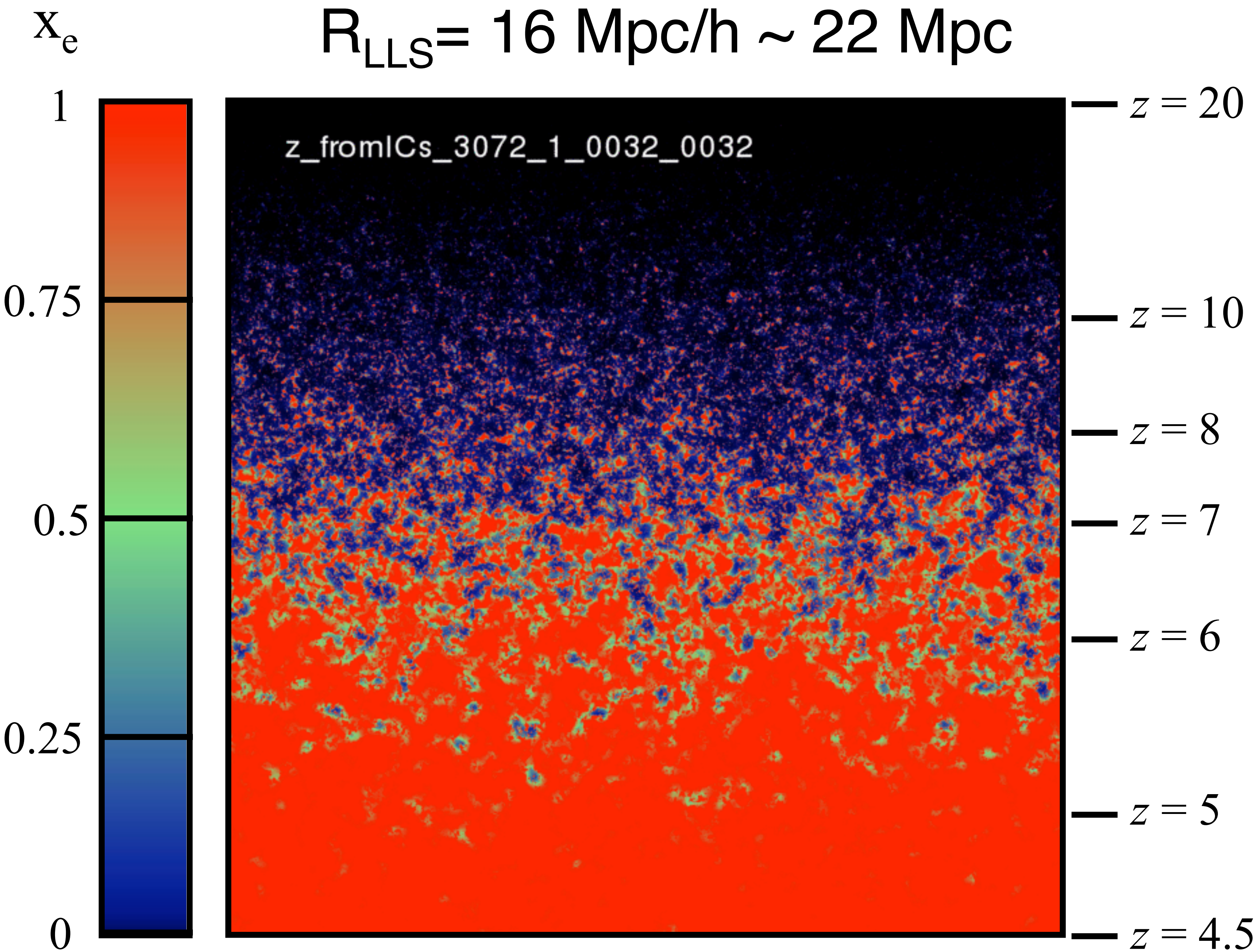

z = 6
R_LLS= 88 Mpc
x_e
1
0.75
0.5
0.25
0
z_fromICs_1024_1_0256_0256_6.0
500 Mpc/h

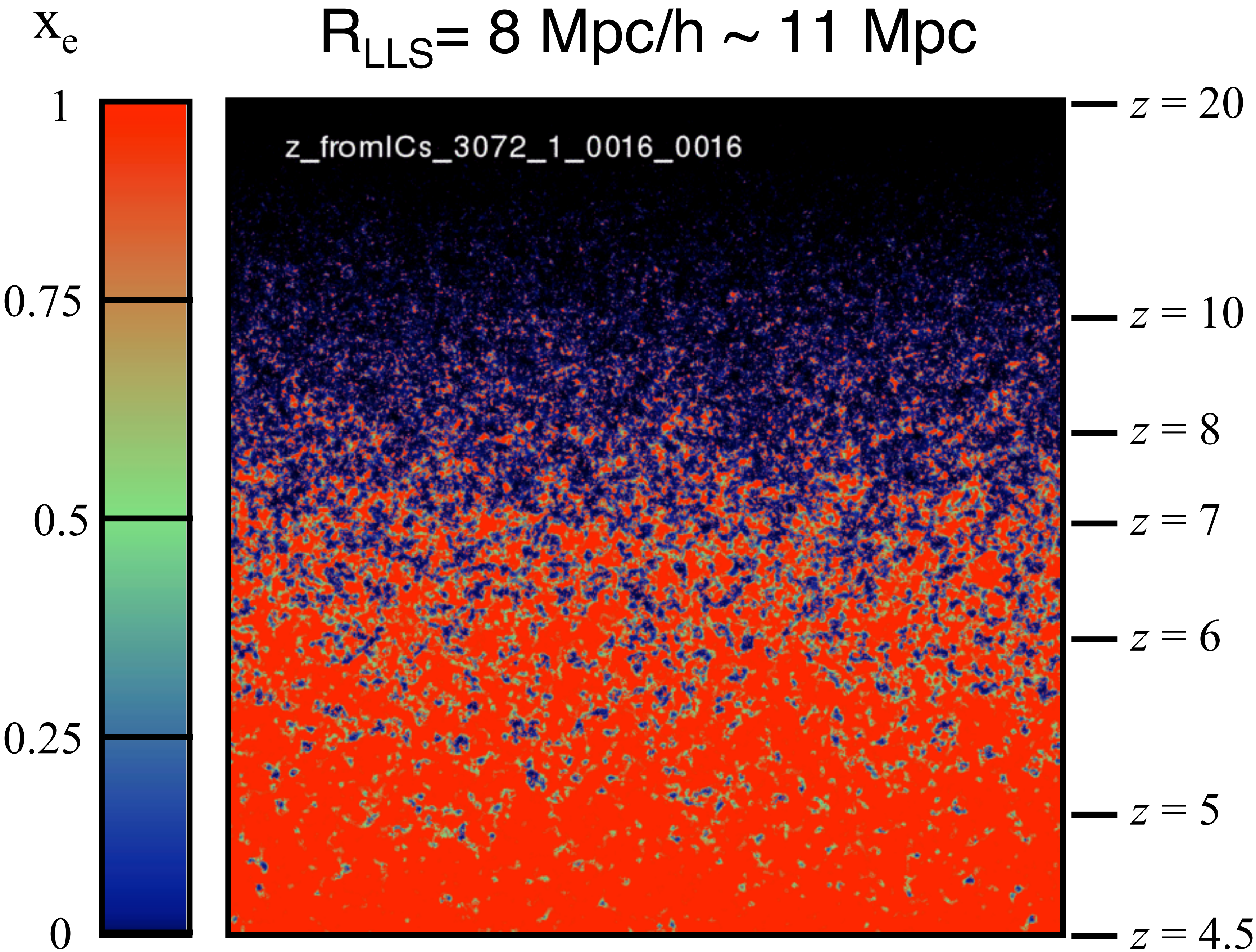


x_e
R_LLS= 64 Mpc/h ~ 88 Mpc
1
0.75
0.5
0.25
0
z_fromICs_3072_1_0128_0128
z = 20
z = 10
z = 8
z = 7
z = 6
z = 5
z = 4.5



x_e
R_{LLS}= 32 Mpc/h ~ 44 Mpc
1
0.75
0.5
0.25
0
z_fromICs_3072_1_0064_0064
$z = 20$
$z = 10$
$z = 8$
$z = 7$
$z = 6$
$z = 5$
$z = 4.5$


R_{LLS}= 16 Mpc/h ~ 22 Mpc
x_e
1
0.75
0.5
0.25
0
z_fromICs_3072_1_0032_0032
$z = 20$
$z = 10$
$z = 8$
$z = 7$
$z = 6$
$z = 5$
$z = 4.5$



x_e
R_{LLS}= 8 Mpc/h ~ 11 Mpc
1
0.75
0.5
0.25
0
z_fromICs_3072_1_0016_0016
$z = 20$
$z = 10$
$z = 8$
$z = 7$
$z = 6$
$z = 5$
$z = 4.5$

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Modeling 21cm fluctuations with 3D reionization calculations

- We use our reionization calculations to predict the power spectrum of 21cm fluctuations
- Limit of $T_S \gg T_{CMB}$ so fluctuations in brightness temperature proportional to HI fluctuations

$$T_0(z) \simeq 23 \text{ mK} \left(\frac{\Omega_b h^2}{0.02}\right) \left[\left(\frac{0.15}{\Omega_m h^2}\right) \left(\frac{1+z}{10}\right)\right]^{1/2}$$

- We focus on effect of Lyman limit systems on ***evolution*** of amplitude and ***shape*** of power spectrum of fluctuations (see e.g. Lidz et al. 2008)

Modeling 21cm fluctuations with 3D reionization calculations

- Box size is 500 Mpc/h
- 1024^3 uniform grid
- Results presented for 3 mean free paths with ionizing efficiency = 30 and $M_{min}=10^8$ M_{sun}

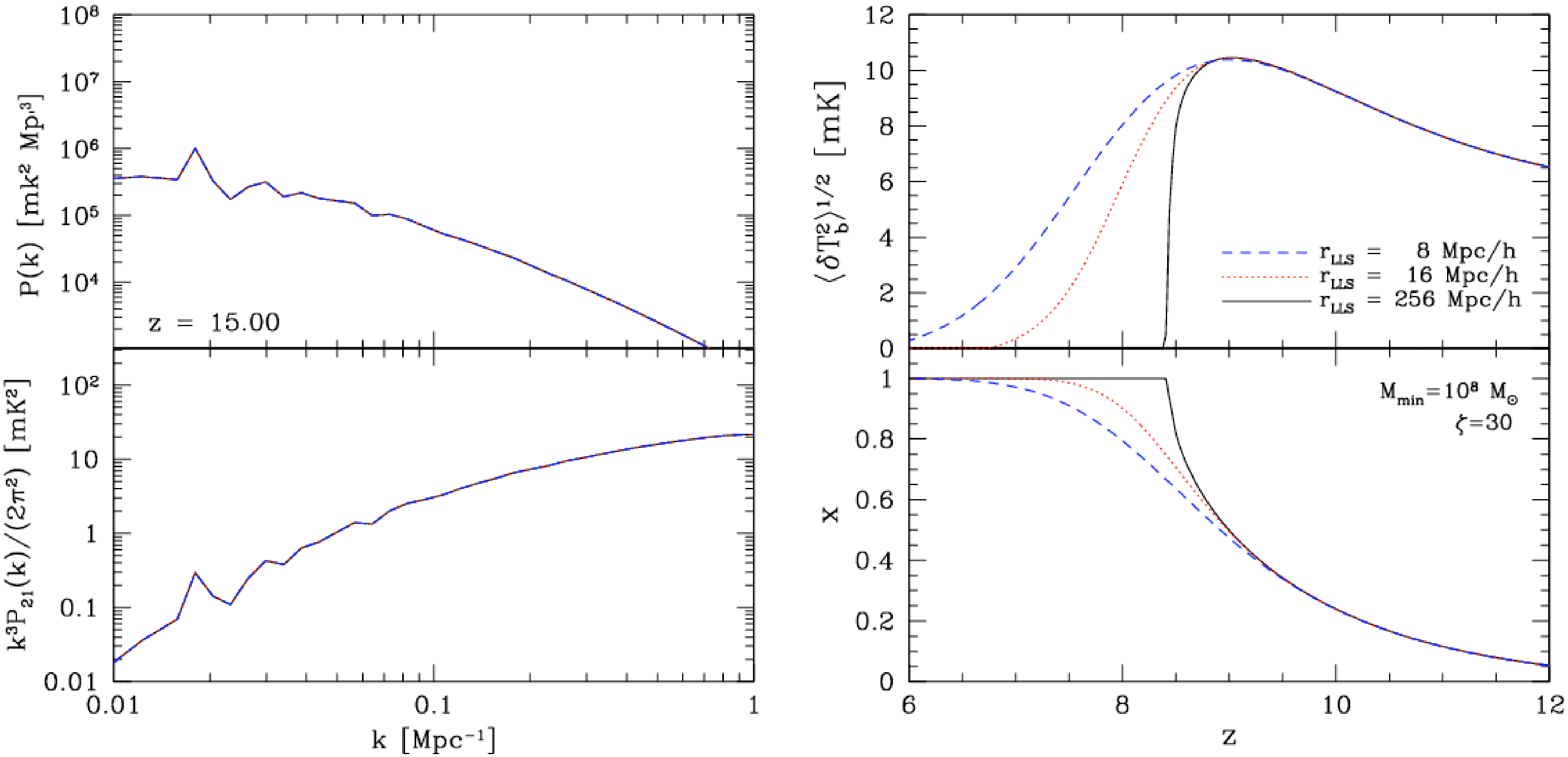
  R_{LLS}= 8 Mpc/h ~ 11 Mpc

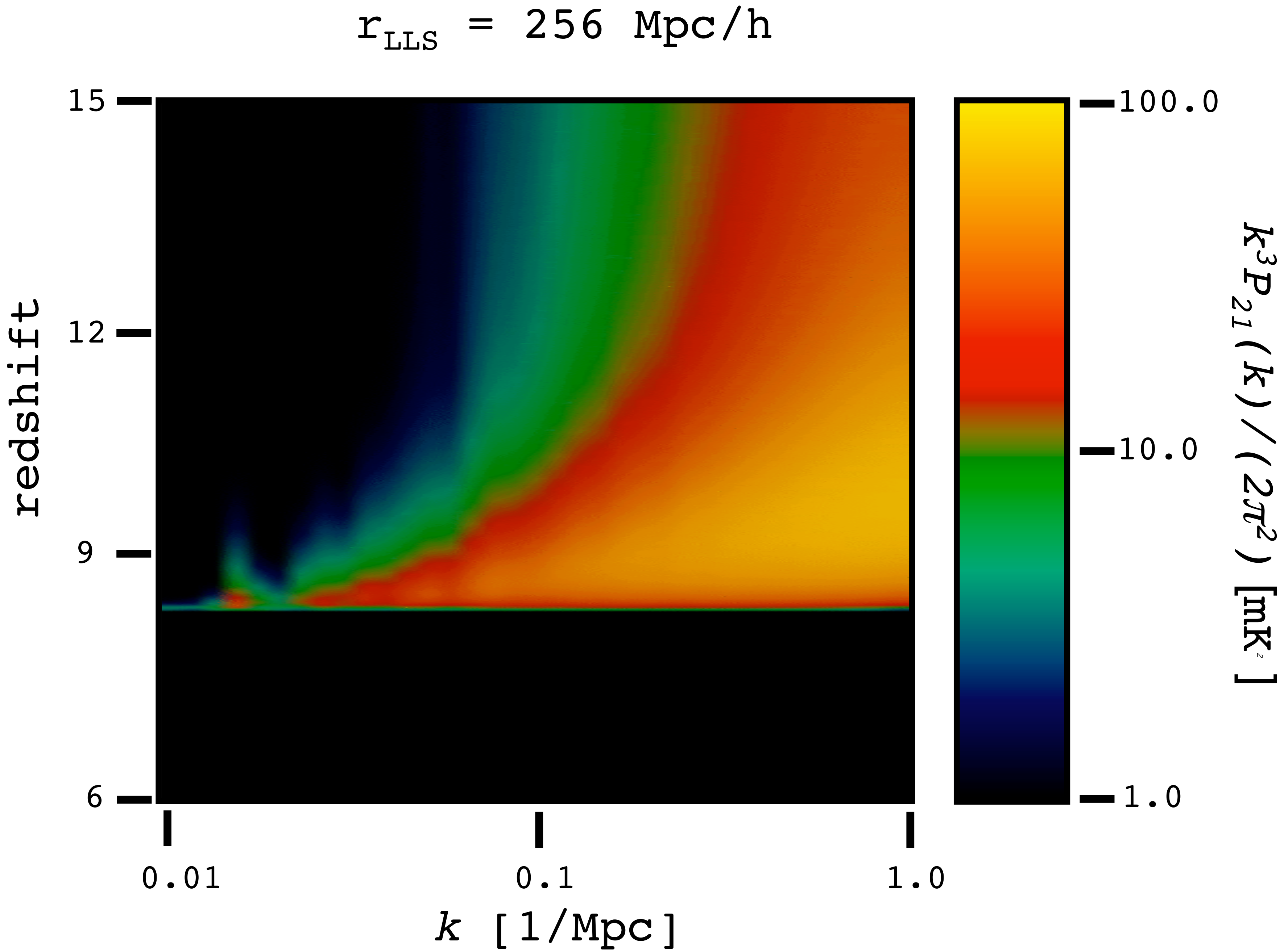
  R_{LLS}= 16 Mpc/h ~ 22 Mpc

  R_{LLS}= 32 Mpc/h ~ 44 Mpc

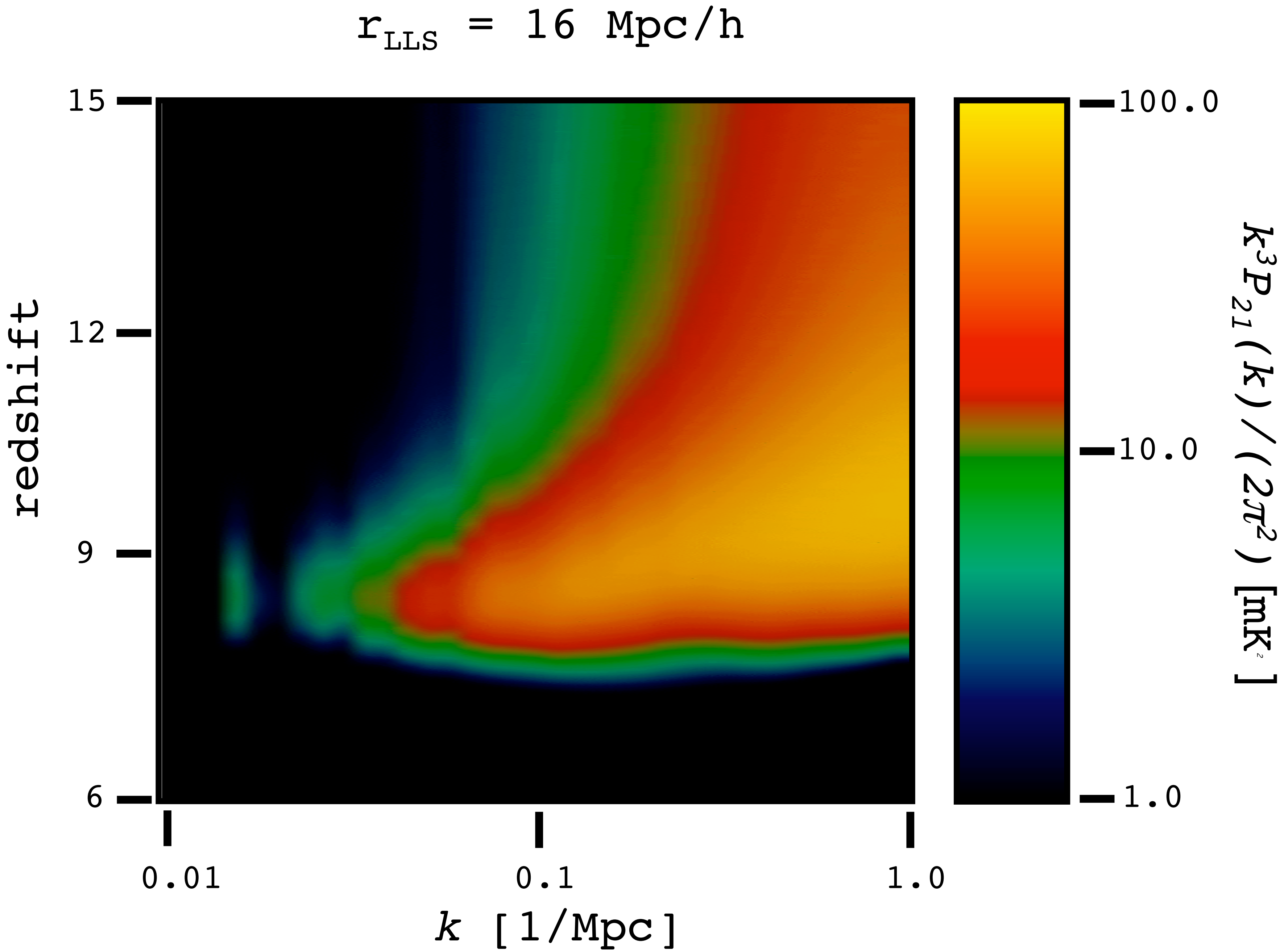
  R_{LLS}= 256 Mpc/h ~ 88 Mpc

Lyman limit systems **increase** the 21cm signal at late times

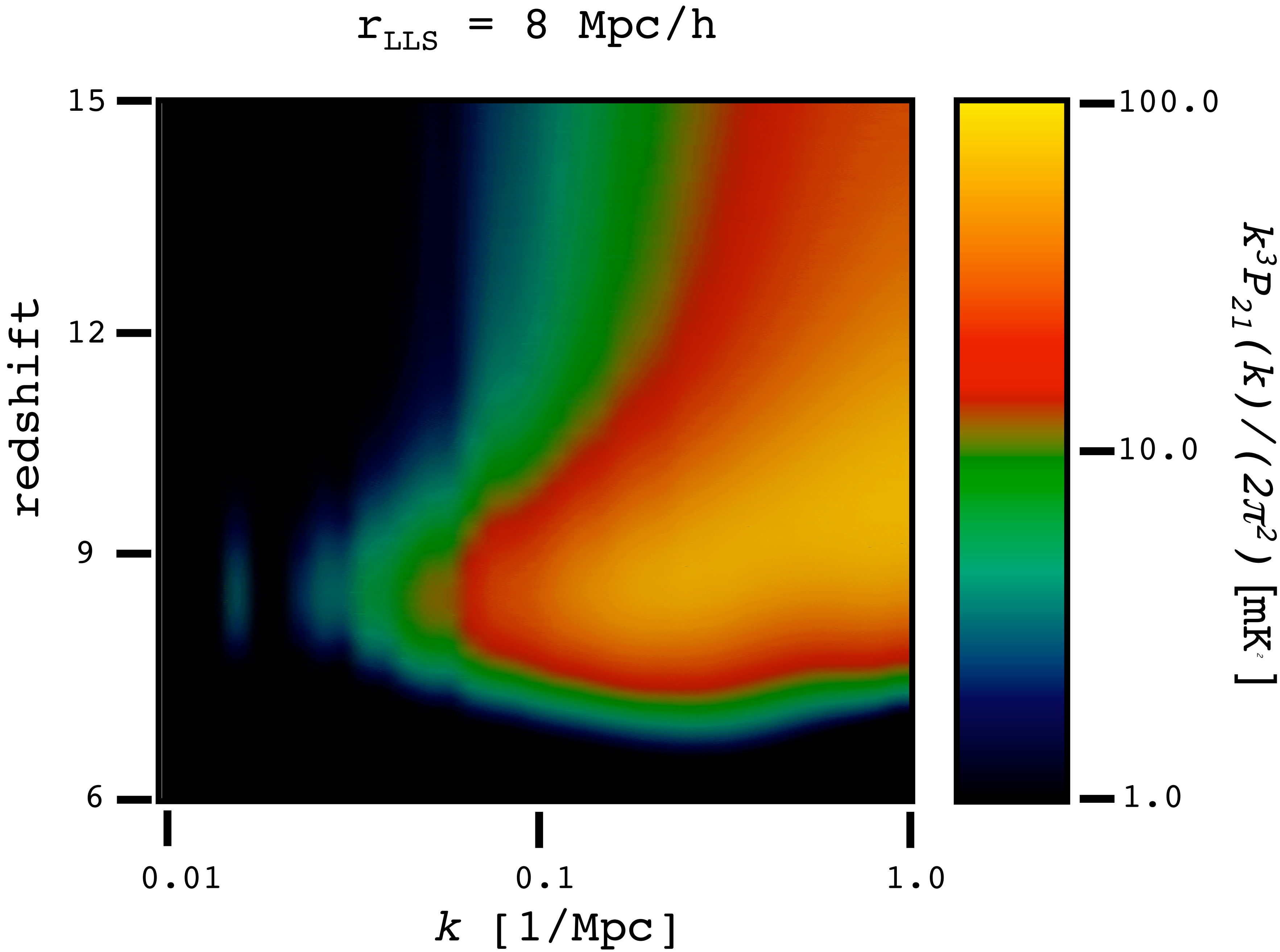




r_{LLS} = 256 Mpc/h
redshift
15
12
9
6
0.01
0.1
1.0
k [1/Mpc]
100.0
10.0
1.0
$k^3P_{21}(k)/(2\pi^2)$ [mK^2]

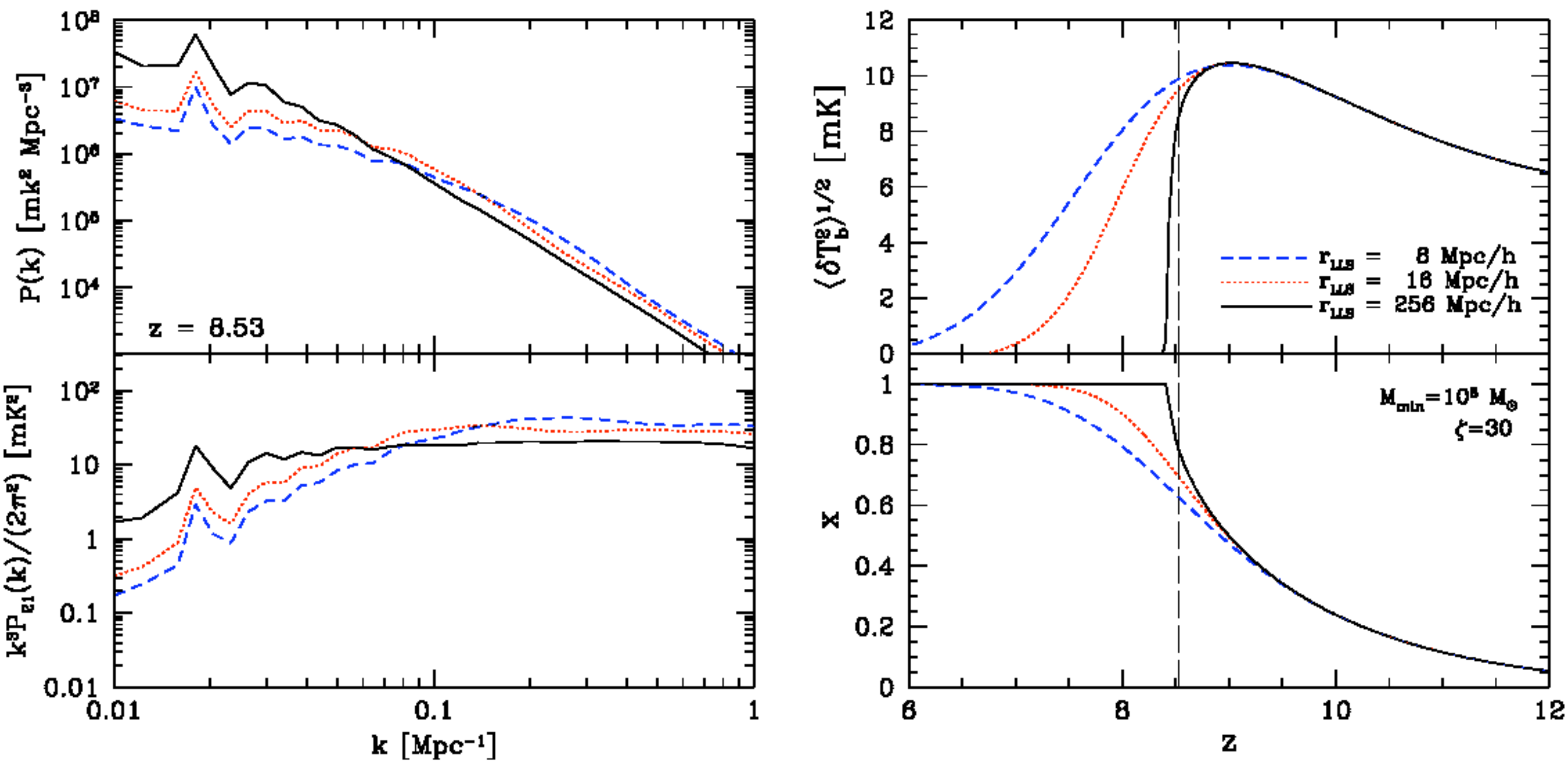


r_{LLS} = 16 Mpc/h
15
12
9
6
redshift
0.01
0.1
1.0
k [1/Mpc]
100.0
10.0
1.0
$k^3P_{21}(k)/(2\pi^2)$ [mK^2]



r_LLS = 8 Mpc/h
15
12
9
6
redshift
0.01
0.1
1.0
k [1/Mpc]
100.0
10.0
1.0
k^3 P_21(k)/(2π^2) [mK^2]

What does and doesn't depend on Lyman limit system abundance?



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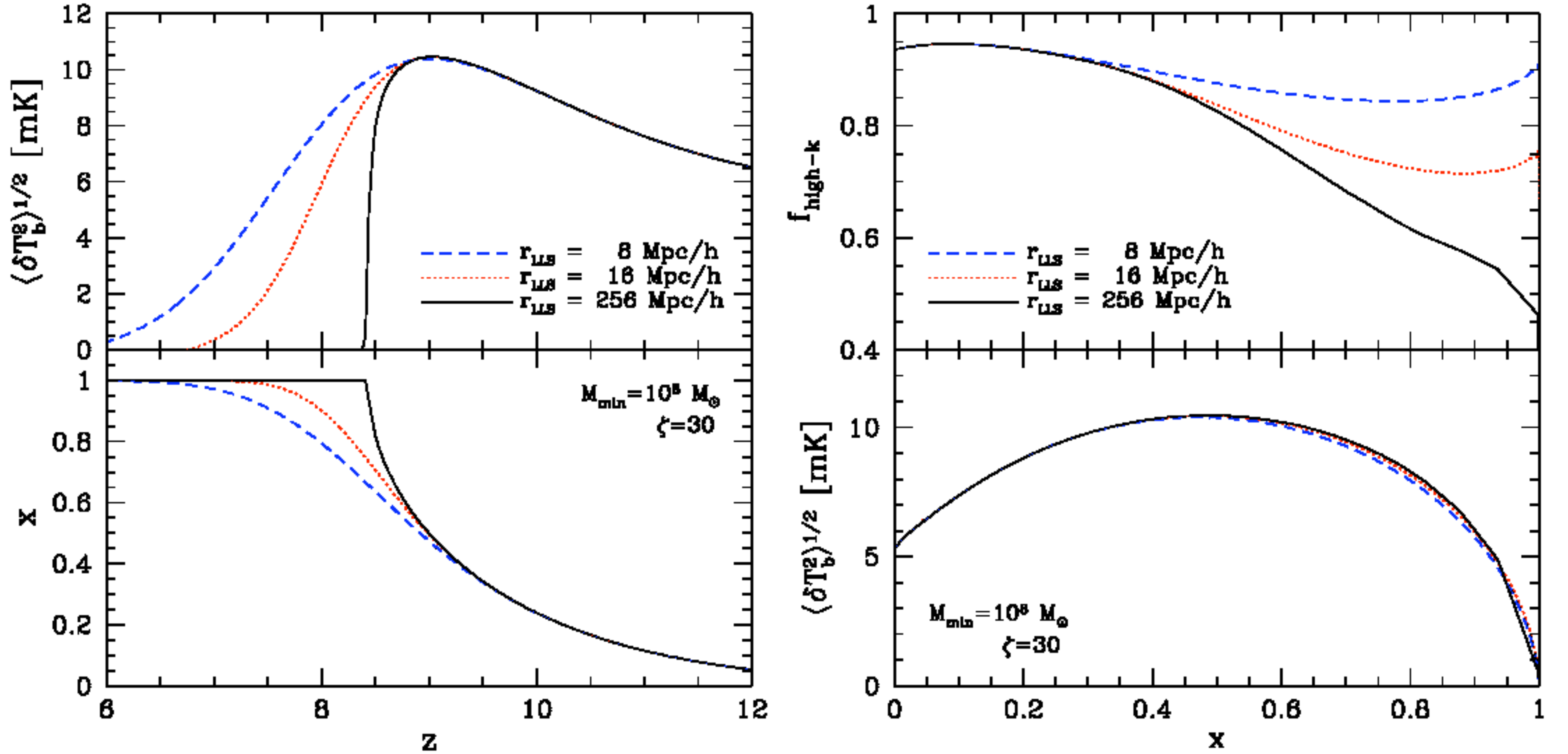
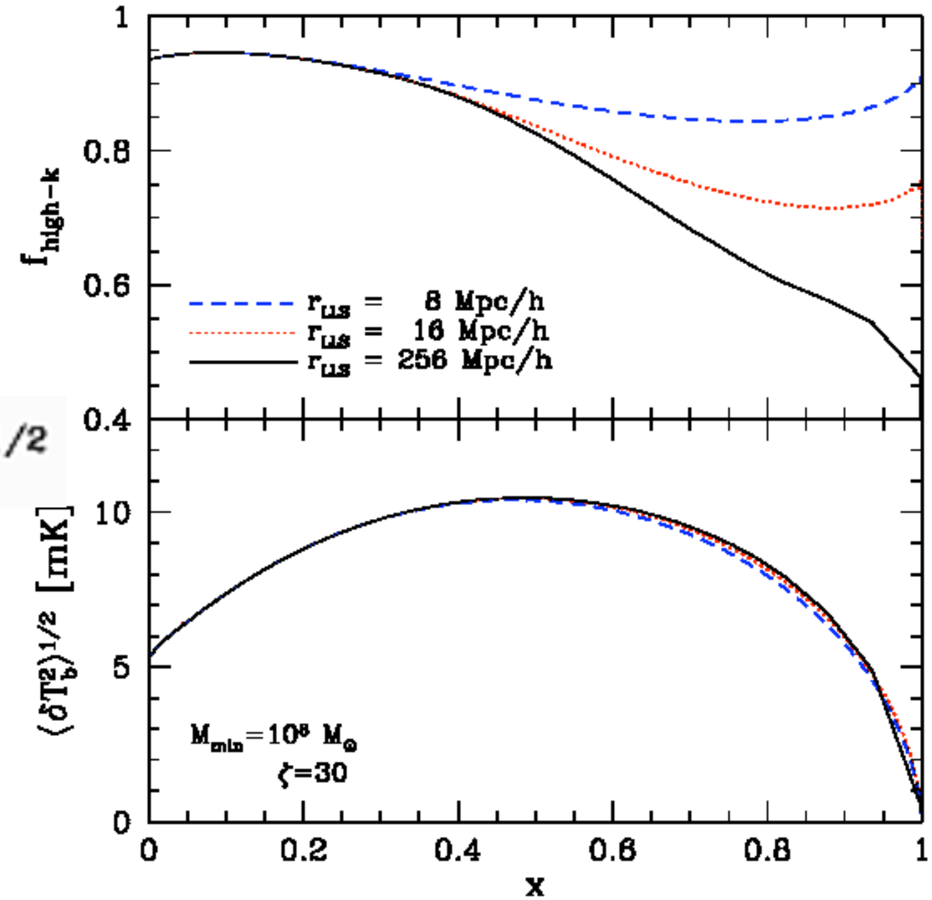


What does and doesn't depend on Lyman limit system abundance?

- Evolution of total power vs. **mean ionized fraction** is invariant
- This is because 21cm signal dominated by bubbles, so **total** power ~

$$23 \text{ mK } [x(1-x)]^{1/2}[(1+7)/10]^{1/2}$$

- This implies the total large scale power should be a robust estimator of the reionization history



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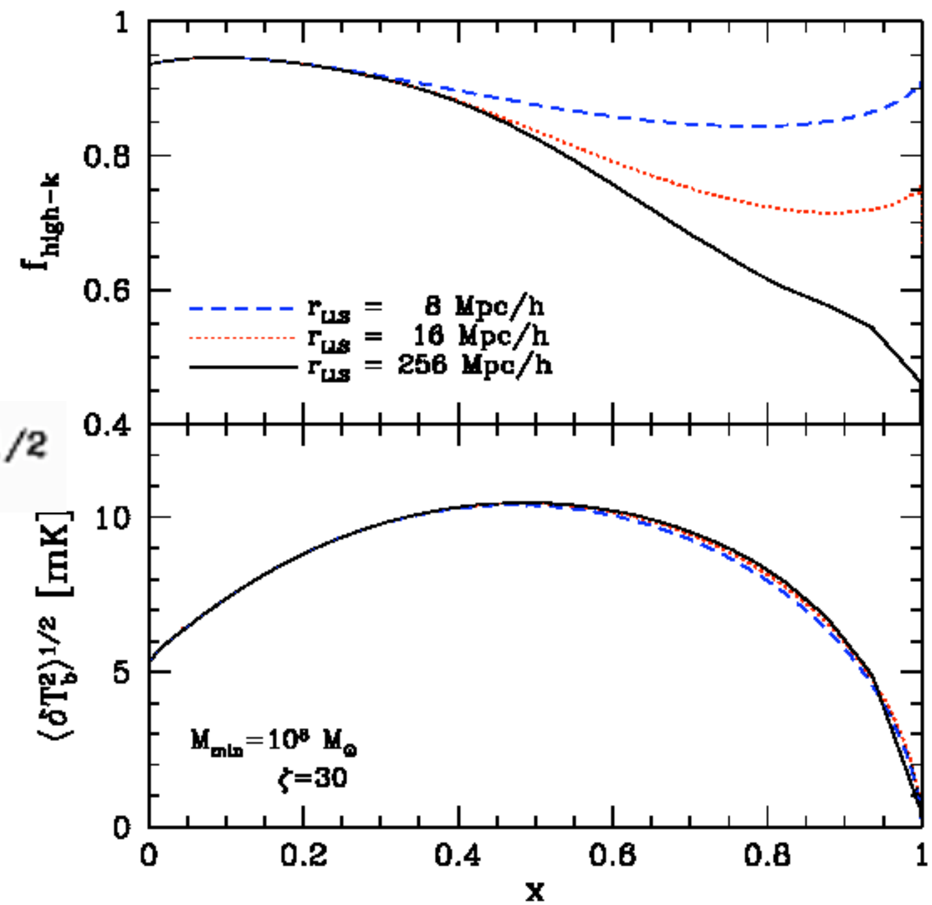

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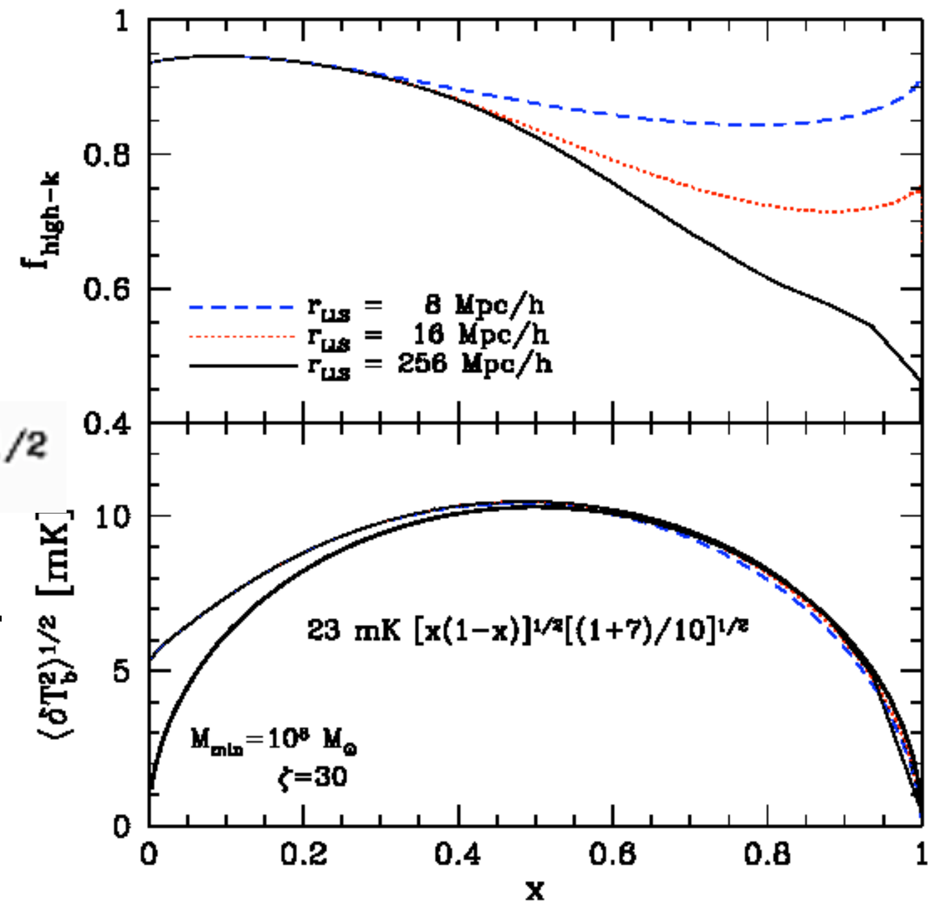
- This is because 21cm signal dominated by bubbles, so **total** power ~

$$23\ \mathrm{mK}\ [x(1-x)]^{1/2}[(1+7)/10]^{1/2}$$

- However, the **shape** P(k) is different -- take **ratio** of power in two **broad** *k*-bands:

  $0.01<k<0.1$ & $0.1<k<1.0$ Mpc^{-1}



Summary

- Fast simulations of reionization very useful for surveying wide parameter space… field is going in this direction (Zahn et al. 2006; Mesinger et al. 2009; Thomas et al 2009)
- Absorption in Lyman limit systems could have extended reionization considerably
- The broadband fluctuation power should be relatively insensitive to details of reionization
- Taking ratio of power in two wide bands may be a good way to beat down noise and constrain reionization with 21cm observations