High-z cosmological structures and reionization

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with

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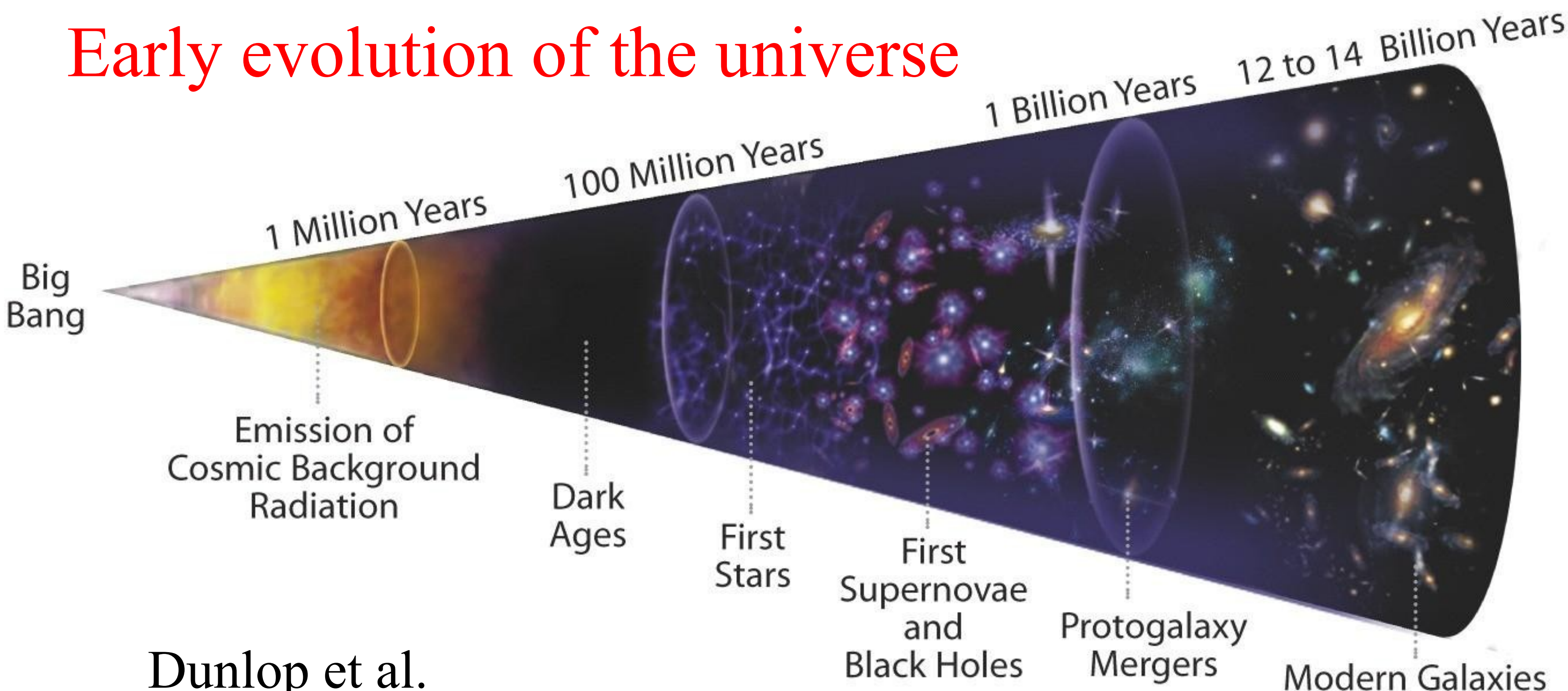
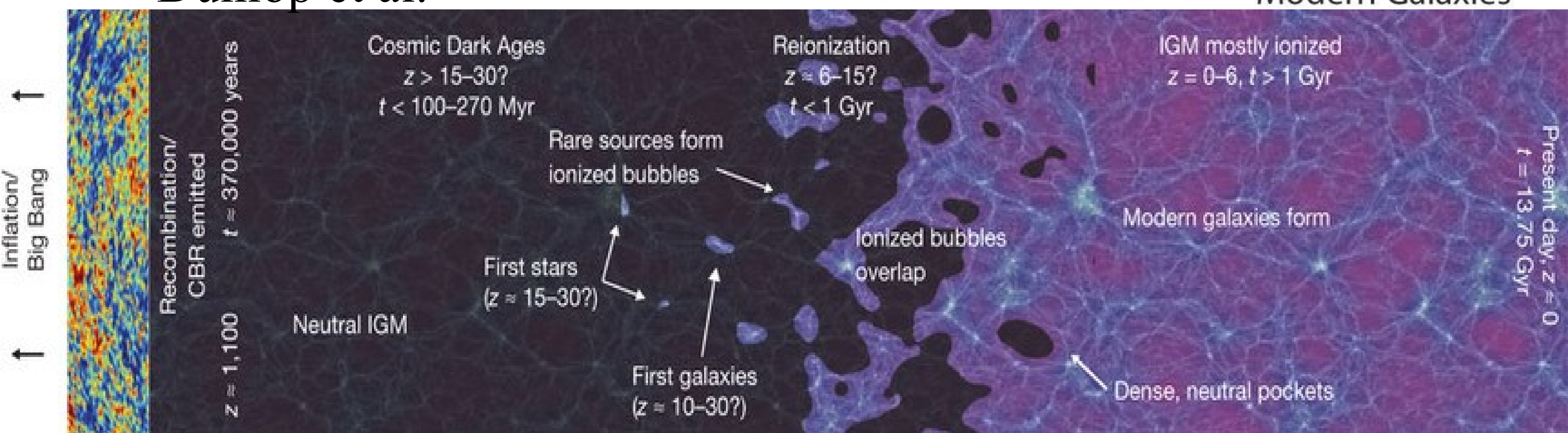
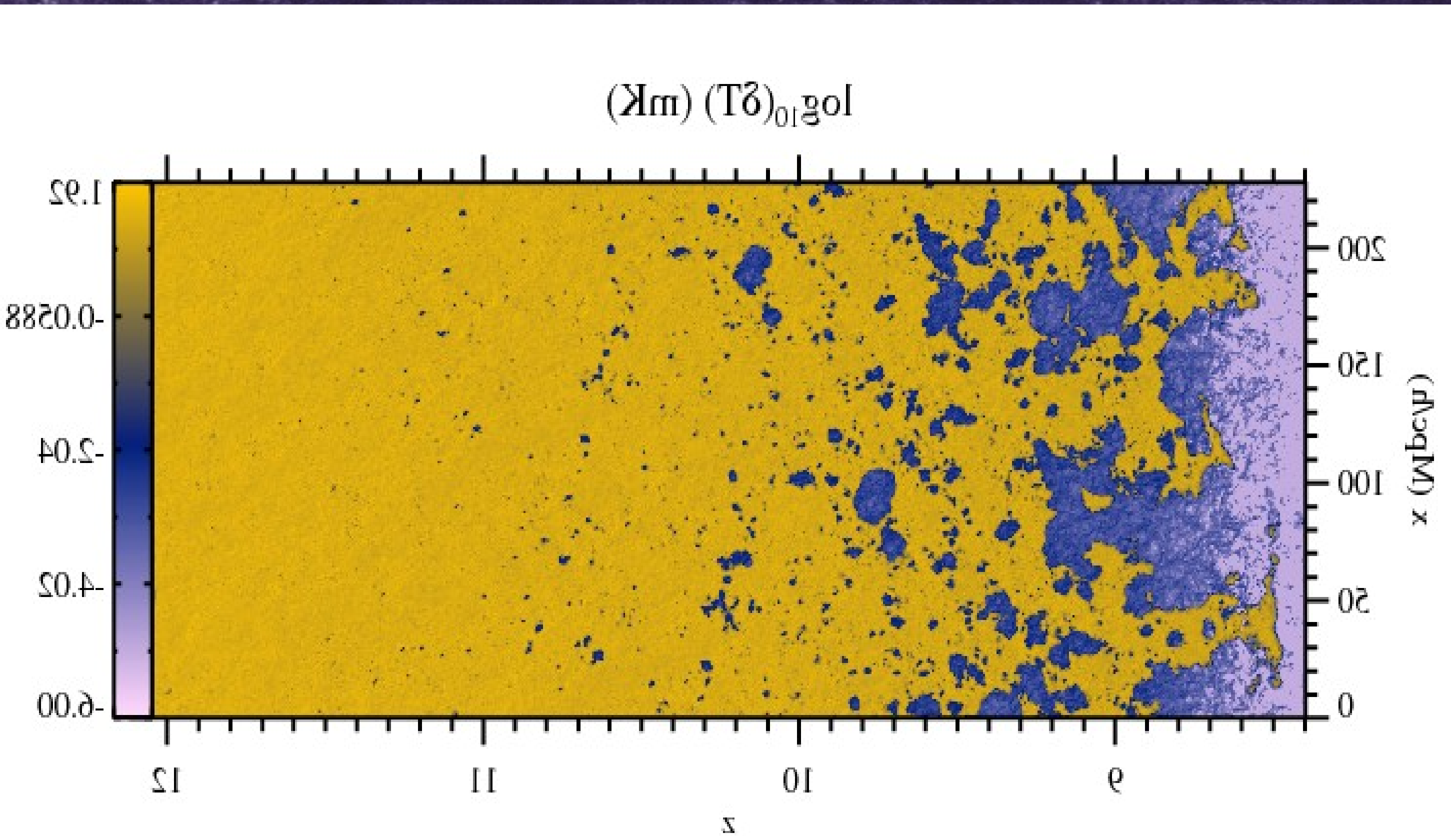
Early evolution of the universe

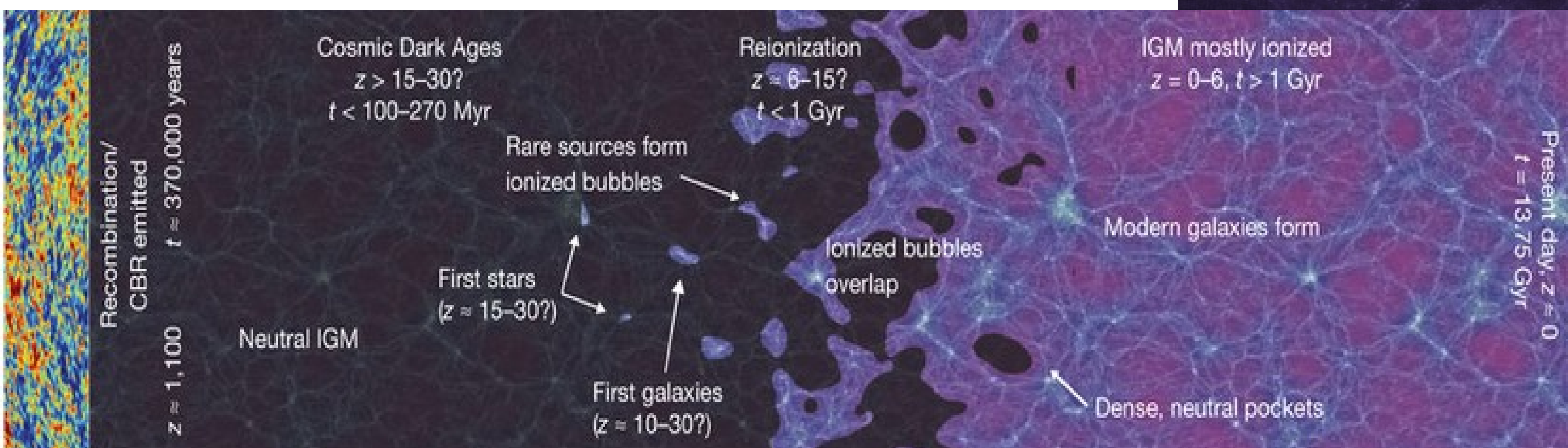


Dunlop et al.





log10(δT) (mK)
1.92
-0.0588
-2.04
-4.02
-6.00
x (Mpc/h)
200
150
100
50
0
12
11
10
9
z



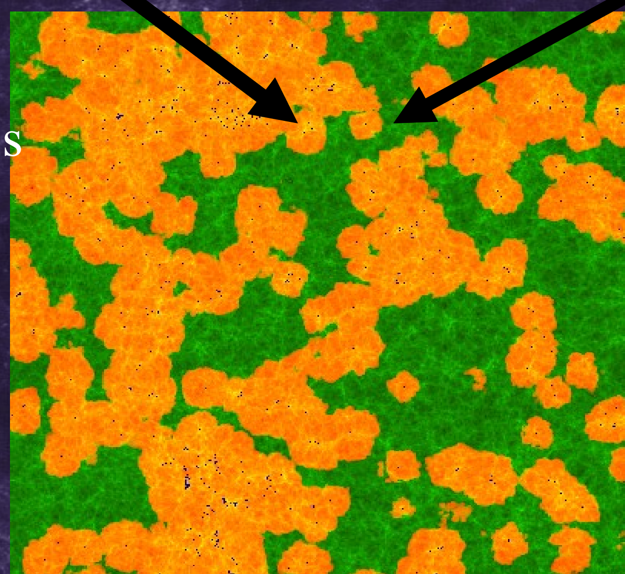
Inflation/
Big Bang
Recombination/
CBR emitted
t ≈ 370,000 years
z ≈ 1,100
Cosmic Dark Ages
z > 15–30?
t < 100–270 Myr
Neutral IGM
Rare sources form
ionized bubbles
First stars
(z ≈ 15–30?)
First galaxies
(z ≈ 10–30?)
Reionization
z ≈ 6–15?
t < 1 Gyr
Ionized bubbles
overlap
IGM mostly ionized
z = 0–6, t > 1 Gyr
Modern galaxies form
Dense, neutral pockets
Present day, z = 0
t = 13.75 Gyr

Progress of reionization: 3D view

Large-Scale Simulations of Reionization

- N-body: CubeP^{3}M (Harnois-Deraps, et al. 2012)
  3072^3-5488^3 particles (29 to 165 billion)
- density slices
- velocity slices
- halo catalogues-sources
- Scales well at least up to 21,952 cores

114-425/h Mpc (CubeP^{3}M)
resolving 10^8 -$10^9 M_{solar}$ halos
up to 120 x 10^6 sources
50-100 dens. snapshots
simple source models
sub-grid clumping
no hydro – large scales.

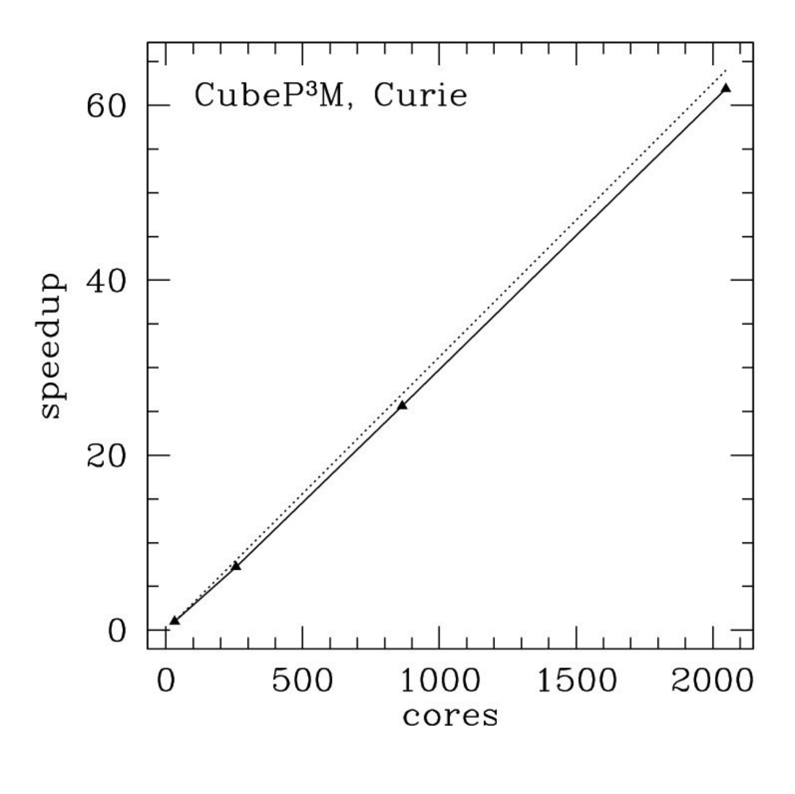


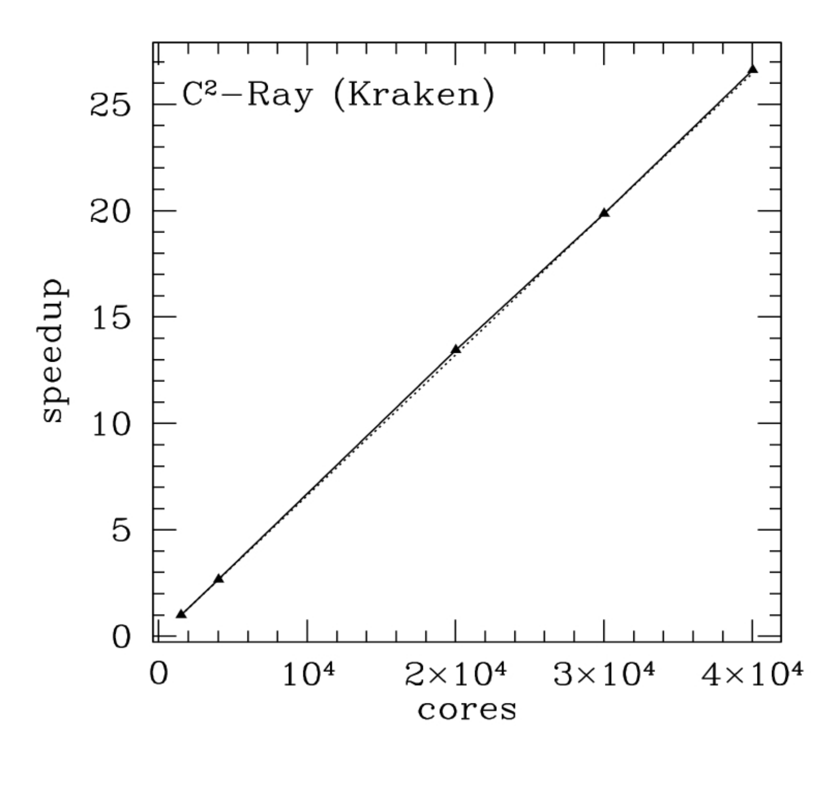
- C^2-Ray code (Mellema, et al. 2006)
- radiative transfer
  - noneq. chemistry
  - precise
  - highly efficient
  - coupled to gasdynamics
    - massively parallel (excellent scaling to 40,000+ cores).

Coupled to hydro

Code scaling

(Iliev et al. 2012, Harnois-Deraps et al. 2012)





The Formation of Early Cosmic Structures

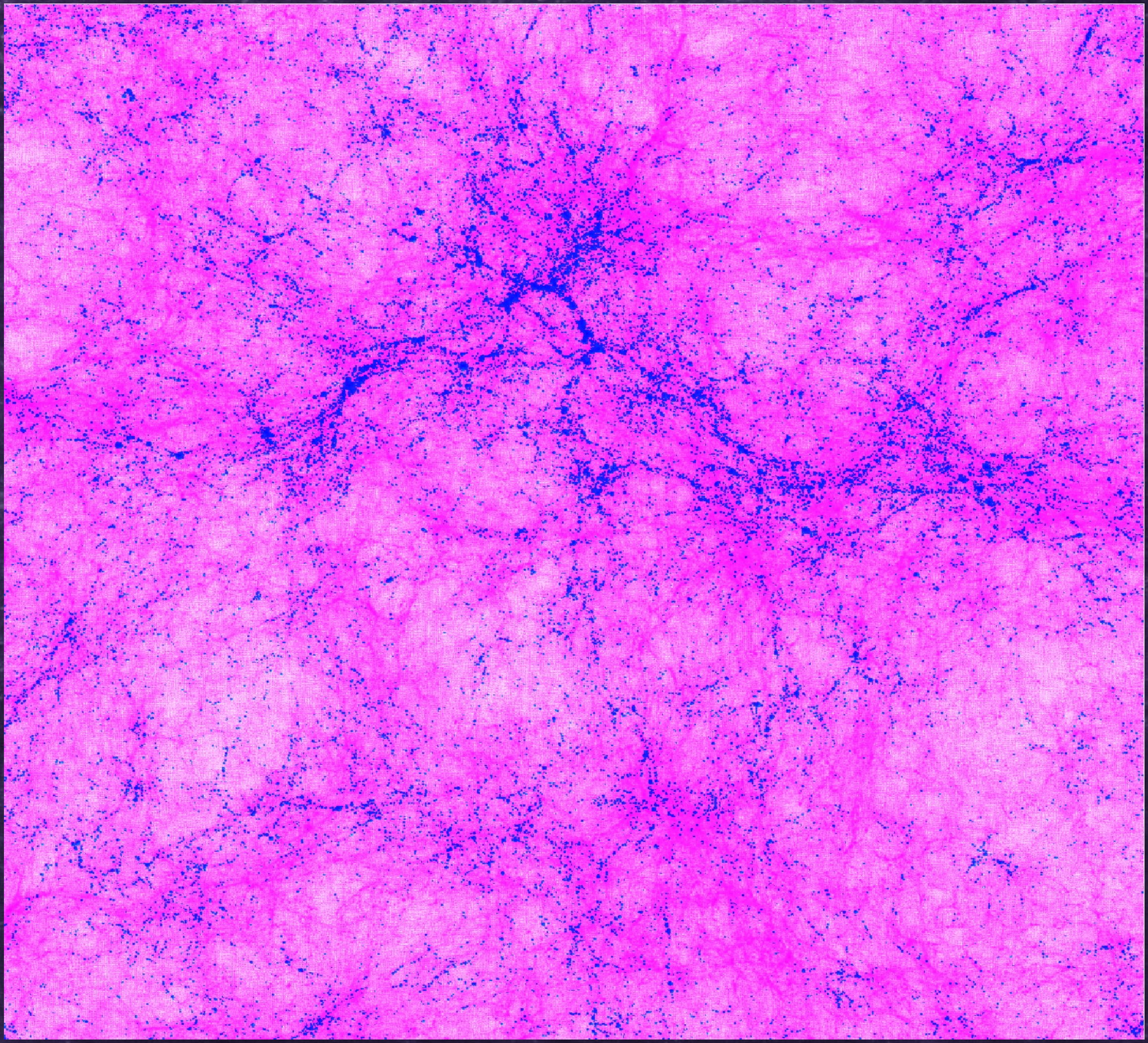
Iliev, et al. 2006a, MNRAS, 369, 1885; Iliev et al. ArXiv1107.4772; and in prep.)

425/h Mpc box @ z=6
5488^3 particles (165 billion),
$10{,}976^3$ cells, P^3M simulation
density=violet, halos=blue
41.5x41.5 Mpc zoomed slice

Halos 10^9 M_{solar} and above resolved. First halos form at z~26; 176 million halos by z=2.6)

Volume comparable to the FOV of EoR radio surveys like LOFAR

All atomically-cooling halos ($>10^8$ M_{solar}) are in the RT (10^8-10^9 M_{solar} modelled sub-grid)



Simulation ran at Texas Advanced Computing Facility on 10,988-21,976 cores.

The Formation of Early Cosmic Structures: The Very Small Scales

(Watson et al. In prep.)

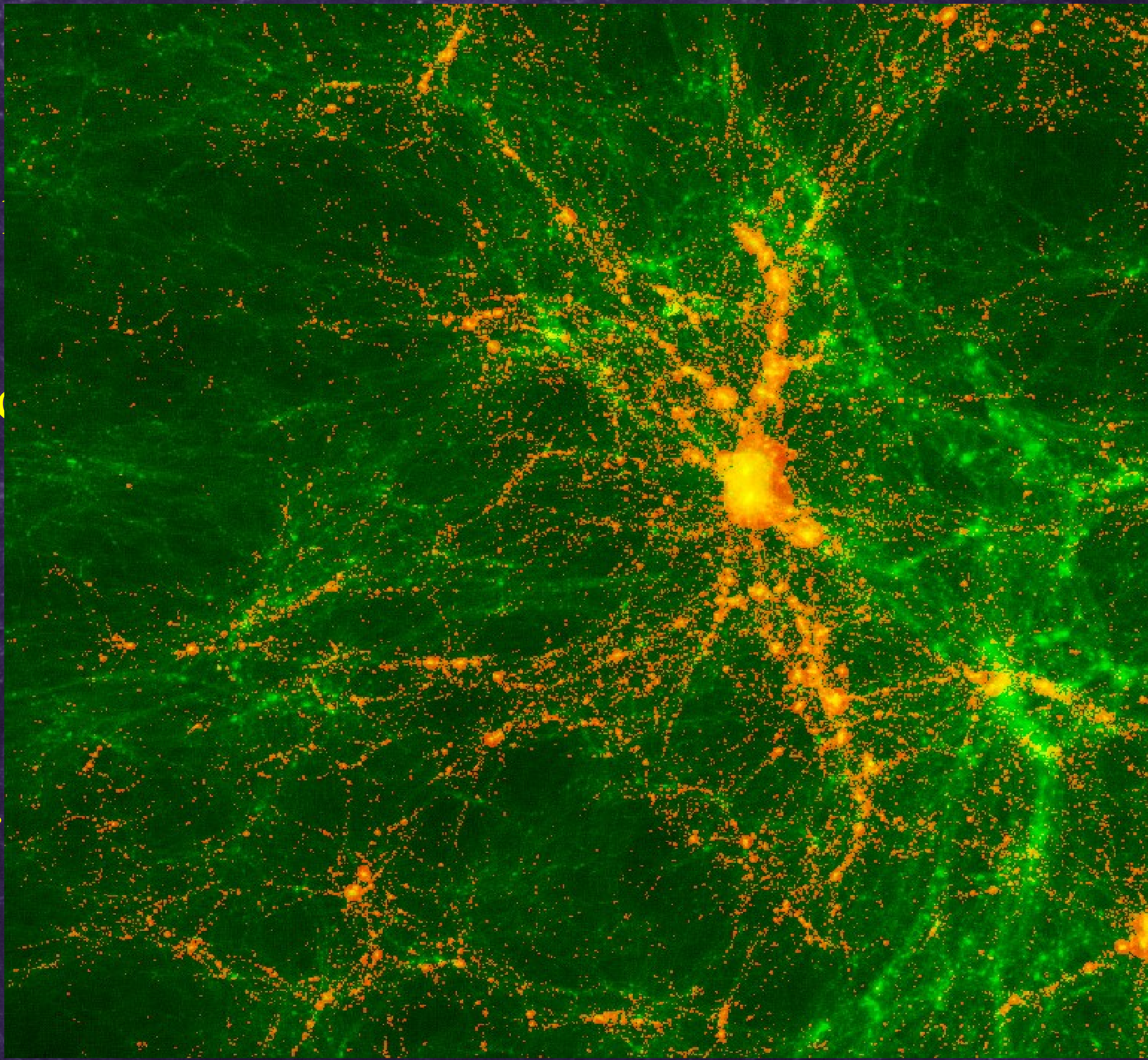
20/h Mpc box @ z=8, zoom
5488^3 particles (165 billion),
$10{,}976^3$ cells, P^3M simulation

Resolves all halos down to small
minihalos (10^5 M_{solar}).

Structures are highly biased
Extend to extremely small
scales (resolution of this
simulation is 182 pc!)

First halos form at z=43.
112+ million halos at z=8.

Very useful for modelling
the effects of small-scale
structure and 21-cm
absorption, etc..



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Computing Center on 10,976-21,952 cores.

The Formation of Early Cosmic Structures: The Very Large Scales

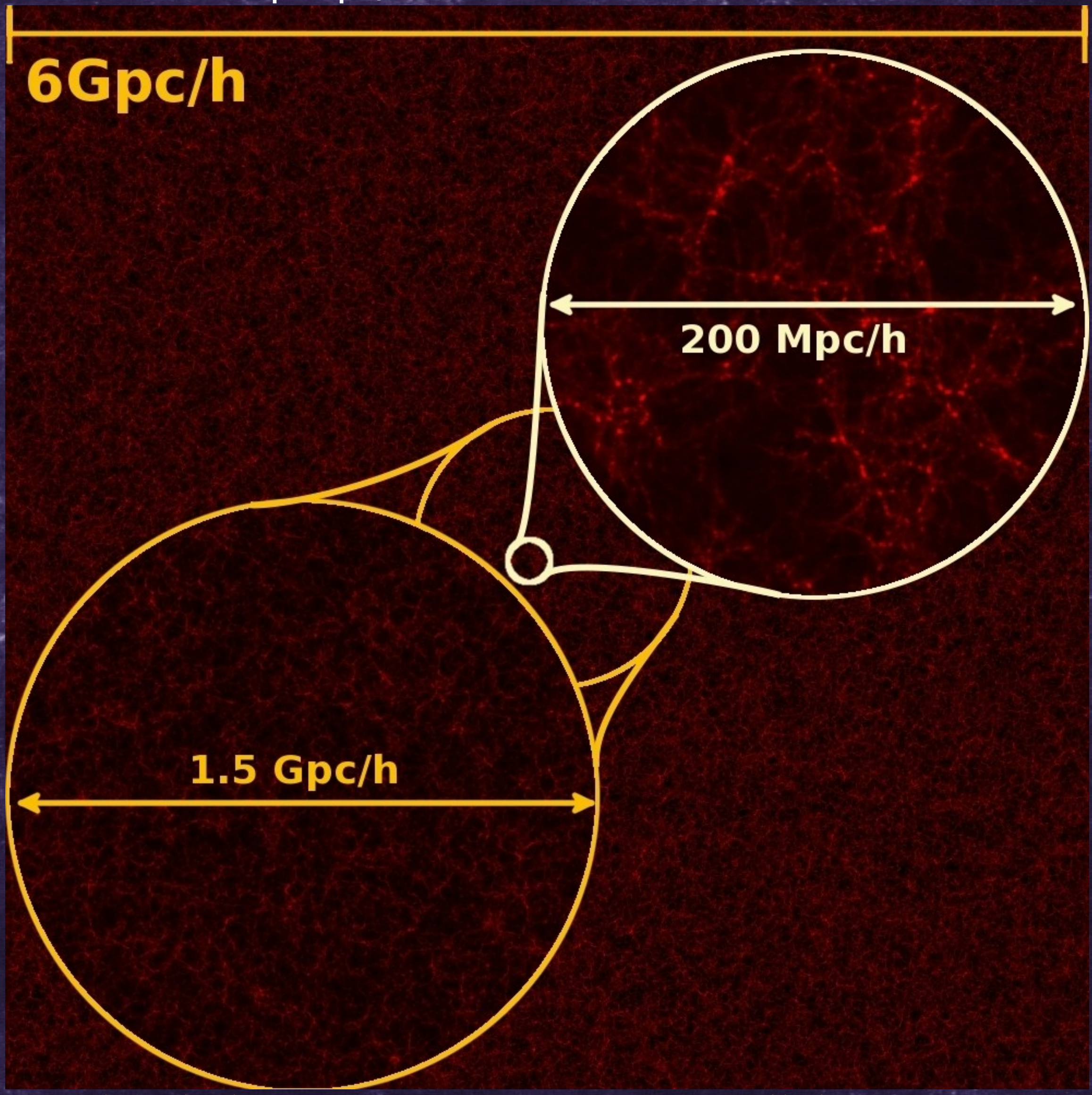
(Iliev et al., in prep.)

JUBILEE project
(S. Gottloeber, G. Yepes, J. Diego, W. Watson and others)
6/h Gpc box @ z=0
6000^3 particles (216 billion), $12{,}000^3$ cells, P^3M simulation

Volume comparable to the observable universe. Resolves all halos above ~2×10^{12} M_{solar}).

Rich statistics: First halos form at z>10, over 350 million halos at z=0, 8.5 million galaxy clusters at z=0.

Useful for studies of statistics and clustering of very massive, rare sources, as well as modelling of galaxy surveys and ISW.



Simulation ran on JUROPA at Juelich Supercomputing Center on 8000 cores.

Halo mass function

(Watson et al., in prep.)

- Halo multiplicity function:

$$f(\sigma, z) \equiv \frac{M}{\rho_0(z)} \frac{dN(M,z)}{d\ln\sigma^{-1}}$$

- Fitting formula (e.g. Tinker et al. 2008):

$$f(\sigma) = A\left[\left(\frac{\beta}{\sigma}\right)^{\alpha} + 1\right] e^{-\gamma/\sigma^2}$$

- Three approaches to halo finding tested: FOF (Gadget), AHF, and CPMSO (CubeP^{3}M).

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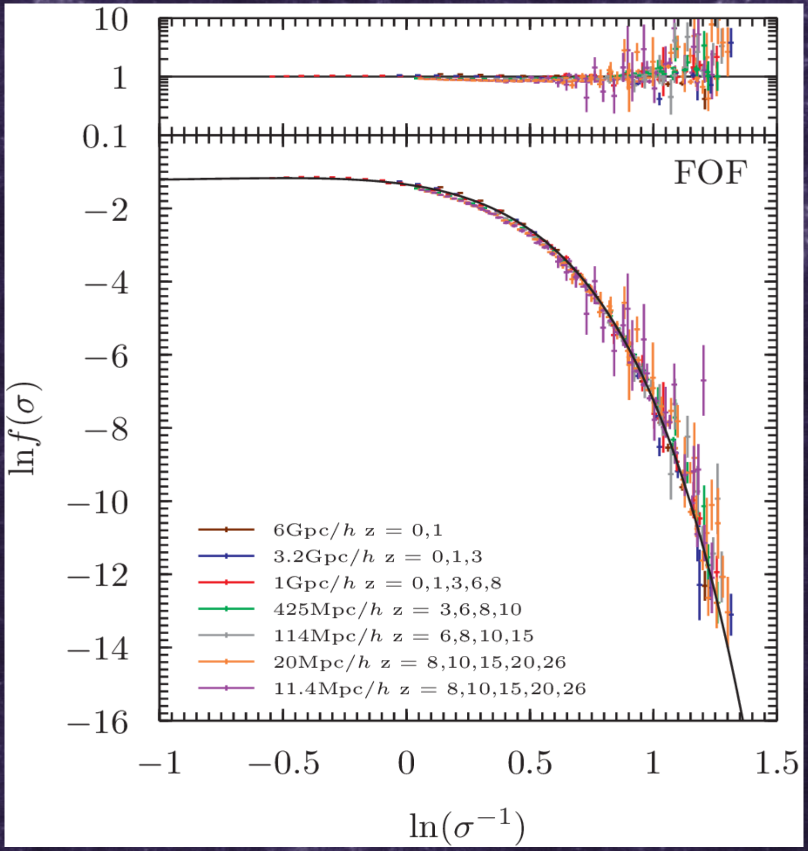
Simulation suite

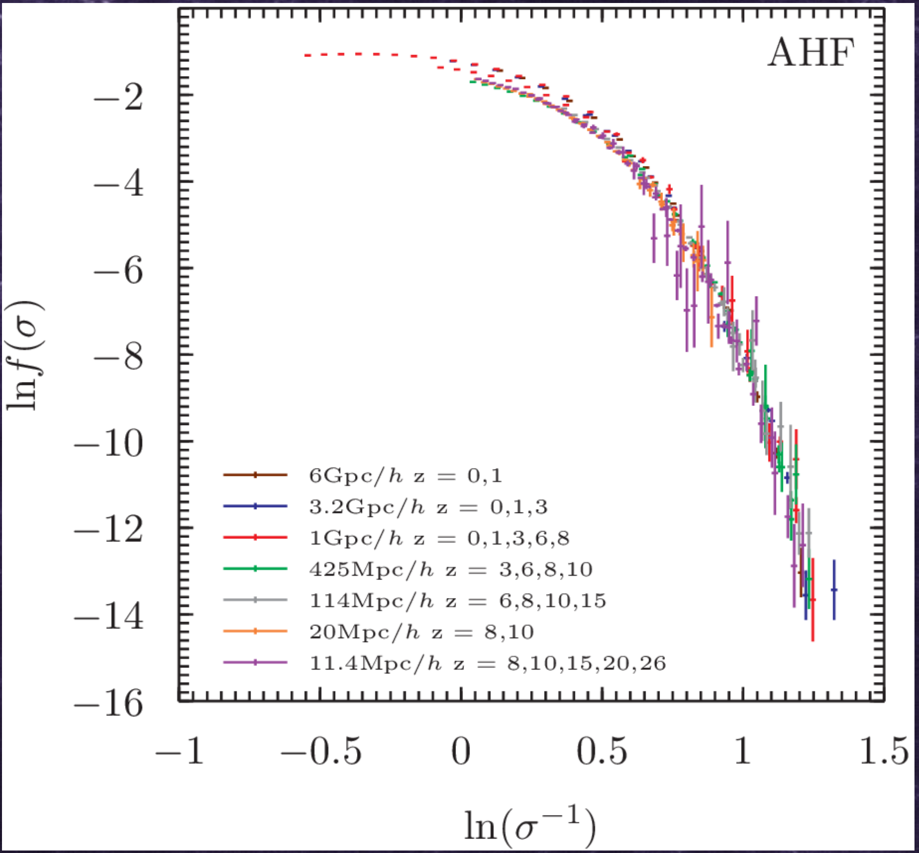
(Watson et al., in prep.)

Box Size	N_{part}	Mesh	Resolution	$m_{particle}$	$M_{halo,min}$	$z_{\rm in}$	$\mathcal{P}(k)_{max}$	δ_{in}^{rms}	$z_{\rm firsthalo}$
11.4 h^{-1}Mpc	3072^3	6144^3	0.18 h^{-1}kpc	5.19×10^3 M$_\odot$	1.04×10^5 M$_\odot$	300	2.0×10^{-5}	0.074	41
20 h^{-1}Mpc	5488^3	10976^3	0.18 h^{-1}kpc	5.19×10^3 M$_\odot$	1.04×10^5 M$_\odot$	300	2.0×10^{-5}	0.090	44
114 h^{-1}Mpc	3072^3	6144^3	1.86 h^{-1}kpc	5.47×10^6 M$_\odot$	1.09×10^8 M$_\odot$	300	1.2×10^{-5}	0.074	30
425 h^{-1}Mpc	5488^3	10976^3	3.87 h^{-1}kpc	5.27×10^7 M$_\odot$	1.05×10^9 M$_\odot$	300	9.5×10^{-6}	0.137	25
1000 h^{-1}Mpc	3456^3	6912^3	14.47 h^{-1}kpc	2.8×10^9 M$_\odot$	5.50×10^{10} M$_\odot$	150	4.6×10^{-4}	0.011	17
3200 h^{-1}Mpc	4000^3	8000^3	40.00 h^{-1}kpc	5.8×10^{10} M$_\odot$	1.16×10^{12} M$_\odot$	120	4.5×10^{-4}	3.39×10^{-6}	11
6000 h^{-1}Mpc	6000^3	12000^3	50.00 h^{-1}kpc	1.07×10^{11} M$_\odot$	2.14×10^{12} M$_\odot$	100	2.8×10^{-5}	1.22×10^{-7}	11

Halo mass function through the cosmic ages

(Watson et al, in prep.)



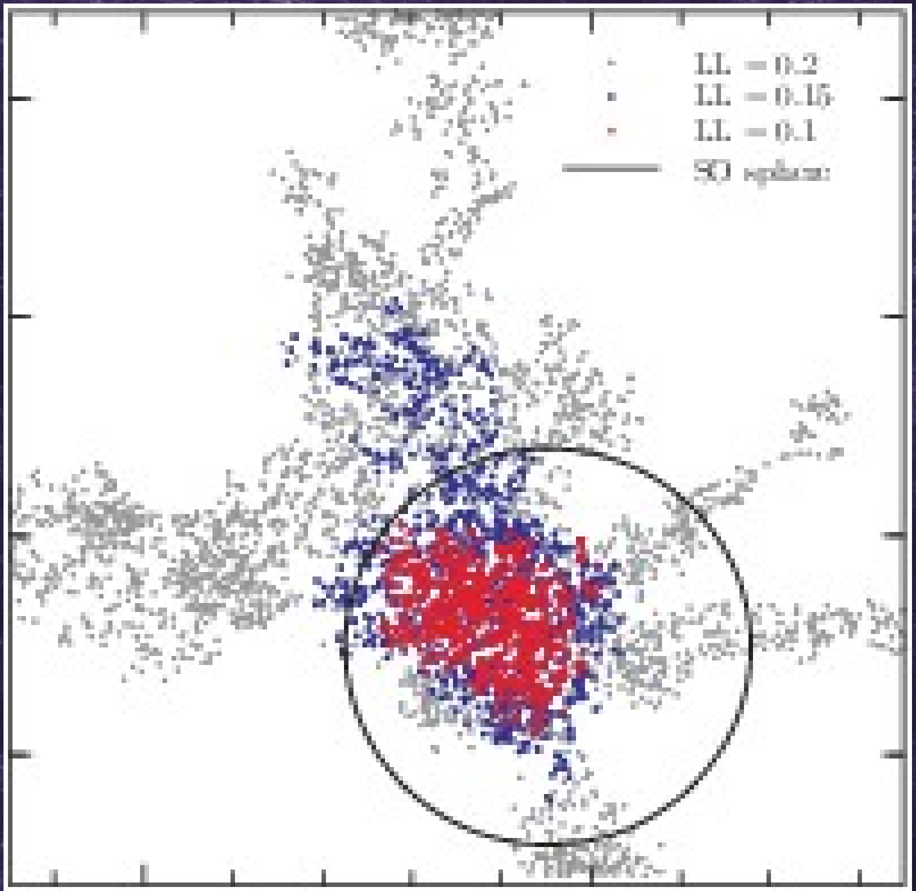


FOF: universal shape

SO: redshift- and Omega-dependent

Effect of FOF linking length

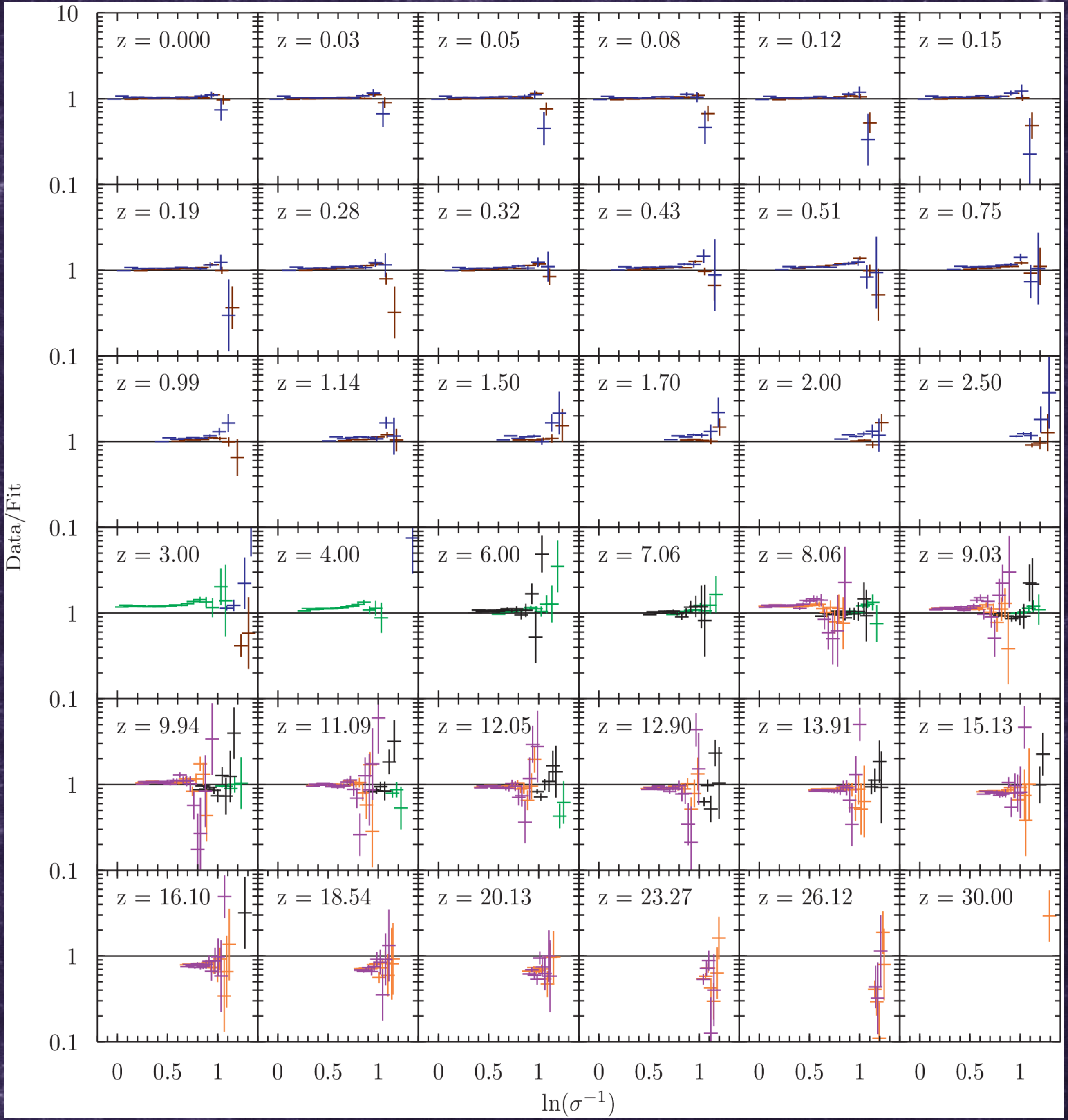
(Watson et al., in prep.)



- Linking length (ll) is a parameter used for defining FOF halos.
- Typically a fixed value of ll=0.2 is used.
- At higher-z this is not appropriate value and among other issues results in over-linking.
- Shorter ll produces more sensible results.

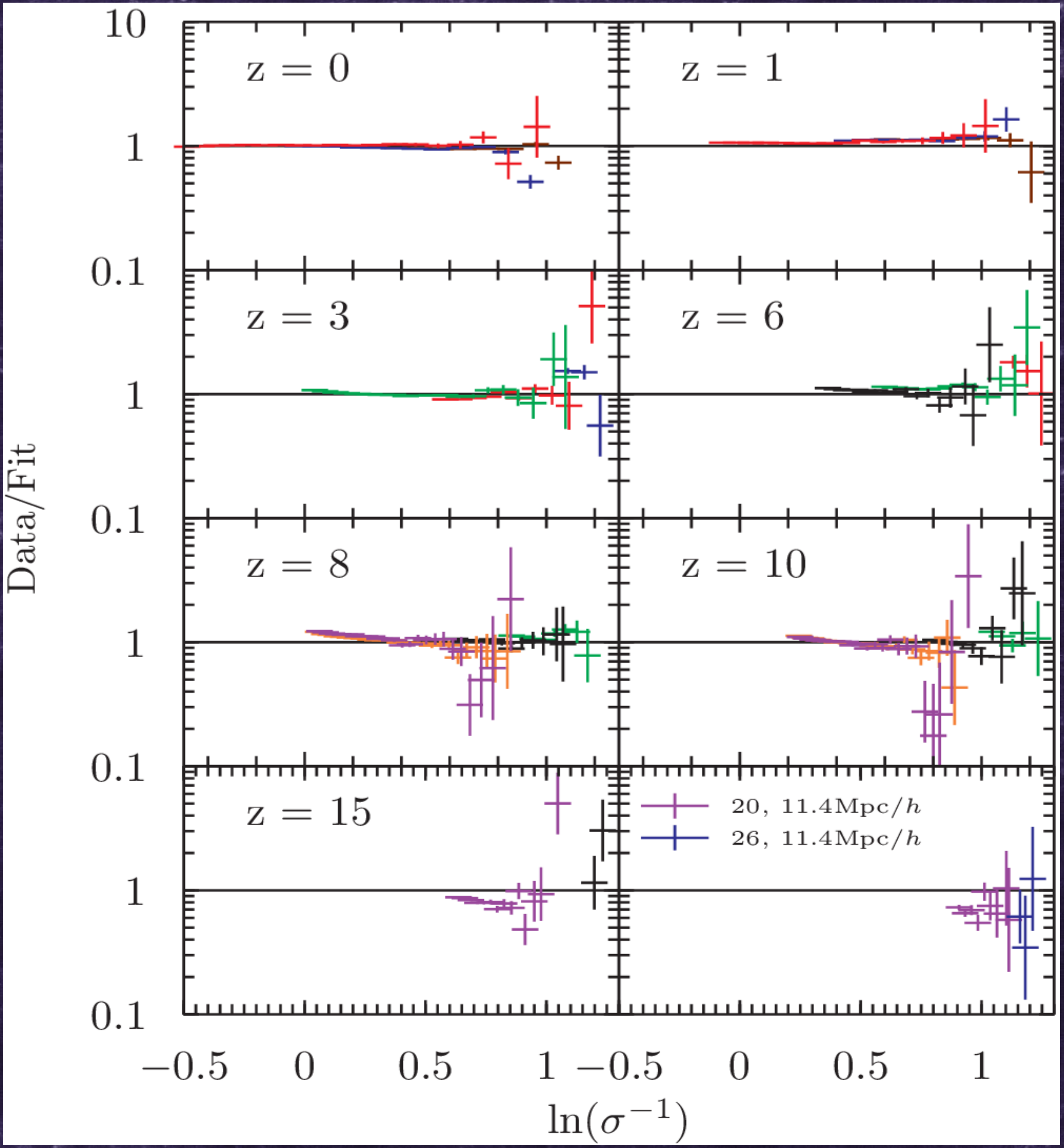
Halo mass function fit: CPMSO

(Watson et al., in prep.)

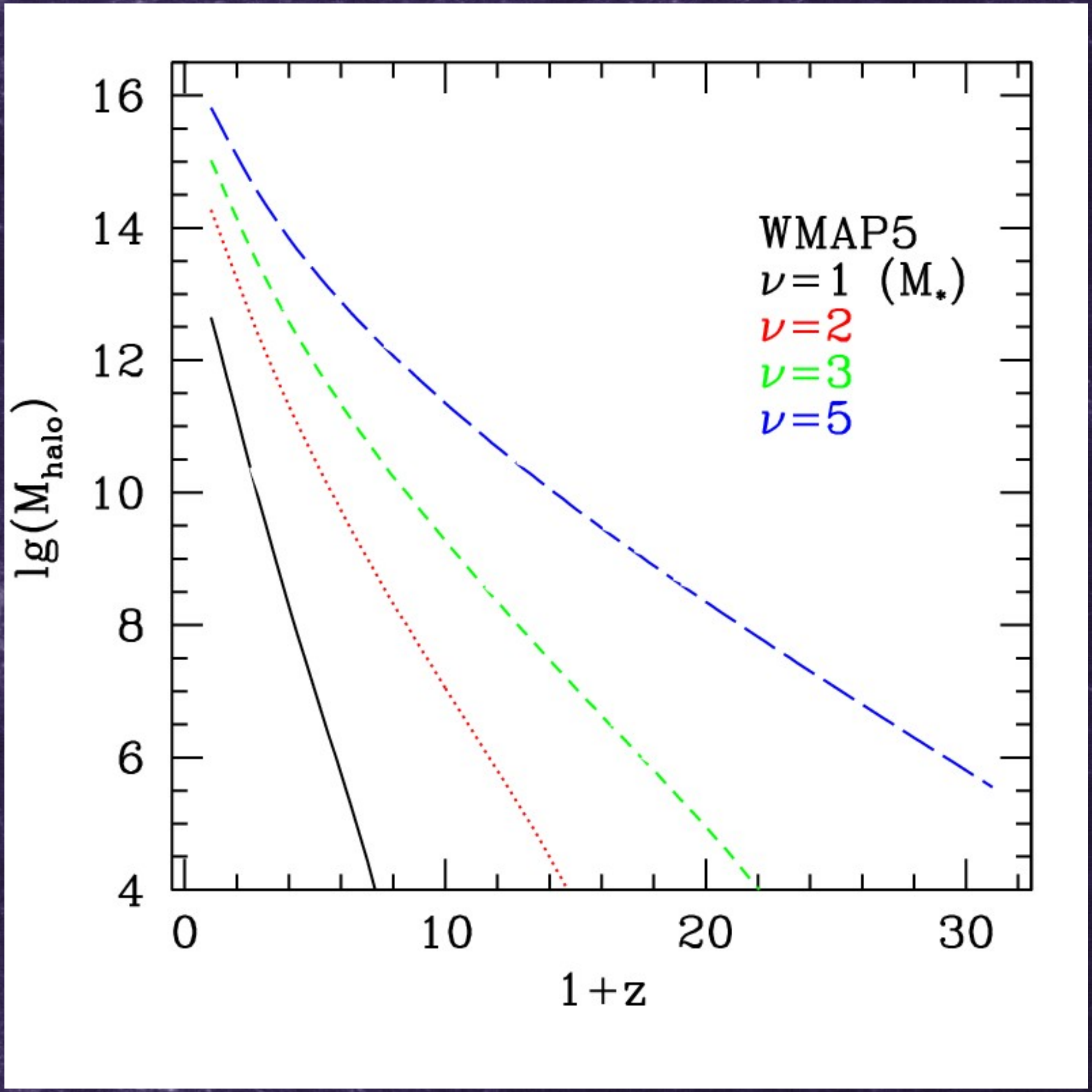


Halo mass function fit: AHF

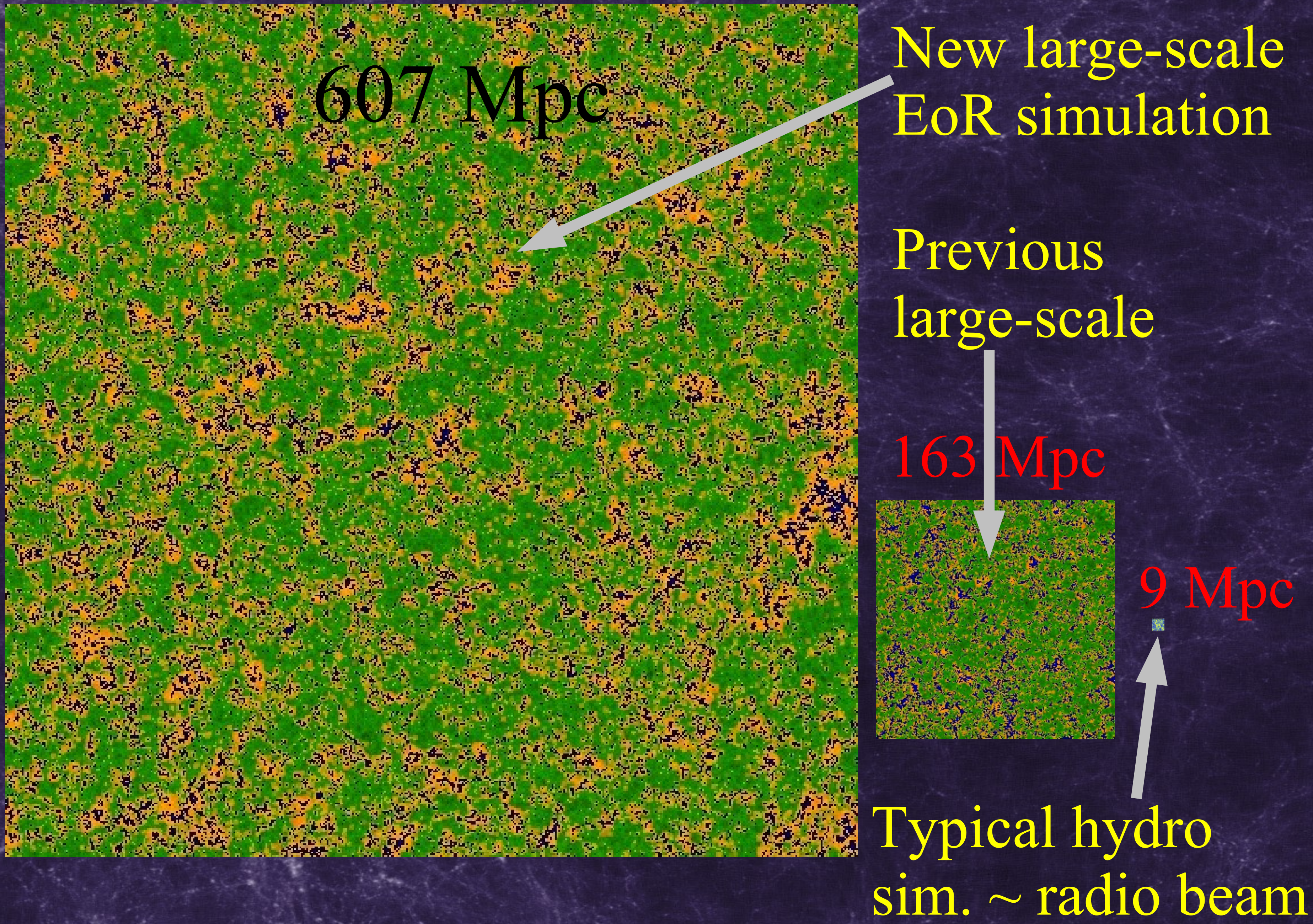
(Watson et al., in prep.)



How rare are halos?

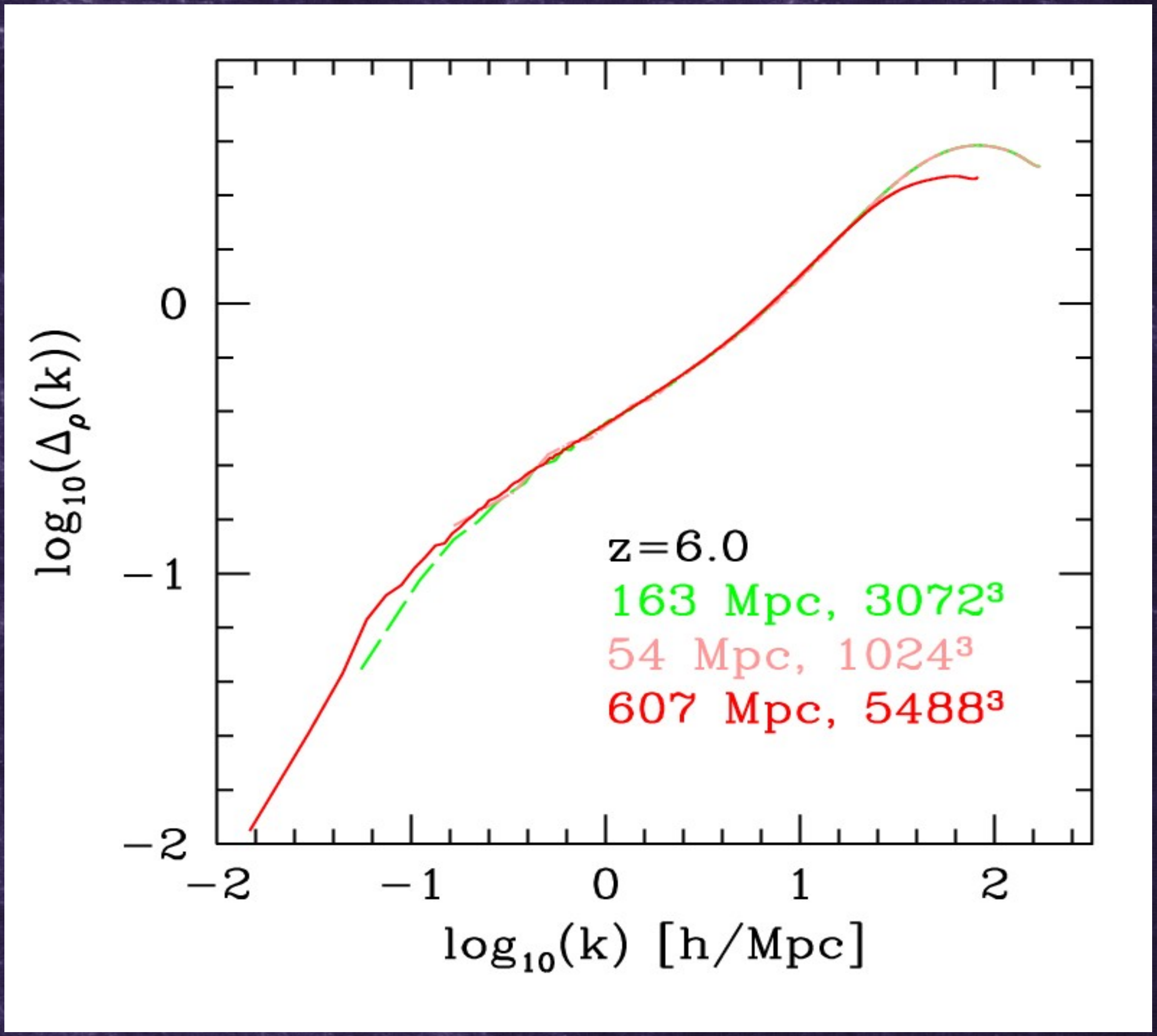


Scales of reionization



Density fluctuations: power

(Iliev et al., in prep.)



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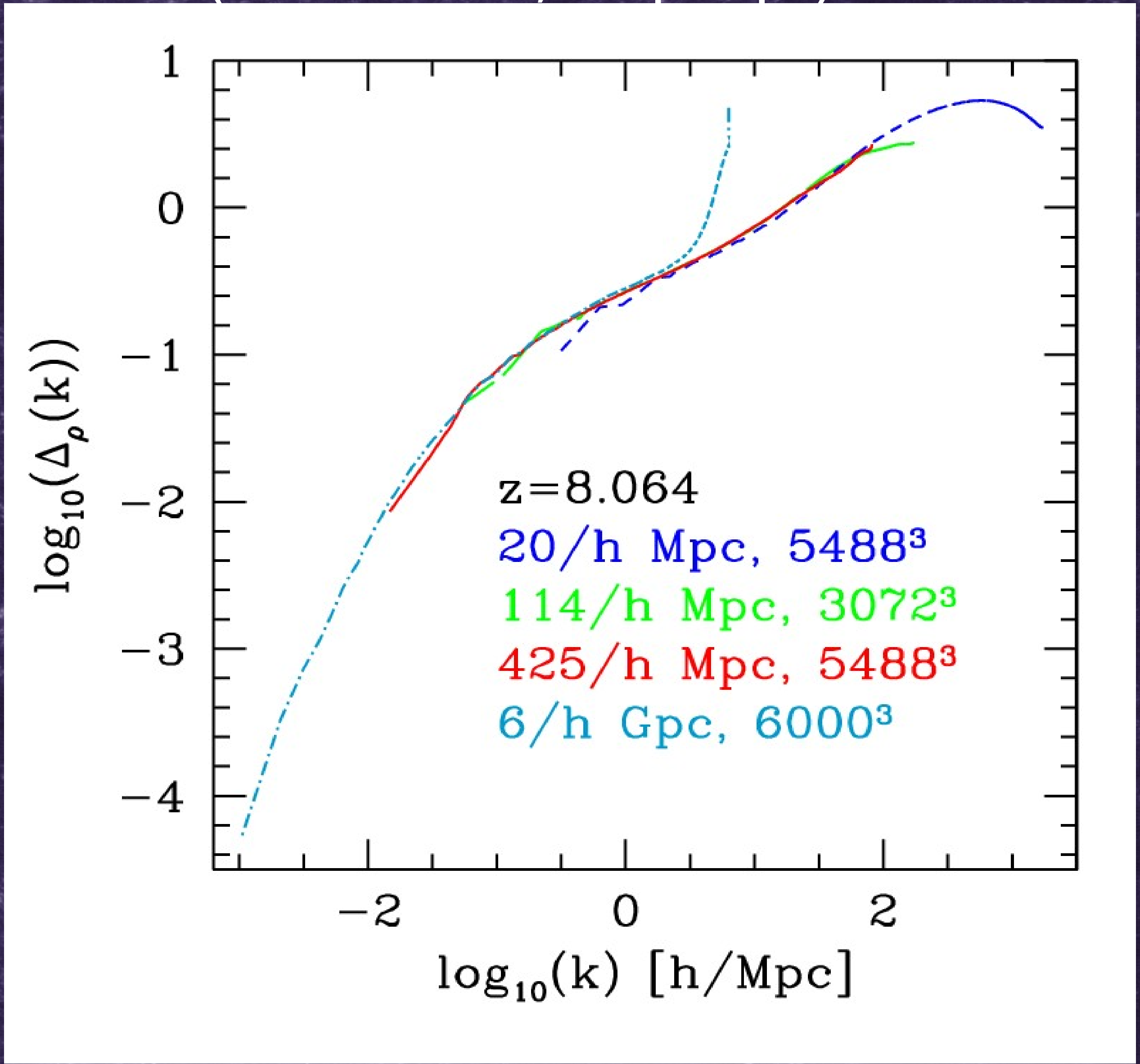
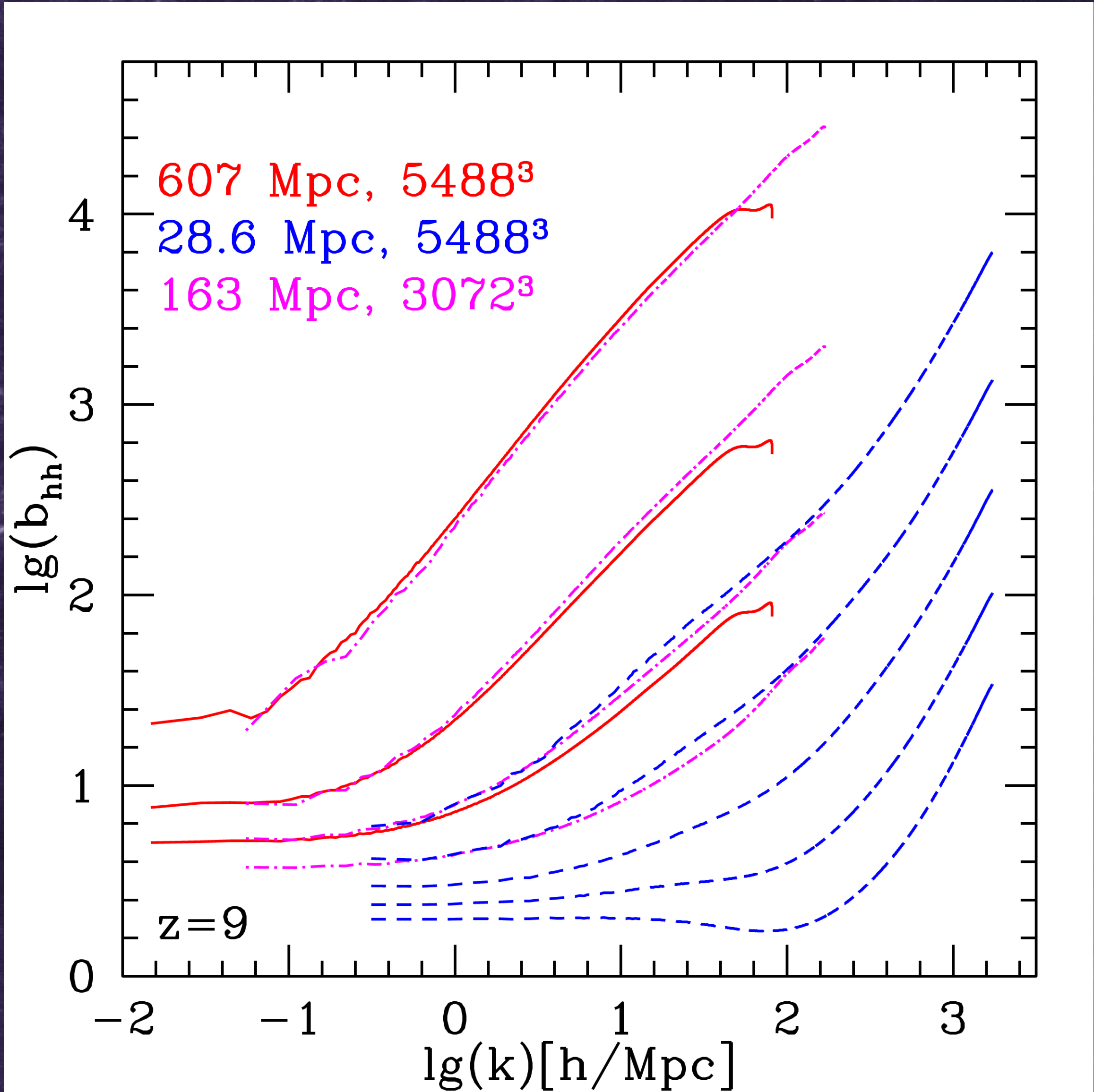


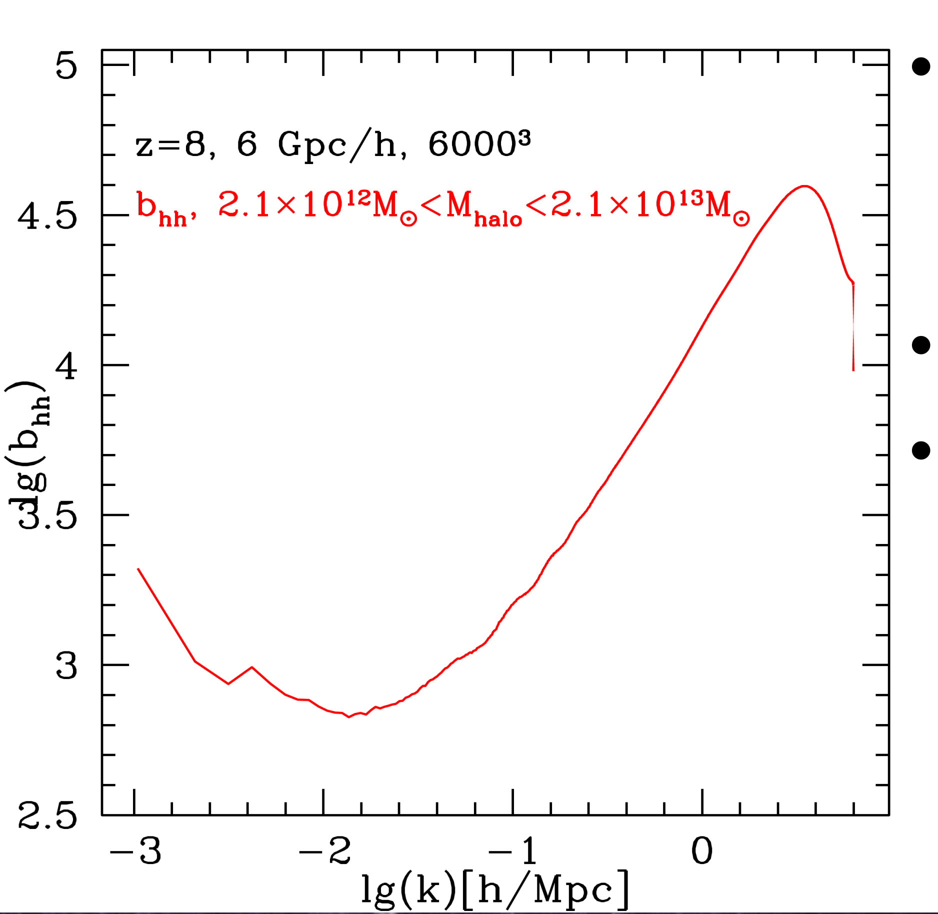
The high-z halo bias
(Iliev et al., in prep.)

- Halos at high-z are strongly clustered.
- Bias increases fast with halo mass and can reach a thousands in the nonlinear regime.
- Scale at which bias becomes linear varies significantly with halo mass.
- Simulations with different resolutions agree farly well in the overlapping mass ranges.



The high-z halo bias: extreme objects

(Iliev et al., in prep.)

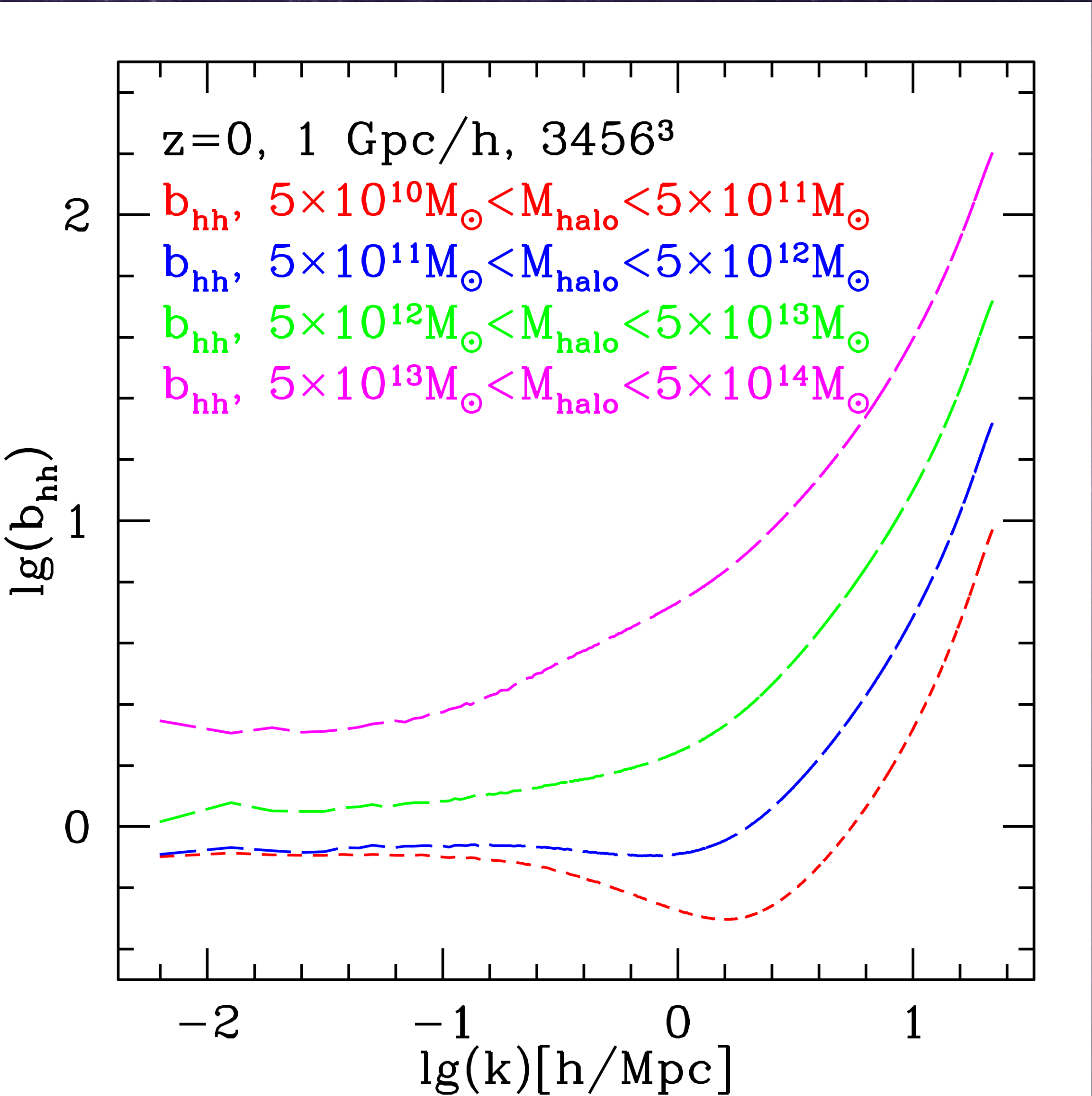


- ~750 MW+-size objects resolved at z=8
-
- Those extreme objects, located at the highest density peaks are very highly clustered at these redshifts

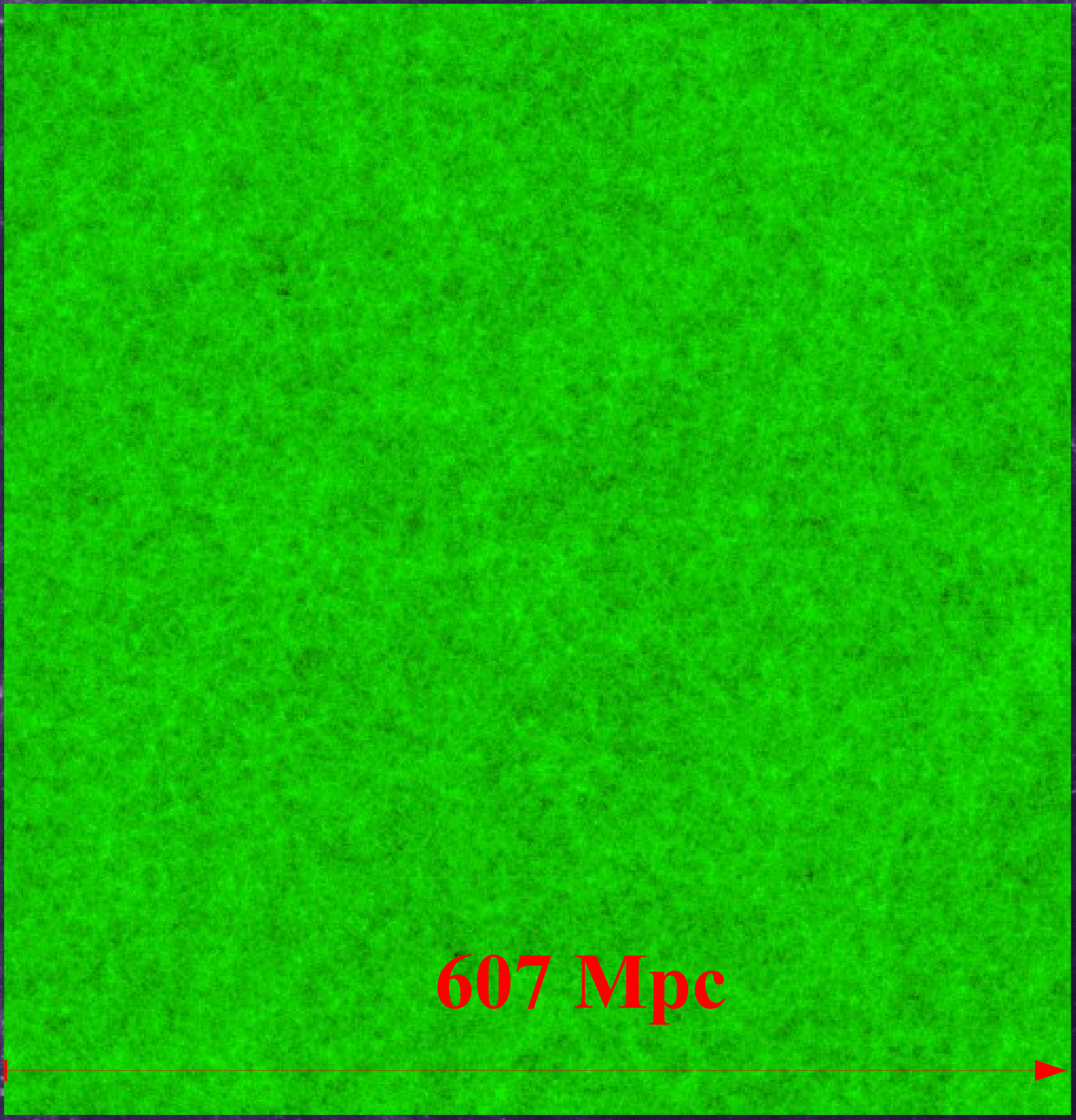
z=0 halo bias

(Iliev et al, in prep.)

- Halos at z=0 are much less clustered.
- Scale at which bias becomes linear varies significantly with halo mass.
- Smallest halos (below $M_* \sim 5e12$) are anti-biased ($b<1$), as expected.

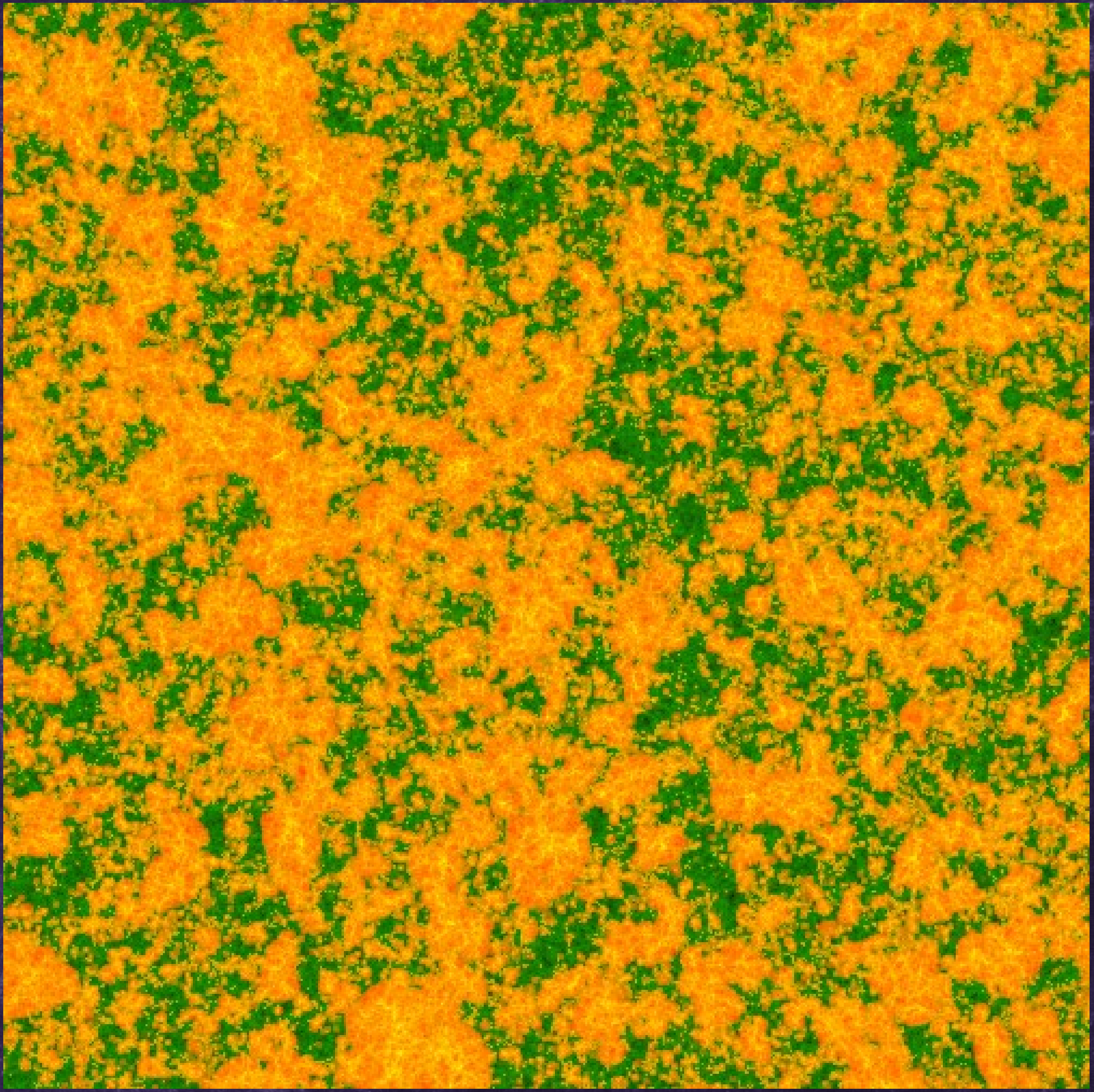


Large-scale reionization: movie



Large-scale Structure of Reionization

(Iliev et al, in prep.)



$z=7.35$

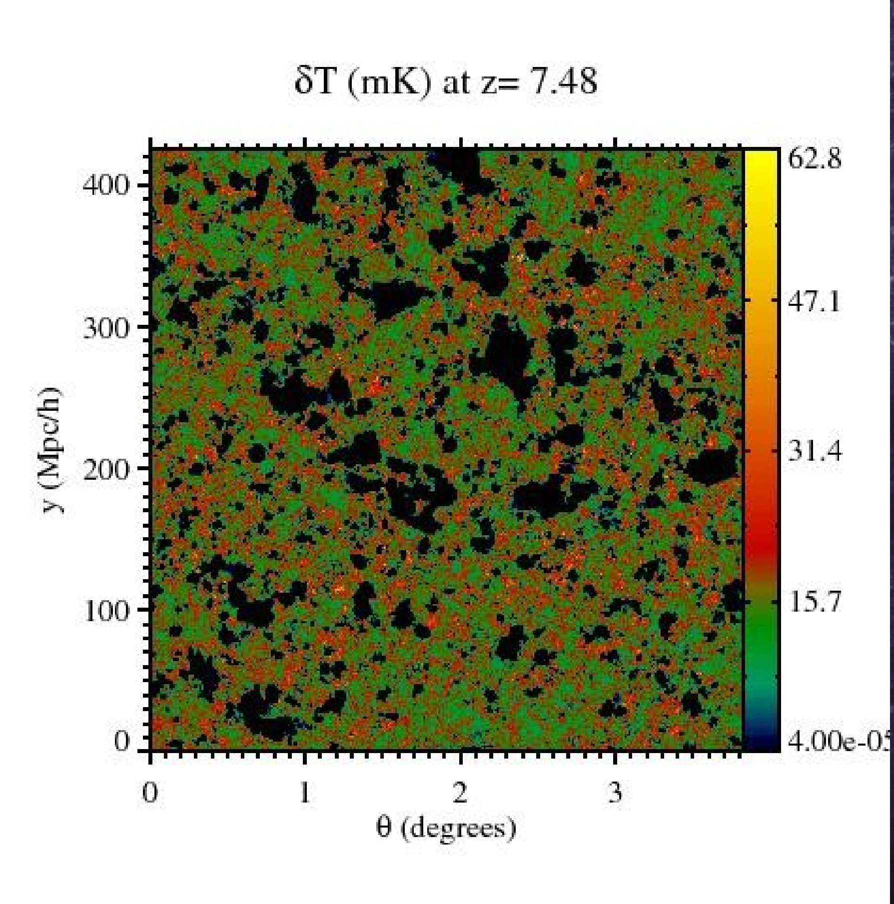
$x_m \sim 0.5$

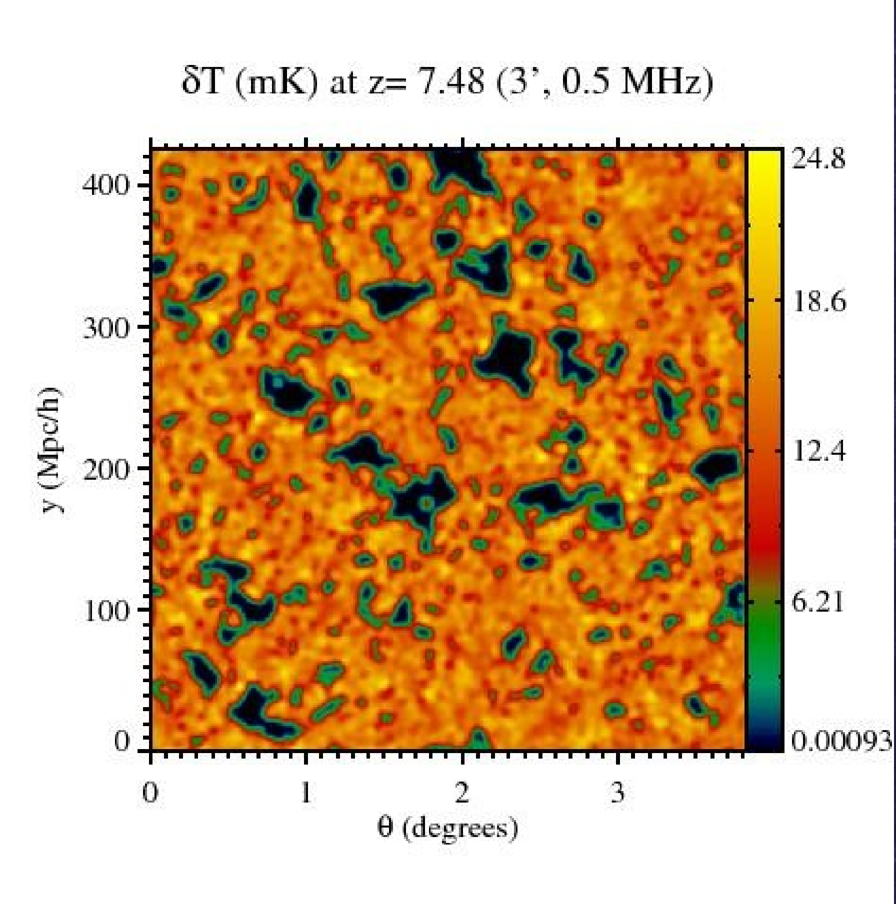
425 Mpc/h

504^3 RT

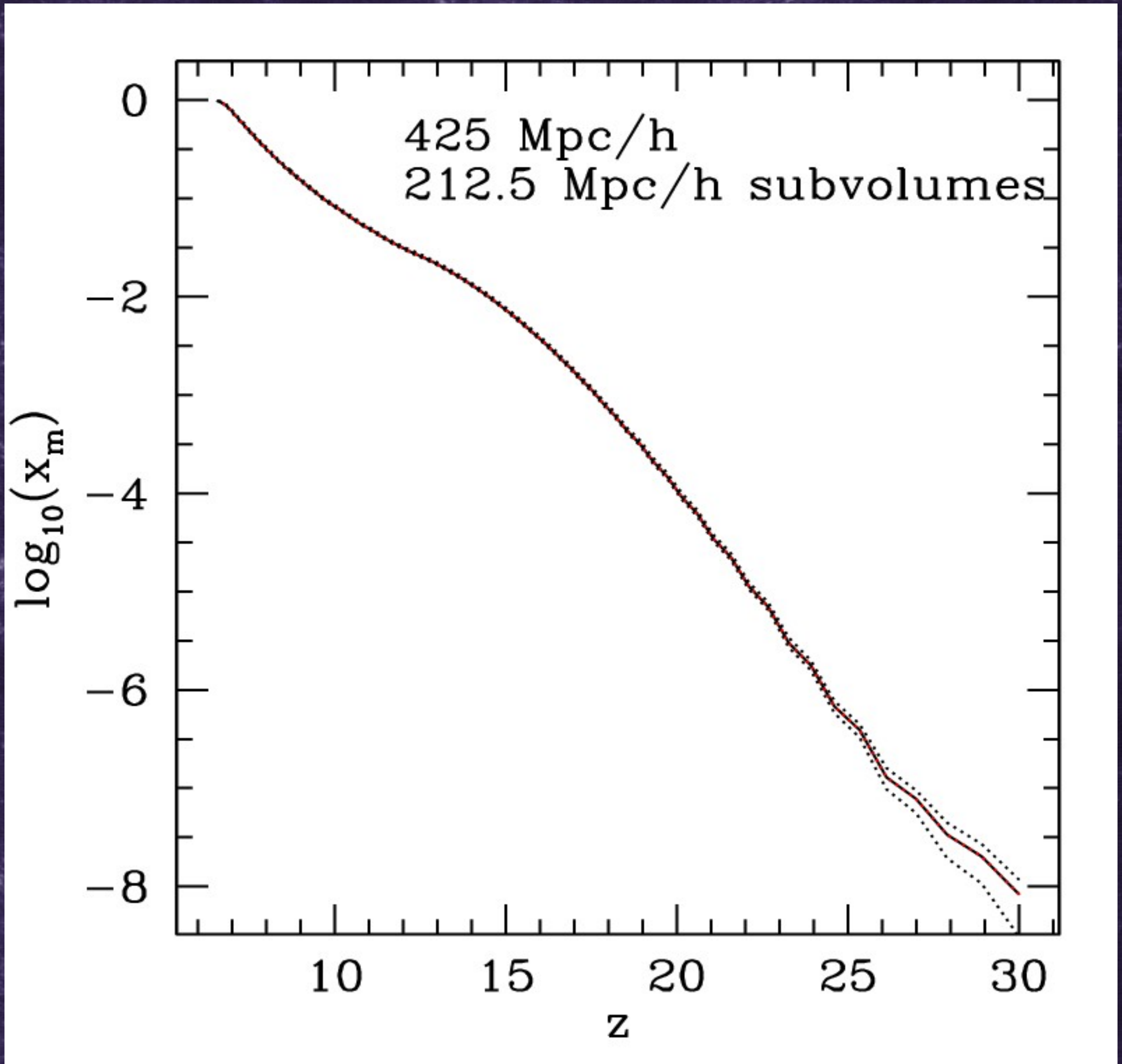
LOFAR resolution

(Iliev et al, in prep.)





Reionization history: how big volume is big enough?
(Iliev et al, in prep.)



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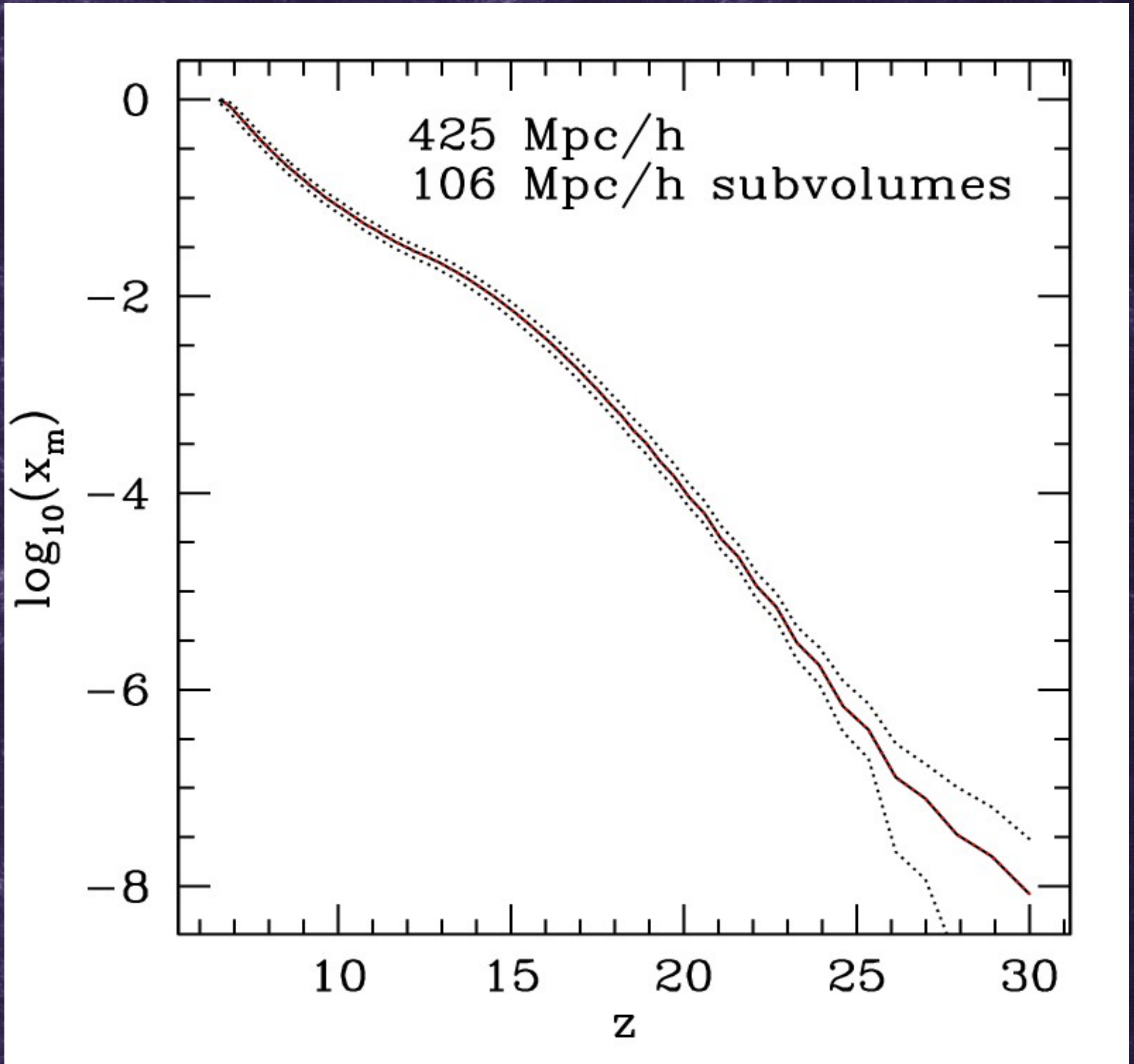

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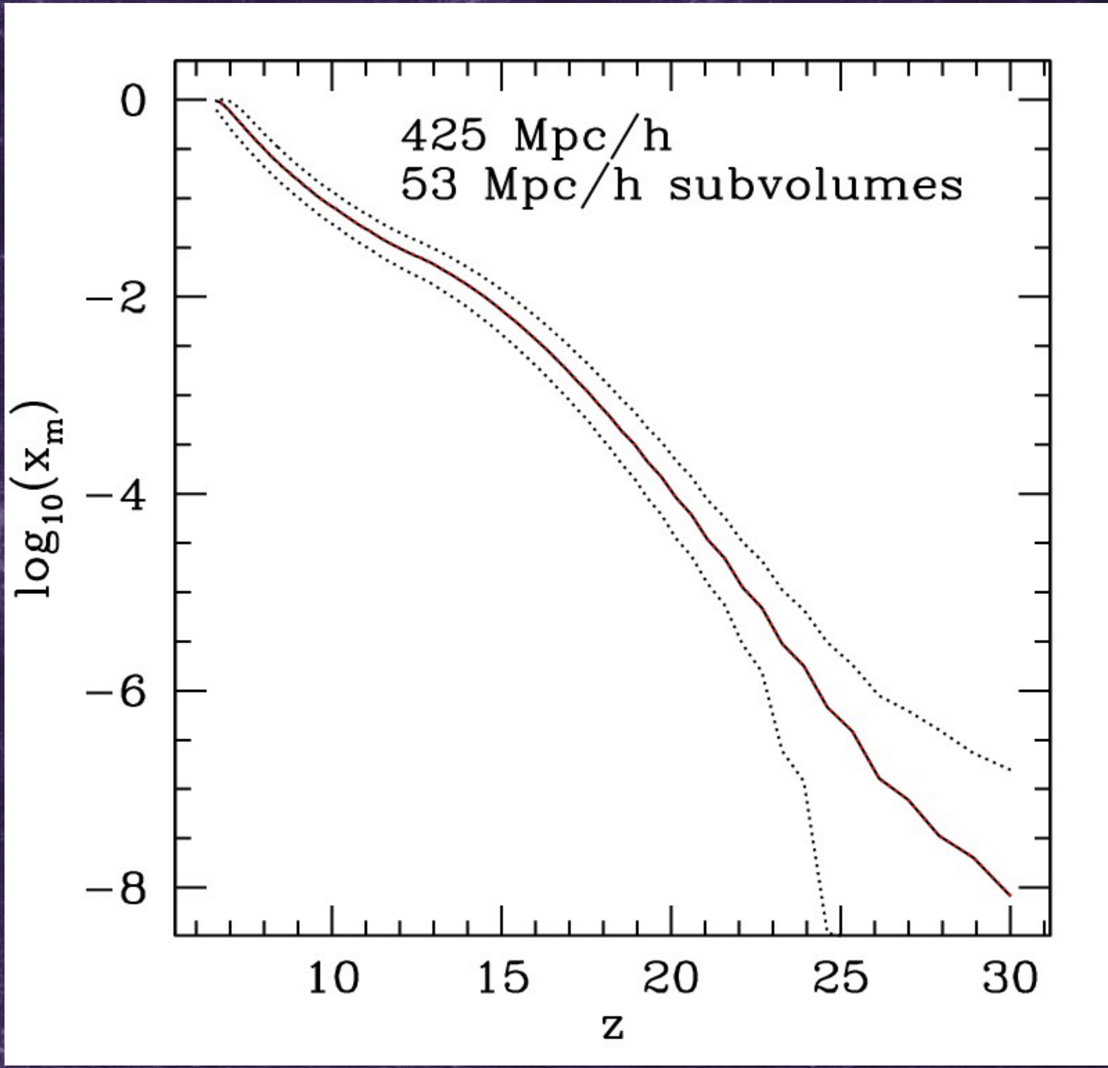
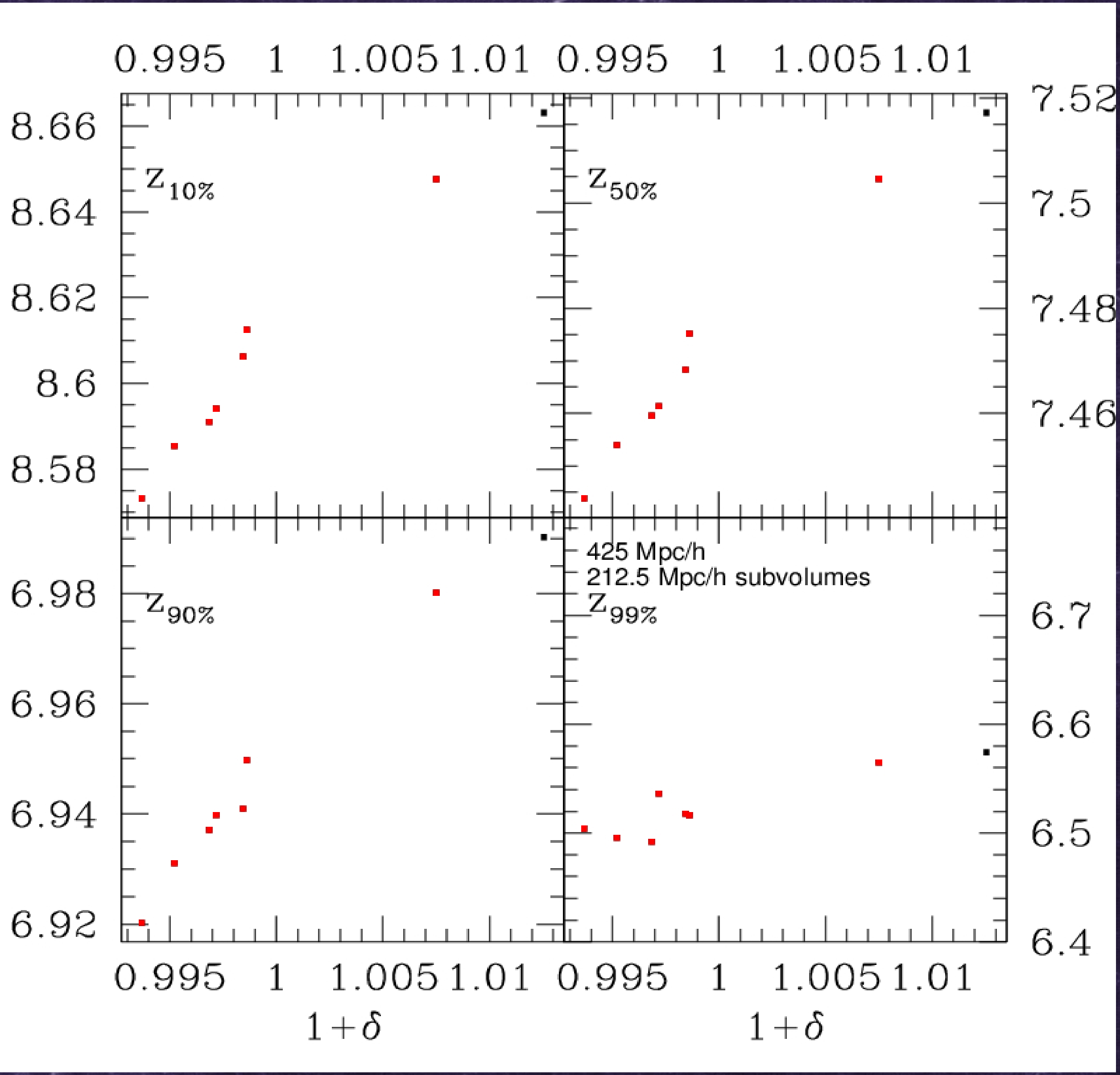


Ionization history stages

(Iliev et al, in prep.)

black: all

red: mean density



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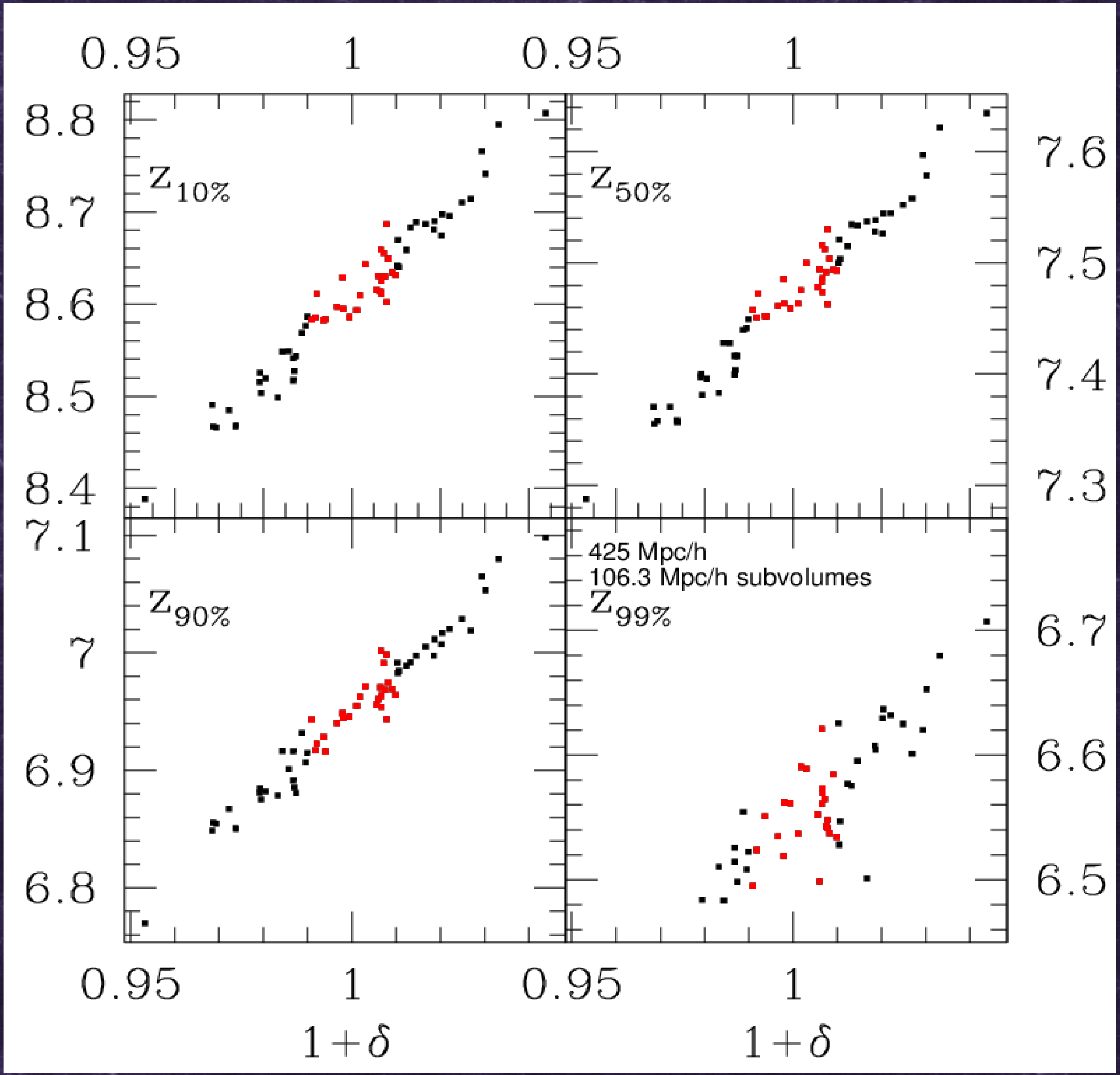

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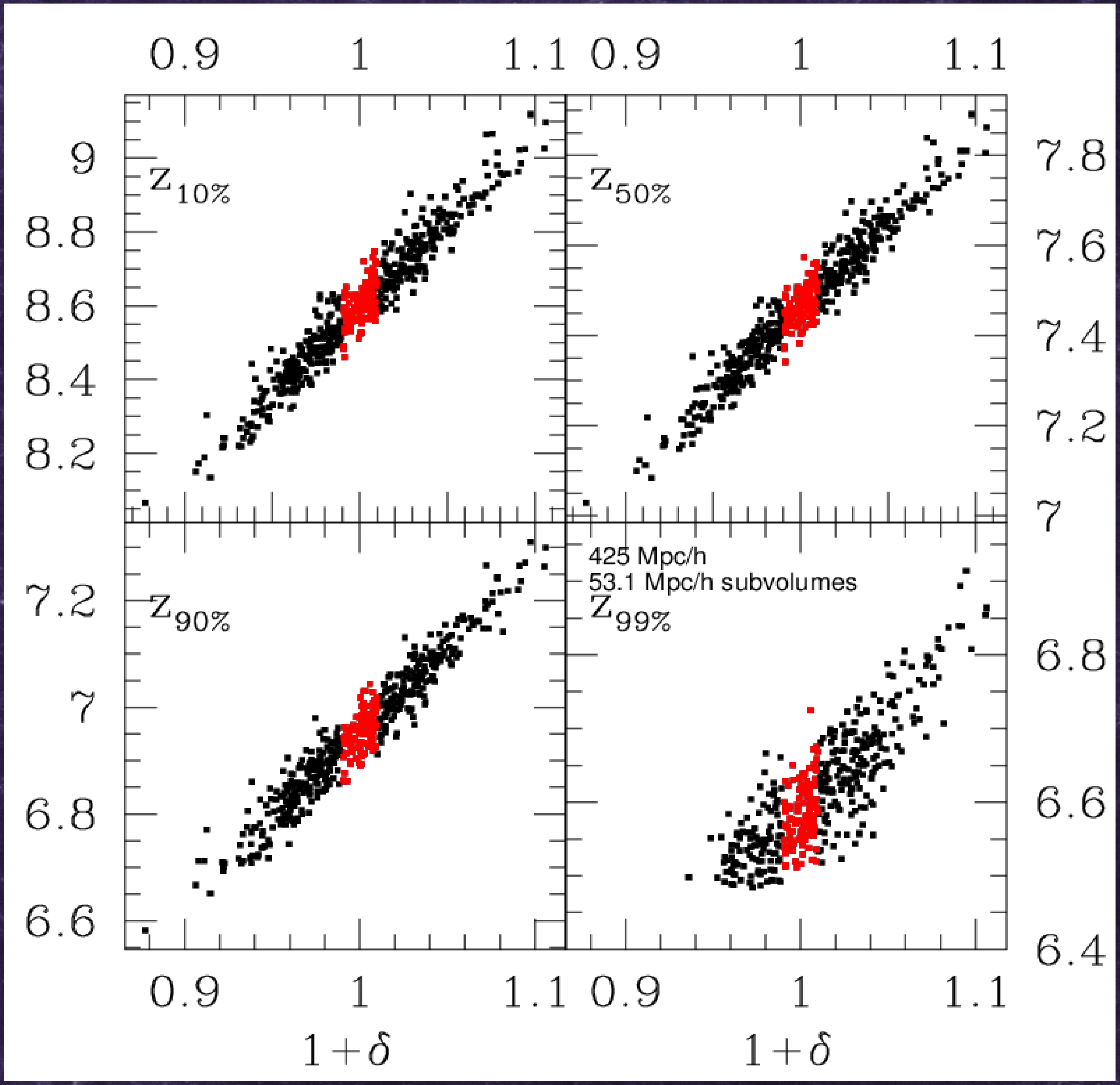


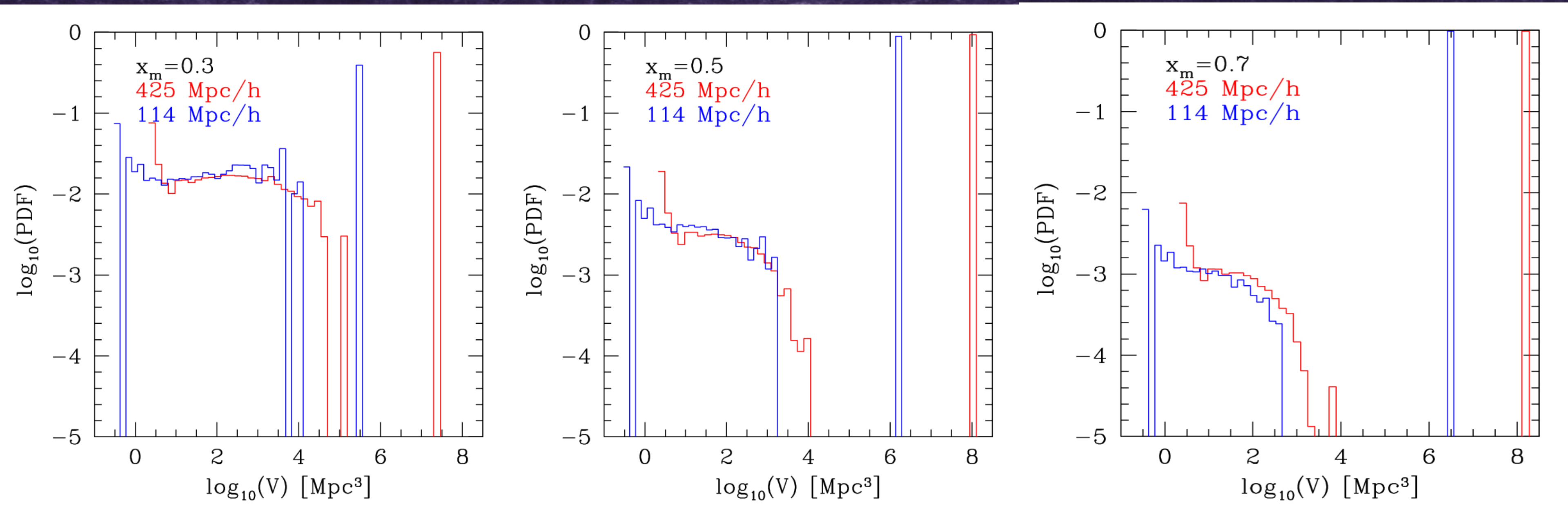
black: all

red: mean density

HII region sizes: FOF

(Iliev et al, in prep.)

- Same volume in regions with V<< V_{box}
- Many more large HII regions in the larger box

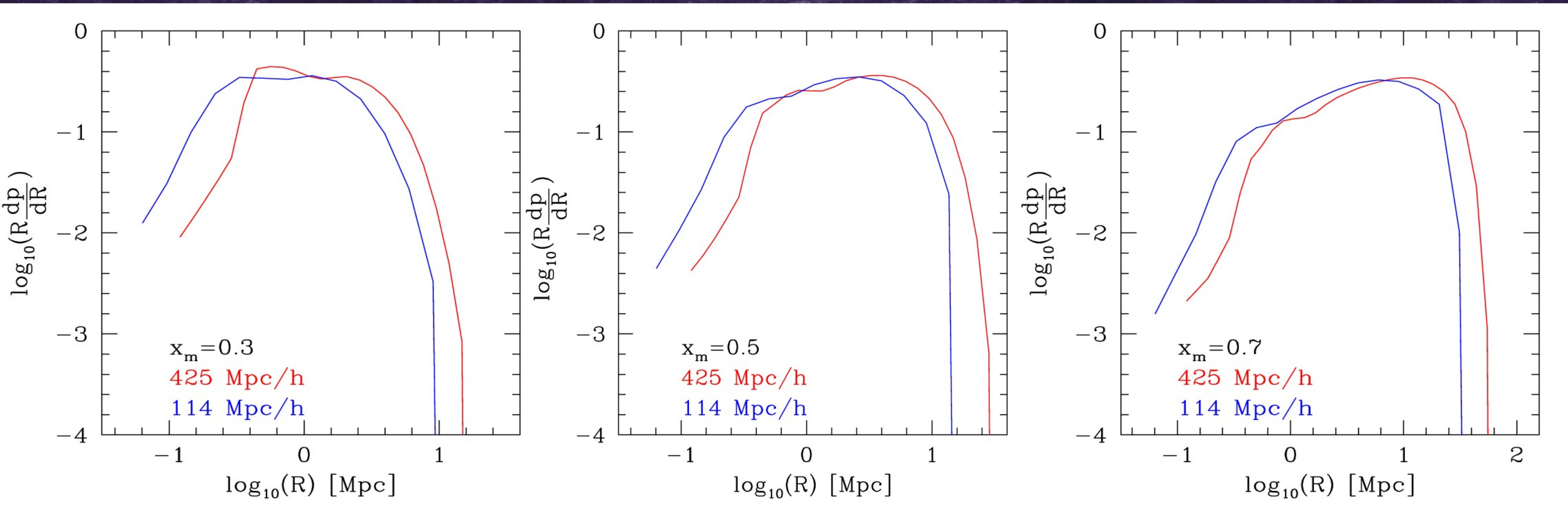


Early **Middle** **Late**

HII region sizes: Spherical Average

(Iliev et al, in prep.)

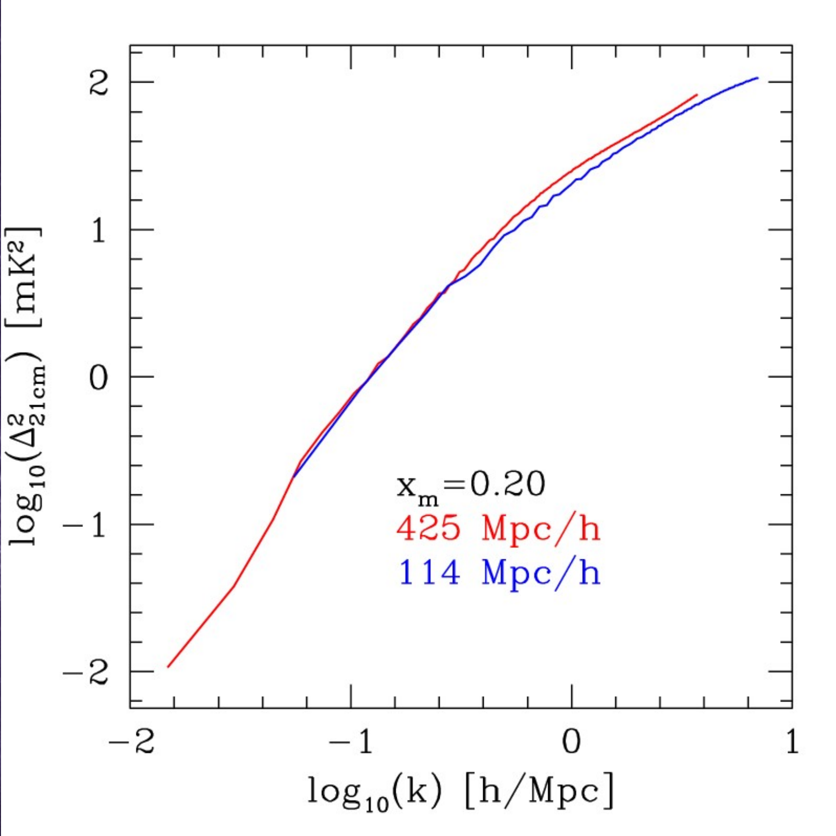
- Same volume in regions with V<< V_{box}
- Again many more large HII regions in the larger box



Early **Middle** **Late**

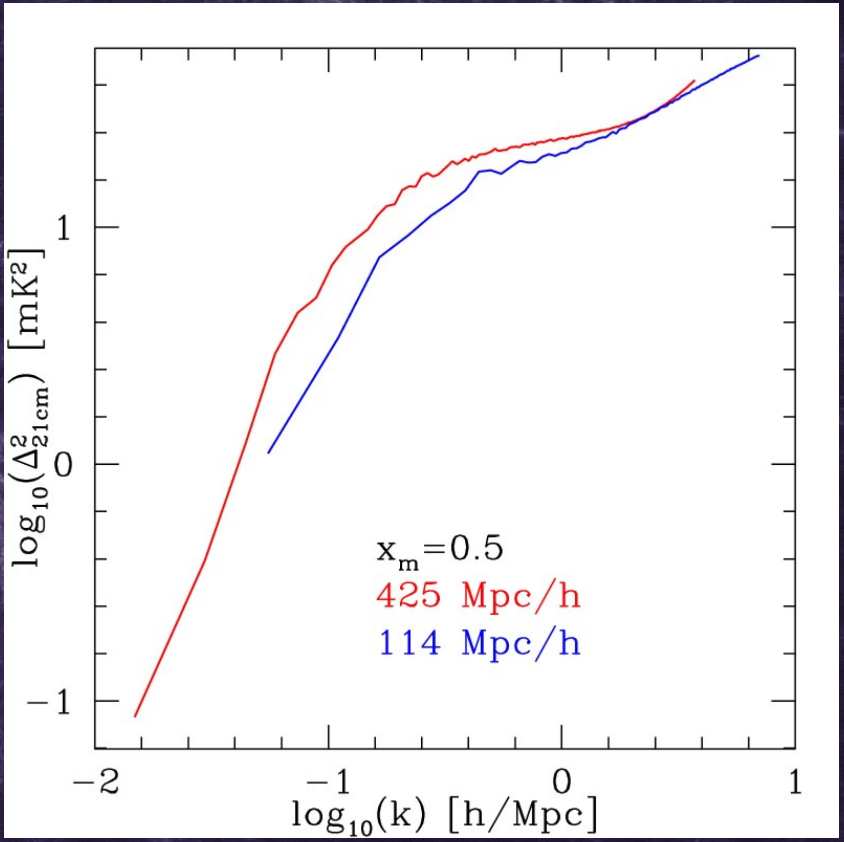
21-cm power spectra: early

(Iliev et al, in prep.)



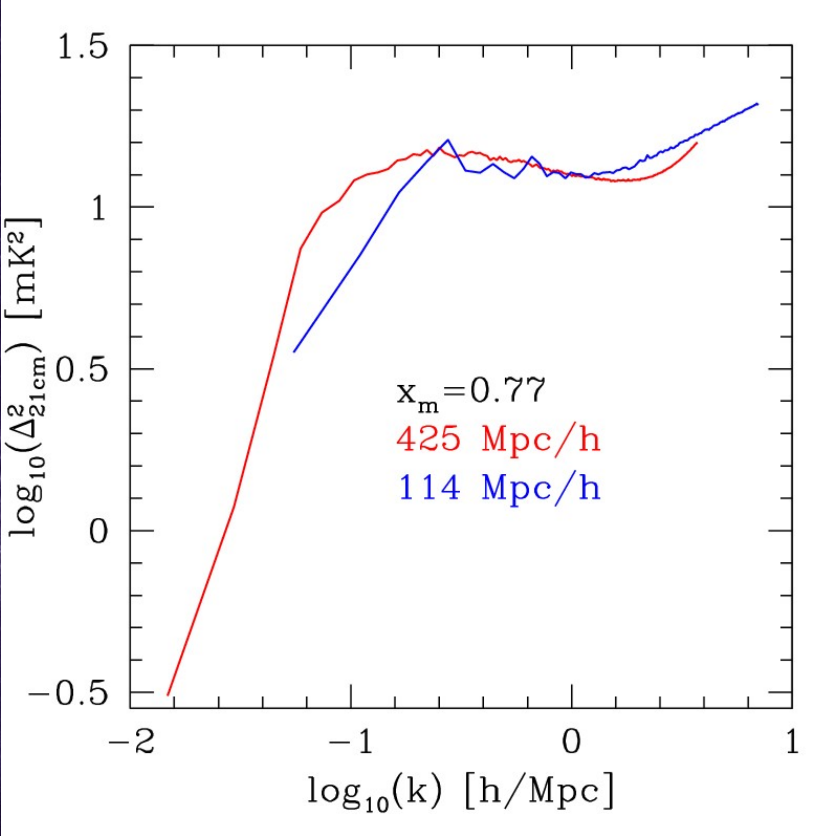
21-cm power spectra: middle

(Iliev et al, in prep.)



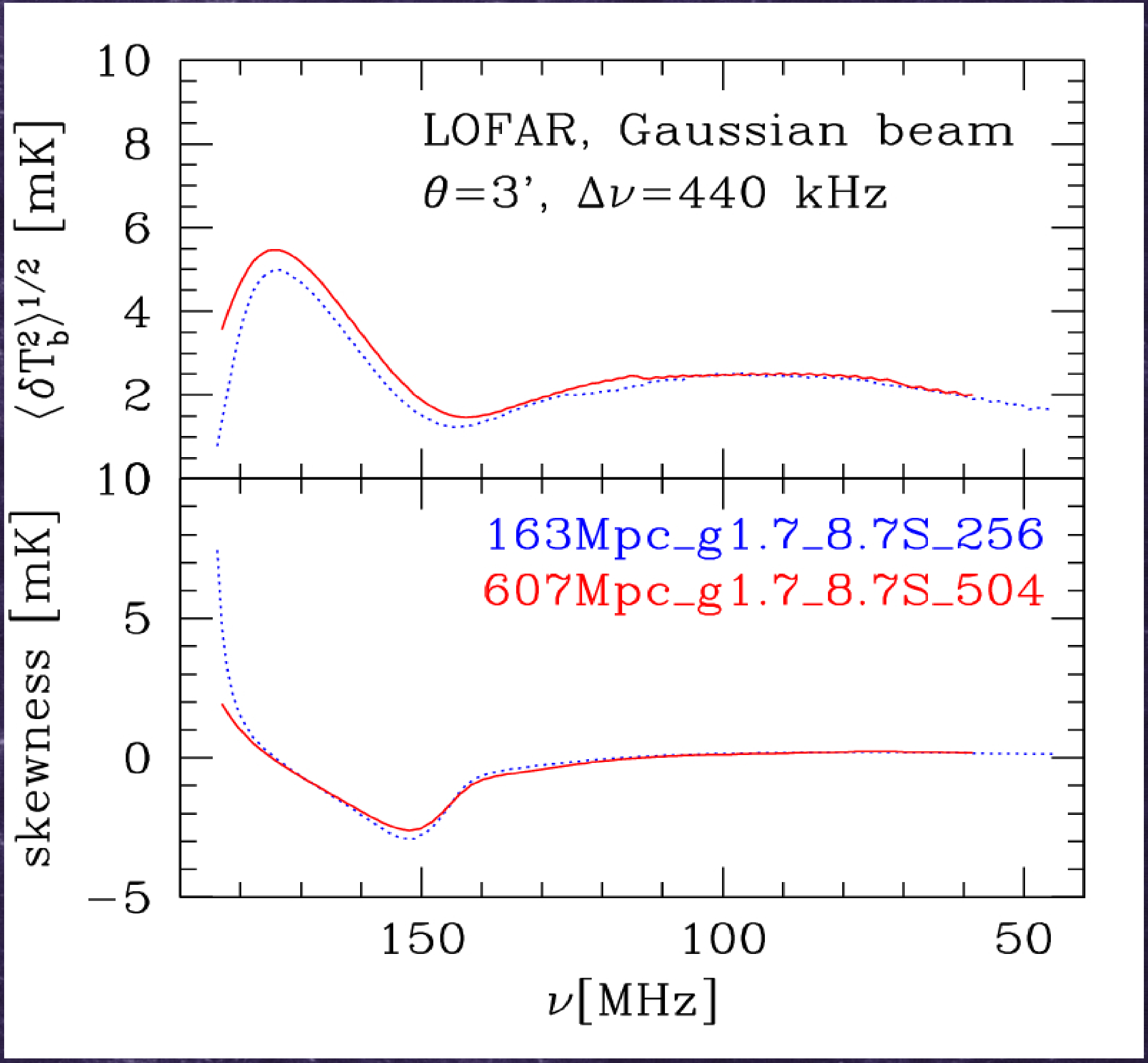
21-cm power spectra: late

(Iliev et al, in prep.)

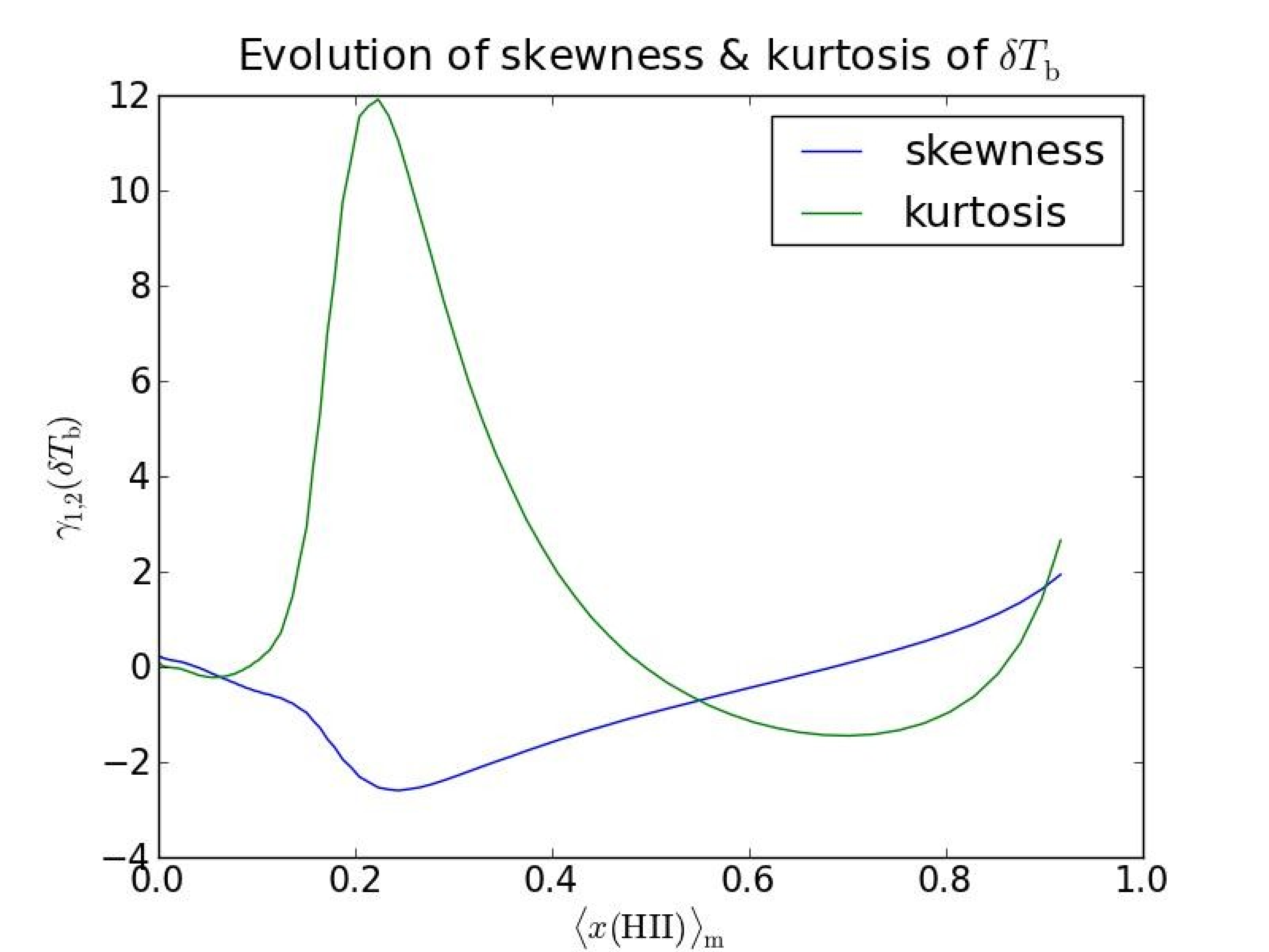


21-cm fluctuations: rms and skewness

(Iliev et al, in prep.)

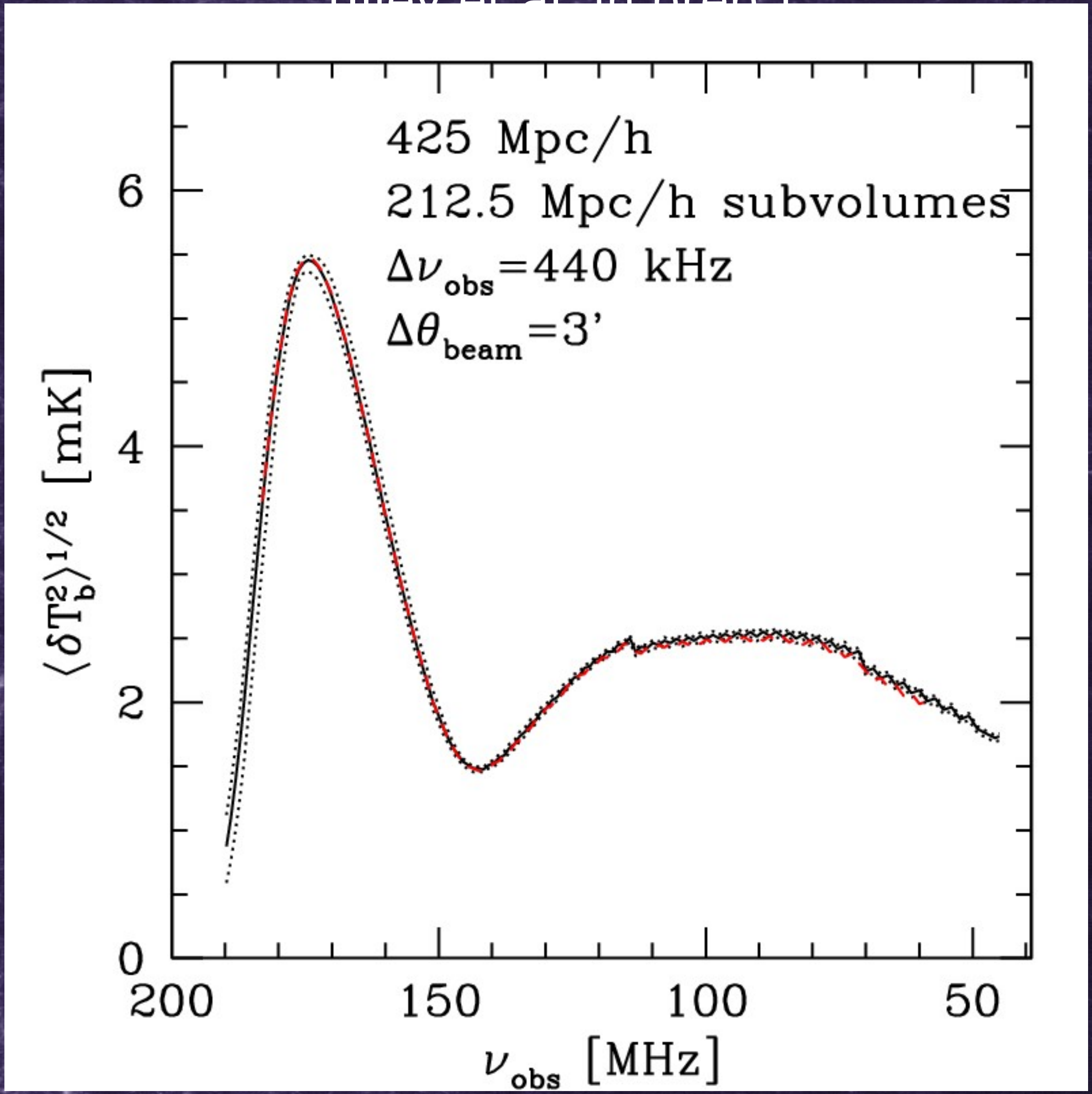


21-cm non-gaussianity (Iliev et al, in prep.)



RMS convergence with box size

(Iliev et al. in prep.)



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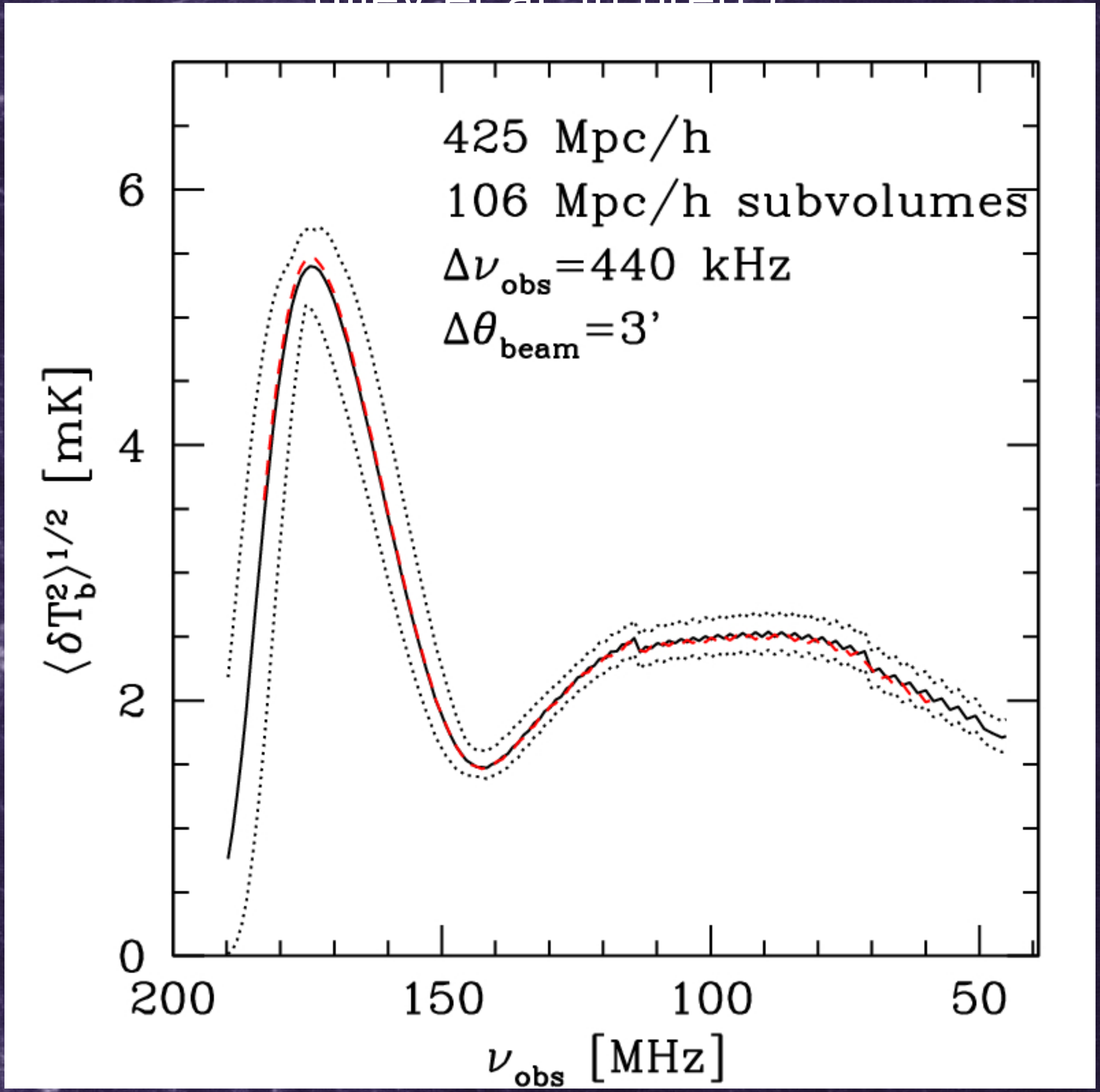

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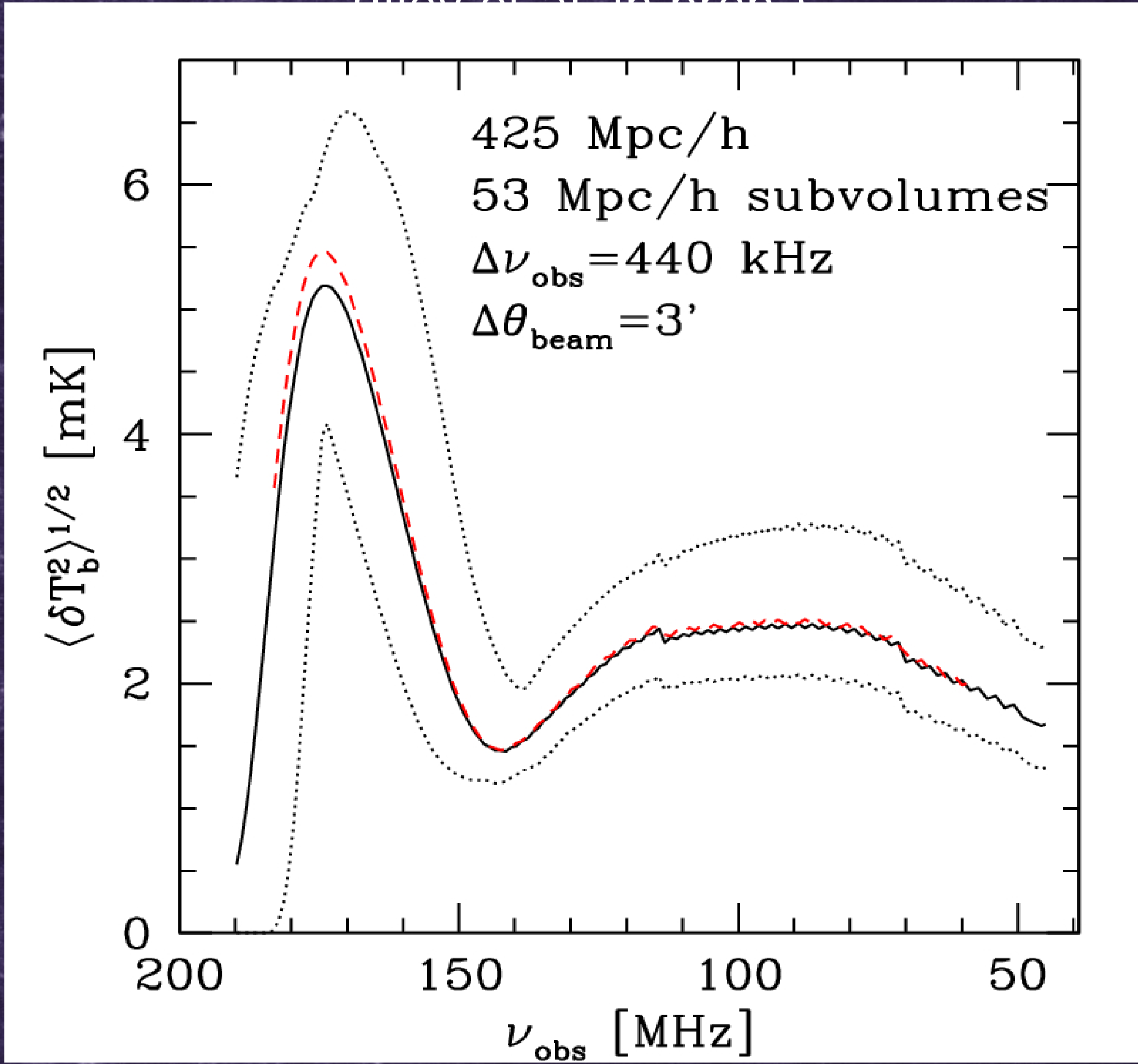
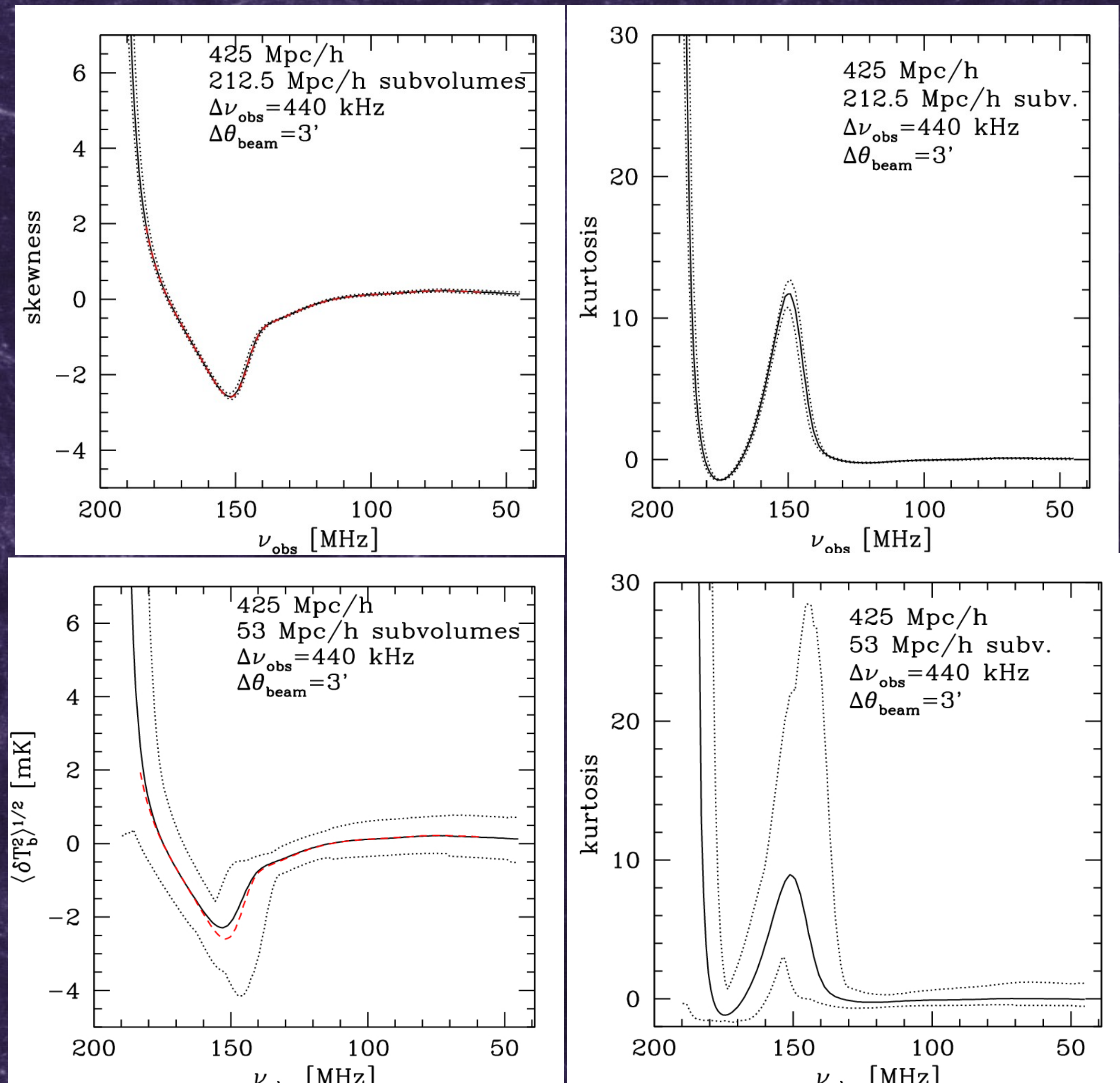


Skewness and kurtosis

(Iliev et al, in prep.)



Redshift-space distortions in the nonlinear regime (Mao et al, in prep.)

- In the linear regime the redshifted 21-cm power spectrum can be written as:

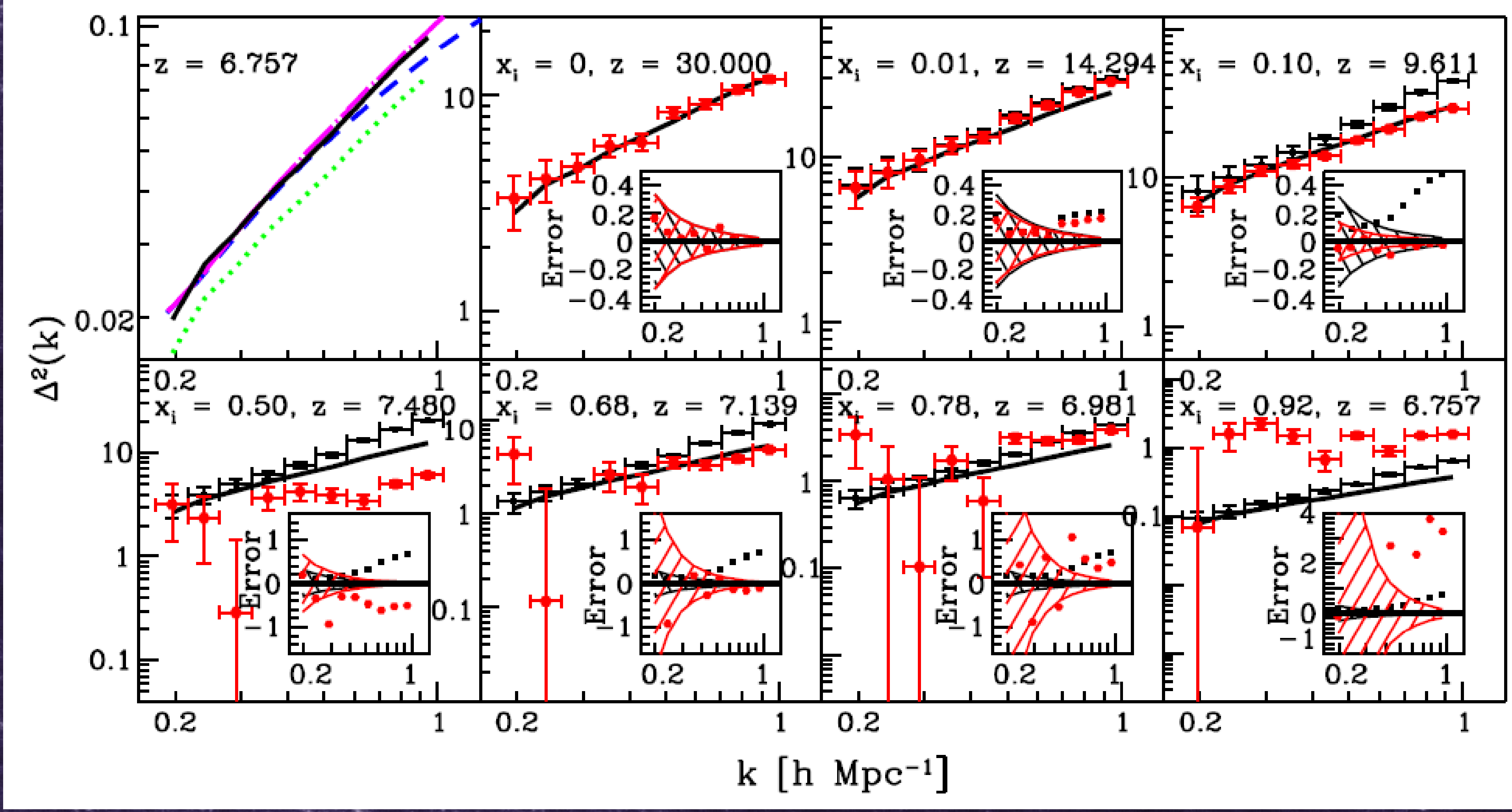
$$P^{s,\mathrm{lin}}_{\Delta T}(\mathbf{k}, z) = P_{\mu^0}(k, z) + P_{\mu^2}(k, z)\mu_{\mathbf{k}}^2 + P_{\mu^4}(k, z)\mu_{\mathbf{k}}^4$$

$$\mu_{\mathbf{k}} \equiv \mathbf{k} \cdot \mathbf{n}/|\mathbf{k}|$$

Astrophysics **Cosmology**

- This assumes that density, velocity and ionization fields are linear. However, that is generally justified only for the velocity and (at large scales) for density field.
- Q: What are the limits of applicability of this approximation?

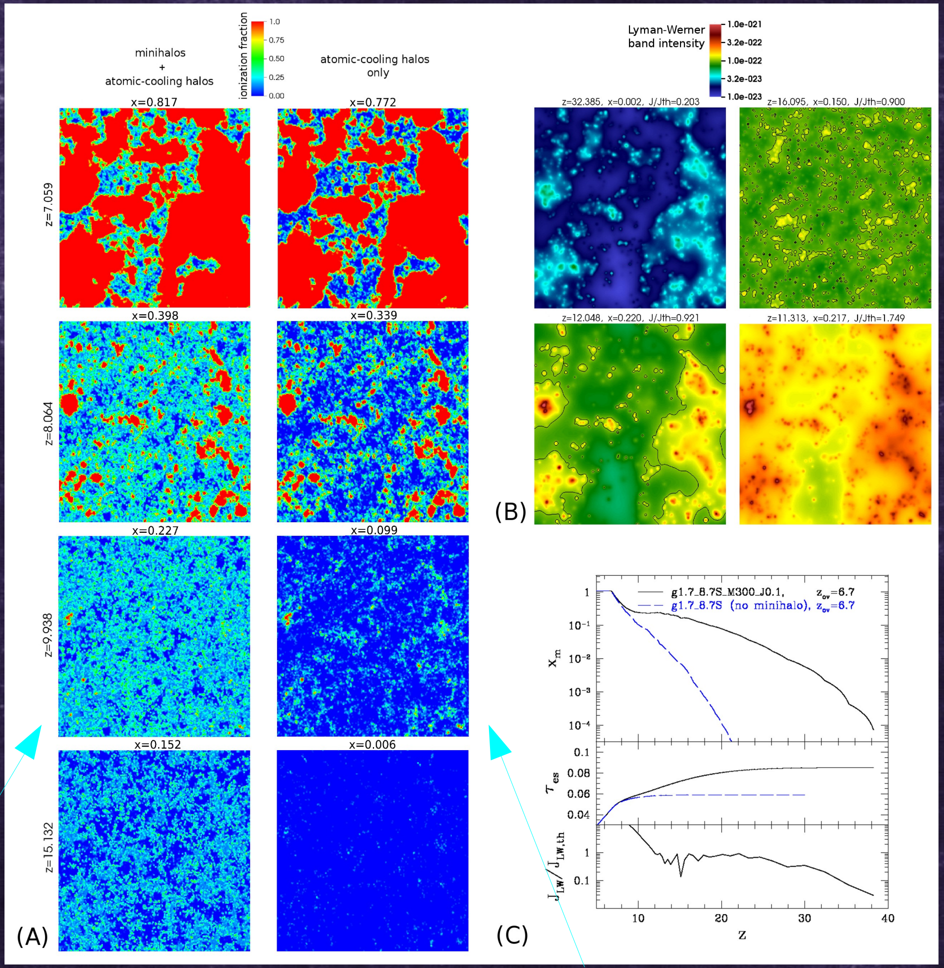
Redshift-space distortions in the nonlinear regime (Mao et al, in prep.)



Contribution of the First Stars to reionization

(Ahn et al, 2012)

- New method for including the formation, contribution and suppression of the First Stars in radiative transfer simulations.
- Lyman-Werner bands radiative transfer added.
- Reionization starts much earlier (z~40), is extended in time and its morphology changes significantly.

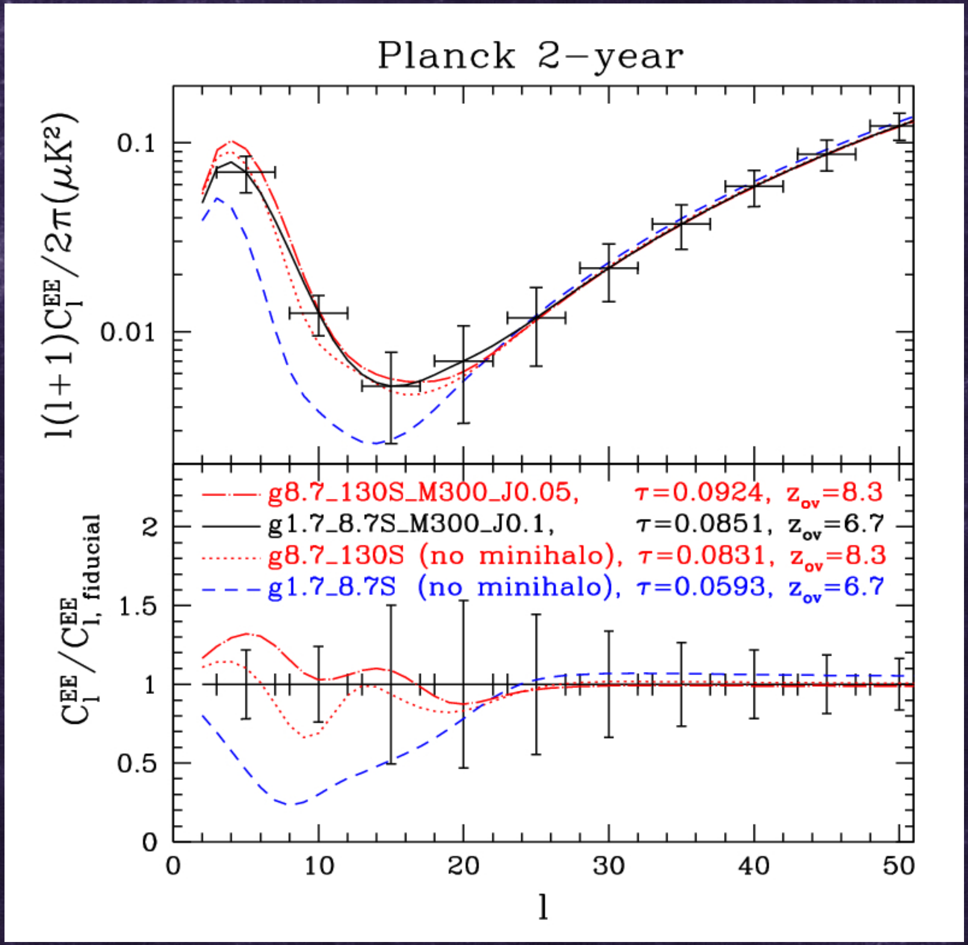


With First Stars No First Stars

Observing First Stars with Planck

(Ahn et al., 2012)

- The effect of First Stars is to both increase τ_{es} and introduce features in the CMB polarization data at large scales (due to the different reionization history)
- Effect should be detectable with Planck



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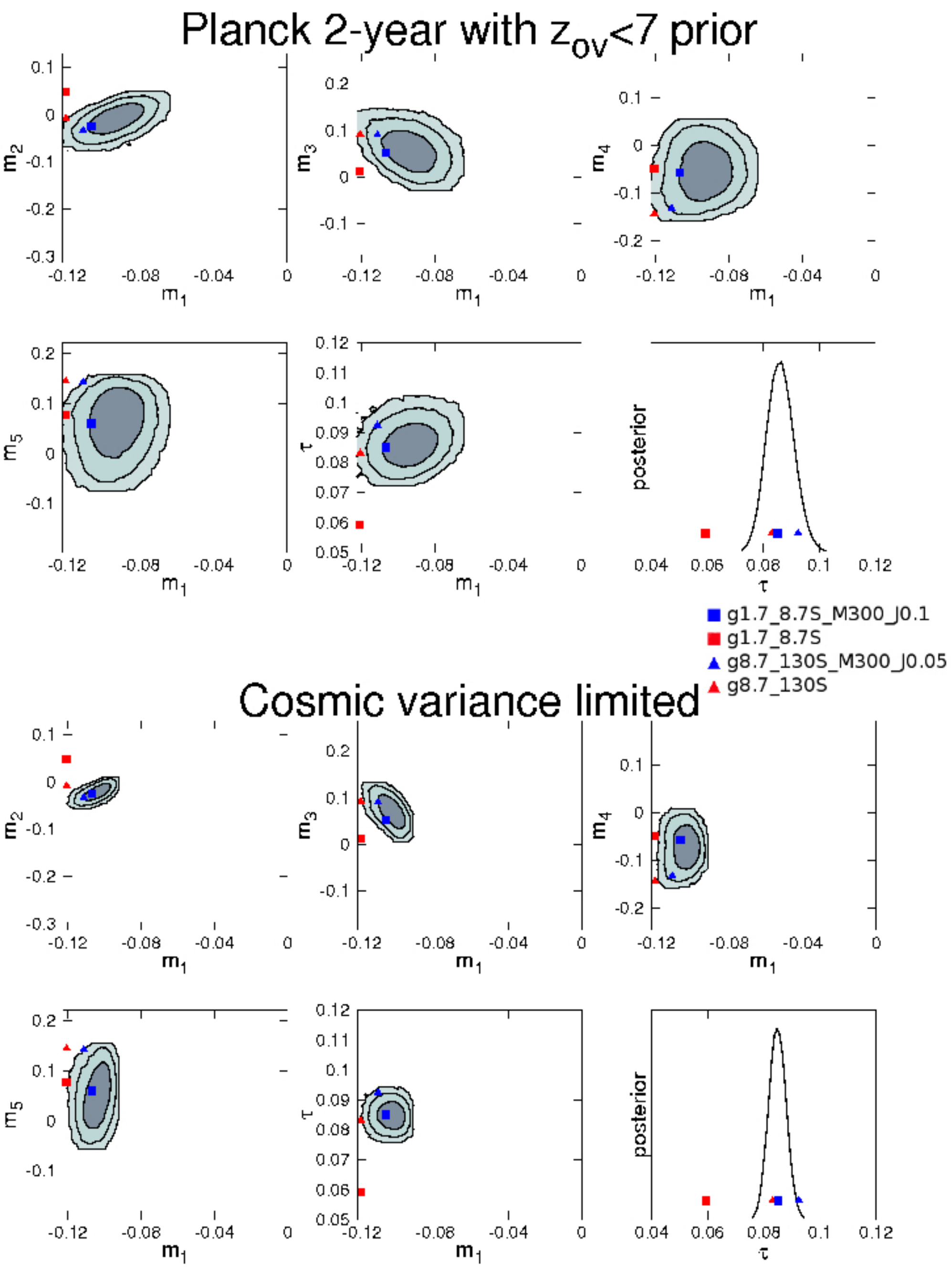
- Principal component analysis shows that effect is detectable with approx. 2–σ confidence level even for fixed τ_{es} if we assume $z_{ov}<7$ prior.



Summary

- Structure formation at high-z is quite different from later times — different halo mass function, higher halo clustering.
- FOF halo mass function has universal shape for fixed linking length, at all scales and redshifts.
- Spherical overdensity mass functions are redshift- and Omega-dependent.
- Very long wavelength density fluctuations increase reionization patchiness and 21-cm signal appreciably.
- Reionization history and patchiness converge at scales above 100 Mpc/h, but vary significantly for smaller volumes, even if they are at mean density.
- μ-decomposition approximation is valid only during the early stages of reionization.
- Effects of the First Stars should be directly detectable with Planck → first direct observation of the Cosmic Dawn?